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The chemical composition of plant and insect flour as a factor that differentiates the development of storage pests

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ABSTRACT

Edible insects, rich in nutrients, have the potential to become a healthy and sustainable alternative to traditional, but often deficit, food products. The availability of this prospective source of protein, without disruptions in the continuity of supply, is only possible with the correct storage method. The conducted research aimed to assess the development of the flour beetle (*Tribolium confusum* Duv.) on wheat flour, ground insect protein, and products with its additives (2%, 5%, 10%, and 50% addition of insect flour to wheat flour). Development monitoring (no-choice test) of *T. confusum* showed that this pest developed most abundantly in combinations with a high content of cricket flour (100%, 50%). The results of these studies proved that insect protein can be a source of food for storage pests. The second part of the experiment, taking into account the food preferences of the analysed insect, showed that in a situation of free choice, this insect is more willing to inhabit plant flour (wheat) and combinations with a small addition of insect flour (2%, 5%). In combination with a high share of insect protein (10%, 50%), the development intensity of the tested beetle was significantly lower, and in combination with pure cricket flour (100%), no progeny of *T. confusum* was found. Although cricket flour is a good food for *T. confusum*, it does not attract adult forms of this pest. This may be due to the lack of volatile attractants in its composition or the masking of these compounds by other substances. The high protein content in cricket flour (68.05%) may indicate that proteins are responsible for these effects, and further studies should explore their effects on the feeding behaviour of *T. confusum*.

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KEYWORDS

Edible insects; food attractiveness; storage pests; storing insect flour

Introduction

Insects are a valuable, although underutilized, source of high-quality food (Patel et al. 2019). They are a rich reservoir of protein, fatty acids, and micro and macro elements. Due to their high fibre content, consuming insects also benefits the gut microbiome, increasing the number of probiotic bacteria (Kipkoeh et al. 2021; Kipkoeh 2023; Stull 2023). In addition, their breeding, compared to conventional plant or animal production, produces less greenhouse gas and ammonia and uses less water (Ooninx & de Boer 2012; Van Huis 2013; Nowakowski et al. 2022; Reddy et al. 2024). Therefore, in 2021, an implementing regulation of the European Commission was also issued authorizing the introduction to the market of dried mealworm larvae (*Tenebrio molitor* L.), migratory locusts (*Locusta migratoria* L.), and house crickets (*Acheta domesticus* L.) as a component of human food (Pilco-Romero et al. 2023; Sogari et al. 2023; Siddiqui et al. 2024).

Apart from production or consumer acceptance, an important direction of development of this market is to provide these products with conditions for safe and long-term storage. Losses during storage of food products are primarily caused by storage pests, which can cause losses even up to 20% (Phillips & Throne 2010). Due to the growing interest in insects in the context of food, it is becoming necessary to know the behaviour and preferences of storage pests feeding on flour products made from insect protein and on products with their additives. This information can provide some guidance for designing safe ways of storing this type of food in warehouses. The flour beetle (*Tribolium confusum* Duv.) (Coleoptera: Tenebrionidae) is considered one of the most dangerous storage pests, developing most

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abundantly on crushed cereal products (Park & Burton 1948; Trematerra et al. 2000; Ajayi et al. 2019). Because of this it was selected as a model species in our research. The dynamics of the development of this species, like other storage pests, depend mainly on temperature, humidity, and the type of food on which it feeds. The food preferences of *T. confusum* are determined by the physical properties of the inhabited products (including hardness, glassiness, thickness, degree of fragmentation) and chemical properties (including protein, starch, crude fibre, fat content) (Trematerra et al. 2000; Laszczak-Dawid et al. 2010a, 2010b; Kordan et al. 2011; Ajayi et al. 2019; Ludwiczak et al. 2023).

Due to the high ecological plasticity of *T. confusum*, an overarching research hypothesis was formulated, assuming that cricket flour and its addition to wheat flour constitute a food source on which the tested pest may feed. This has not yet been adequately verified in the scientific literature; therefore, to fill this information gap, the study aimed to test this assumption and analyse the nature of the impact of this type of food on the tested pest. The research hypothesis was tested by:

- assessment of the developmental parameters of the *T. confusum* population developing on pure cricket flour and with its various additions to wheat flour;
- analysis of the differences in the development of *T. confusum* on cricket flour and wheat flour resulting from the different chemical composition of the food;
- examination of whether the chemical composition of cricket flour can affect the process of finding and accepting this type of food.

The impact of the above assumptions was assessed in tests in which *T. confusum* fed on a selected type of food (no-choice test) or had the free opportunity to choose the food (free-choice test).

Materials and methods

Materials

Entomological observations of the development of *T. confusum* were conducted on wheat flour (Control), house cricket (*Acheta domesticus* L.) flour (Cf_100%), and wheat flour with 2%, 5%, 10%, and 50% addition of insect flour. The experiment used wheat flour of the Belissa variety (Biobabalscy) and flour made from 100% dried and ground adult house crickets (Food Bugs). The study was conducted in a SANYO MLR-350 H climatic chamber (Sanyo Electric Co., Ltd., Japan) under constant temperature (30°C) and humidity (70%) conditions and in complete darkness (Park & Burton 1948; Howe 1960; Gołębiowska et al. 1976). The flours used in the study were conditioned for 7 days in the planned laboratory conditions before the start of the experiment. The *T. confusum* population came from a conservative culture conducted at the Department of Entomology, Phytopathology and Molecular Diagnostics (University of Warmia and Mazury in Olsztyn, Poland) on mountain oat flakes (Melvit S.A.) with the addition of yeast (Khalequzzaman et al. 1994). Pupae of the studied species were obtained from the mother cultures and then separated by sex based on the shape of the external sexual appendages (Howe 1960; Gołębiowska et al. 1976).

Bioassays

No-choice test

We weighed samples of the flour material (10 g) (laboratory scale WPS220/C/2, Radwag, Radom, Poland) and placed in vinidur containers (width 10 cm, height 3 cm) with a ventilation hole (10 mm hole secured with a chiffon mesh). The experiment was performed in 10 replications for each of the six combinations:

- Control – pure wheat flour;
- Cf_2% – 2% addition of cricket flour to wheat flour;
- Cf_5% – 5% addition of cricket flour to wheat flour;
- Cf_10% – 10% addition of cricket flour to wheat flour;
- Cf_50% – 50% addition of cricket flour to wheat flour;
- Cf_100% – pure cricket flour.

Four individuals of the tested beetle (previously isolated, two individuals of each sex, approximately 14 days old) were introduced into containers with weighed flour. These insects were then removed after 23 days from settlement. The duration of the experiment was determined based on our previous observations and studies on the development of *T. confusum*. Entomological observations began on the 30th day after the removal of *T. confusum* and were repeated every 7 days until all adults were obtained. Monitoring the development of this pest included an analysis of its numbers. In addition, after the end of the experiment, the material left after *T. confusum* feeding was weighed, and its weight loss was calculated.

Free-choice test

The study assessed the flour beetle's food preferences in constant laboratory conditions. The experiment used arenas made of plexiglass in a cuboid shape with a hexagonal base (side length 10 cm, height 6 cm). The arenas had six ventilation holes (on the side walls of the polyhedron) with a diameter of 2 cm, secured with a chiffon mesh to prevent the beetles from escaping. In the middle of the arena, six dishes with flour in all tested combinations were placed in the shape of a circle. In the centre of the circle formed by the dishes, 12 couples of approx. 14-day-old imagines of the beetle were placed (Figure 1). The design of the experiment was planned in such a way as to allow the tested beetles to freely penetrate the arena and access the flour placed in the dishes in various combinations. After 7 days from the beginning of the experiment, adult forms of *T. confusum* were counted and removed from the arena and the tested material. The dishes with the tested flour combinations and the eggs laid therein were placed in vinidur containers with ventilation holes secured with a net. Further development of insects took place in constant, homogeneous thermal and humidity conditions. The experiment was performed with 5 replications.

Chemical properties of grain

The chemical analysis of wheat flour and domestic cricket flour was carried out using the methodology described in our previous publications (Ludwiczak et al. 2023, 2024).

Statistical analysis

Data describing the developmental parameters of *T. confusum* concerning the number of offspring generations, the average loss of flour mass, and the average mass of one offspring individual were subjected to distribution assessment using the Shapiro-Wilk test. The test results revealed that a normal

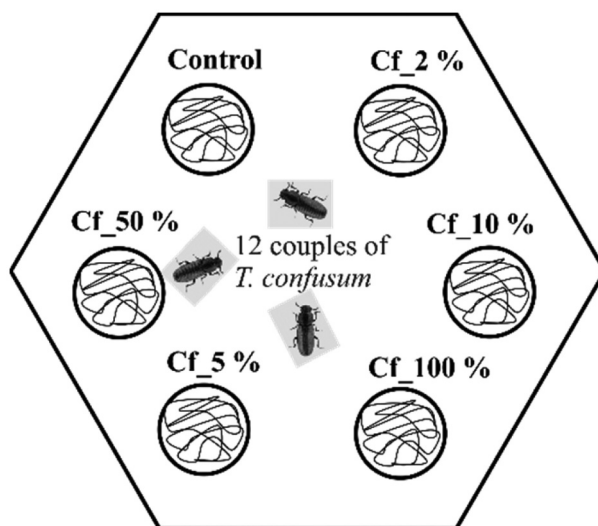


Figure 1. Schematic diagram of the arena (a vinyl container with a hexagonal base, 10 cm sides, and 6 cm height) in which *T. confusum* oviposition site selection was studied in a free-choice test, with graphically depicted vessels containing the flour combinations analysed. The centre illustrates the location where adult *T. confusum* were released and were free to choose their food.

distribution characterized the values of the first two parameters. In contrast, the values describing the average mass of one offspring individual had a unimodal distribution. Therefore, data with a unimodal distribution were subjected to logarithmic transformation ($\ln x + 1$), and a one-way analysis of variance (ANOVA) was used to assess the significance of differences in the studied variables in combinations with different additions of cricket flour. Groups of average, studied parameters related to the development of *T. confusum*, which did not differ statistically, were marked with the same letter index: a, b, c ... (Tukey Honestly Significant Difference (HSD) test). The evaluation of the similarity of selected chemical parameters (dry mass, crude ash, total protein, crude fat, and crude fibre) characterizing the chemical composition of wheat flour (Control) and cricket flour (Cf_100%) was performed using non-metric multidimensional scaling (NMDS), using Bray-Curtis's measure of similarity. A non-parametric Analysis of Similarities (ANOSIM) test (Clarke 1993) was applied to statistically assess differences. The statistical analysis also used the redundancy analysis (RDA) method and canonical correspondence analysis (CCA). 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) (Ter Braak & Smilauer 1998). Statistical calculations and their graphical interpretation were performed using Statistica 13.1, Canoco 4.51, and PAST 2.01.

Results

The development of *T. confusum* on media with different cricket flour contents was assessed in the no-choice test and free-choice test combinations.

No-choice test

The ANOVA showed significant differences between the variable content of cricket flour addition and the parameters describing the intensity of flour beetle development that were distinguished. The number of the progeny generation of the tested beetle species ($F = 21.03$; $p < .01$) and the loss of mass of the flour on which this pest developed ($F = 7.32$; $p < .01$) were significantly differentiated by the factor of the variable addition of cricket flour. However, no significant effect of this factor on the average mass of the progeny beetle was found ($F = 0.95$; $p = .46$) (Table 1).

The best conditions for development, expressed by the number of individuals in the offspring generation, were found by the studied beetle species developing on pure cricket flour (average 202.8 individuals) and on the combination in which this flour constituted a 50% addition to wheat flour (average 204.8 individuals). A significantly smaller offspring generation of *T. confusum* appeared in the combinations with the minor addition of cricket flour (10% – 142.4 individuals; 5% – 116.3 individuals and 2% – 130.4 individuals). The smallest number of offspring beetles was recorded when the beetle developed on pure wheat flour (average 109.1 individuals) (Figure 2).

The loss of mass of food on which *T. confusum* fed varied significantly, depending on the addition of cricket flour (Table 1). The pest ate the most food in combination with a 50% addition of cricket flour (Cf_50%); on average, it was 1.08 g. Significant losses in food mass were also noted with a 2% addition of Cf (average 1.01 g), 10% (0.84 g), and 5% (0.83 g). A similar average value of this parameter (0.81 g) was described for the control combination (Control). The lowest weight of eaten food was noted for the combination where *T. confusum* developed on pure cricket flour – on average 0.63 g (Figure 3).

Table 1. The result of the one-way analysis of variance (ANOVA) for the studied developmental parameters of *T. confusum* growing on combinations with different additions of cricket flour.

Developmental parameter studied	df*	ANOVA	
		F value	p^{**}
Progeny of beetles	5	21.03	.00
Loss of flour mass	5	7.32	.00
Mass of 1 progeny beetle	5	0.95	.46

*Degrees of freedom; **test probability p value.

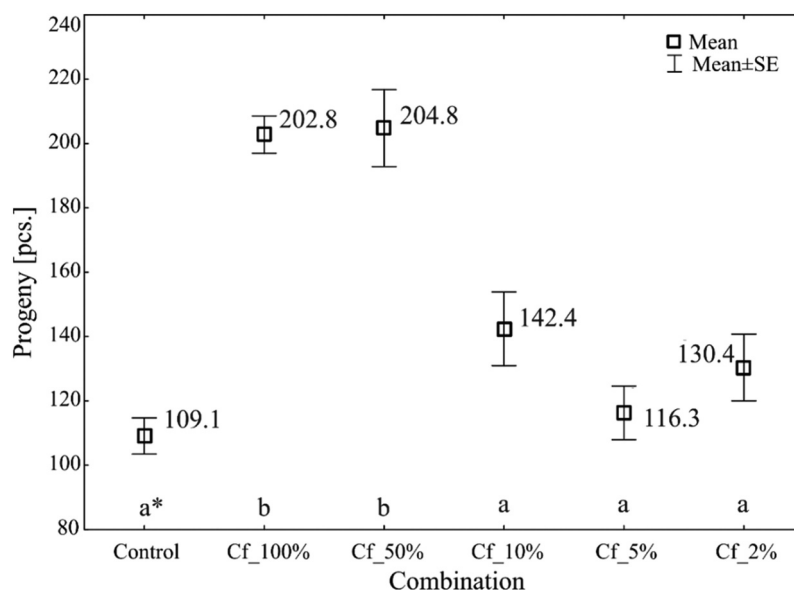


Figure 2. Average number of *T. confusum* progeny developing on flour with different additions of cricket flour (*means marked with the same letter do not differ significantly, by Tukey's HSD test). SE: Standard Error.

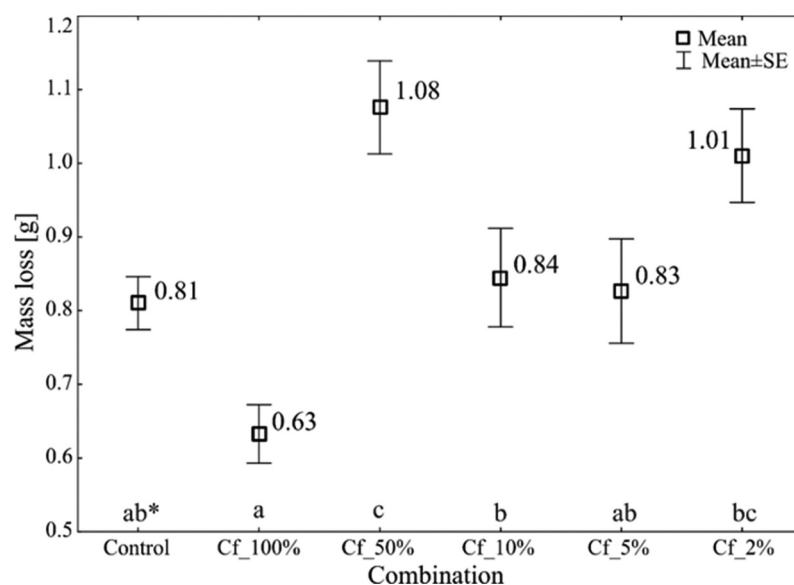


Figure 3. The average value of weight loss of food on which *T. confusum* was growing depending on the addition of cricket flour (*means marked with the same letter do not differ significantly, by Tukey's HSD test). SE: Standard Error.

The average weight of one offspring beetle did not differ significantly between the tested combinations (Table 1). The highest weight of offspring was observed on pure cricket flour (average 0.0025 g), while the lowest was found on on the control wheat flour (0.0020 g) (Figure 4).

Free-choice test

In the tested experimental variant, the ANOVA showed significant differences between the variable content of cricket flour addition and the parameters describing the intensity of *T. confusum* development. The number of individuals in the offspring generation of the tested beetle species ($F = 14.3; p < .01$), the loss of flour mass on which this pest developed ($F = 10.5; p < .01$), and the average mass of the offspring beetle ($F = 10.2; p < .01$) were significantly differentiated by the factor of the variable addition of cricket flour (Table 2).

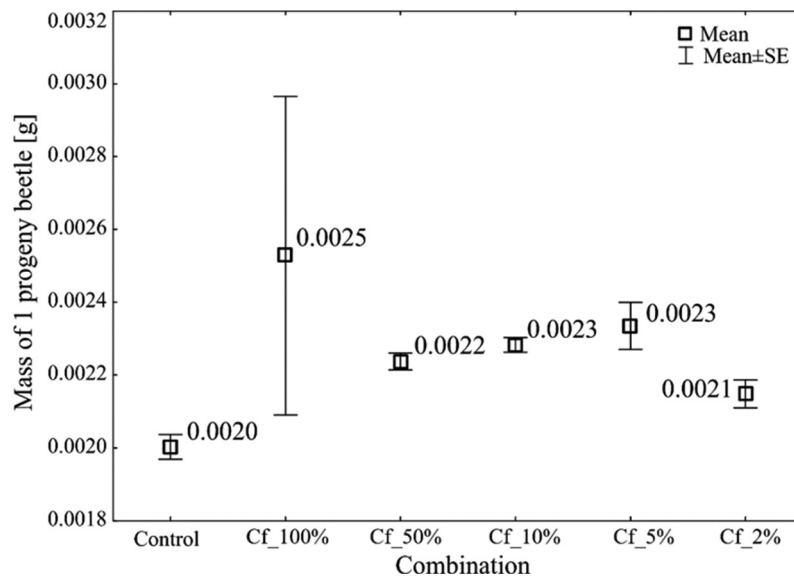


Figure 4. The average weight of 1 *T. confusum* offspring beetle developed on the tested combinations depending on the addition of cricket flour (*means marked with the same letter index do not differ significantly, by Tukey's HSD test). SE: Standard Error.

Table 2. The result of the one-way analysis of variance (ANOVA) for the studied developmental parameters of *T. confusum* growing on combinations with different additions of cricket flour (test with free choice).

Developmental parameter studied	df*	ANOVA	
		F values	<i>p</i> **
Progeny of beetles	5	14.3	.00
Loss of flour mass	5	10.5	.00
Mass of 1 progeny beetle	5	10.2	.00

*Degrees of freedom; **test probability *p* value.

Beetles in the free-choice combination more often chose food with a small addition of cricket flour (Cf_5% and Cf_2%) and pure wheat flour (Control) as a place to lay eggs. The highest number of offspring was found in the Cf_5% combination – mean 69.0 offspring individuals. Lower numbers were found in the Cf_2% combination (mean 35.2 individuals) and the control combination (mean 38.6 individuals). Increasing the share of cricket flour in the food caused a significant decrease in the number of offspring of *T. confusum* (Cf_10% – mean 12.8 individuals; Cf_50% – mean 0.2 individuals). The pest did not lay eggs in combination with pure cricket flour, so no offspring appeared here (Figure 5).

The results concerning the loss of food mass recorded during the pest's feeding and development were almost identical to those for the number of the pest's progeny generation. The largest losses in food mass were recorded for the control combination (mean 0.5786 g) and Cf_5% (mean 0.5412 g). Significantly lower values of this parameter were recorded for the Cf_2% combination (mean 0.3784 g) and Cf_10% (mean 0.1216 g). No loss in food mass was recorded for pure cricket flour, and the combination with its 50% share was minimal (Cf_50% – mean 0.0033 g) (Figure 6).

A similar tendency for the two *T. confusum* development parameters discussed above was observed for the values describing the mass of one progeny beetle (Figure 7).

The differences in the chemical composition of wheat flour (Control) and cricket flour (Cf_100%) were studied by assessing their basic chemical content parameters (dry matter, crude ash, total protein, crude fat, and crude fibre). The two tested flours differed significantly regarding chemical composition (Tables 3 and 4).

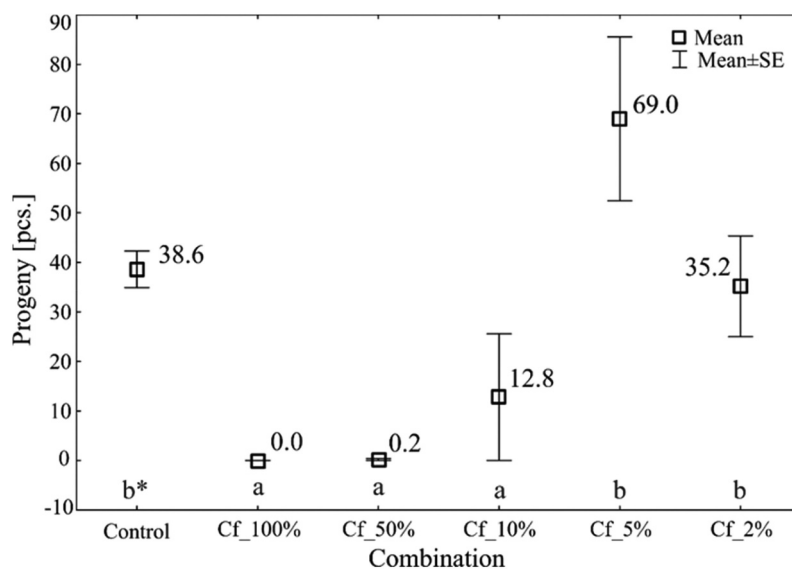


Figure 5. The average number of progeny beetles of *T. confusum* observed on the tested combinations with different shares of cricket flour in the free-choice test. (*means marked with the same letter index do not differ significantly, by Tukey's HSD test) SE: Standard Error.

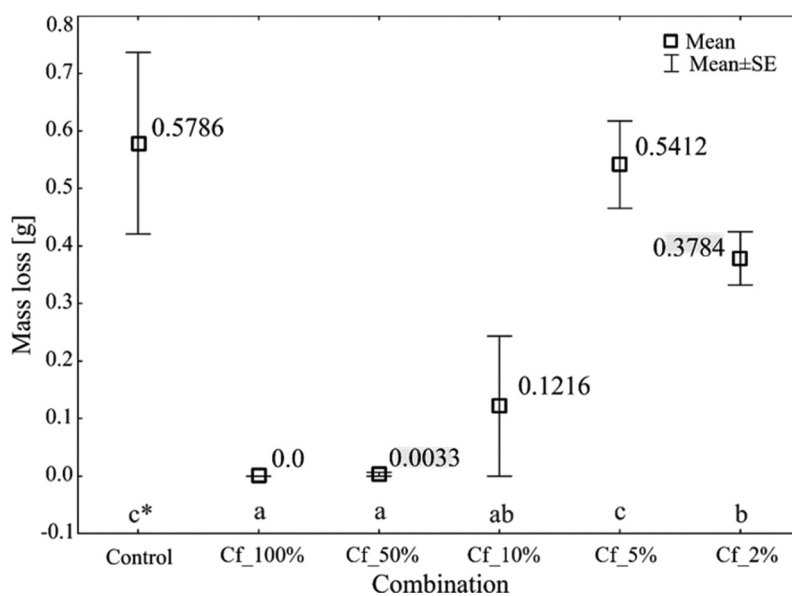


Figure 6. The loss of flour mass during the development of *T. confusum* was observed in the tested combinations with different shares of cricket flour in the free-choice test. (*means marked with the same letter index do not differ significantly, by Tukey's HSD test) SE: Standard Error.

Cricket flour differed significantly from wheat flour regarding the chemical composition studied. It contained more dry matter, crude ash, total protein, and crude fat. Substantial differences were found for total protein content (Control -10.12% ; Cf_100% -68.05%) and crude fat (Control -0.41% ; Cf_100% -16.78%). Crude fibre was also noted in cricket flour, which was not present in wheat flour (Table 4).

Graphical interpretation and confirmation of the difference in chemical composition was obtained using NMDS analysis, and the resulting dendrogram presents separated polygons on the graph describing the chemical composition of the tested combinations with wheat and cricket flour (stress = 0.00, $R = 0.98$, $p < 0.01$) (Figure 8).

To determine the effect of the chemical composition of the tested types of food on the development of *T. confusum*, CCA was performed. The selected parameter, the number of individuals in a generation of *T. confusum*, strongly correlated with the content of crude ash, total protein, crude fat, and crude fibre in the

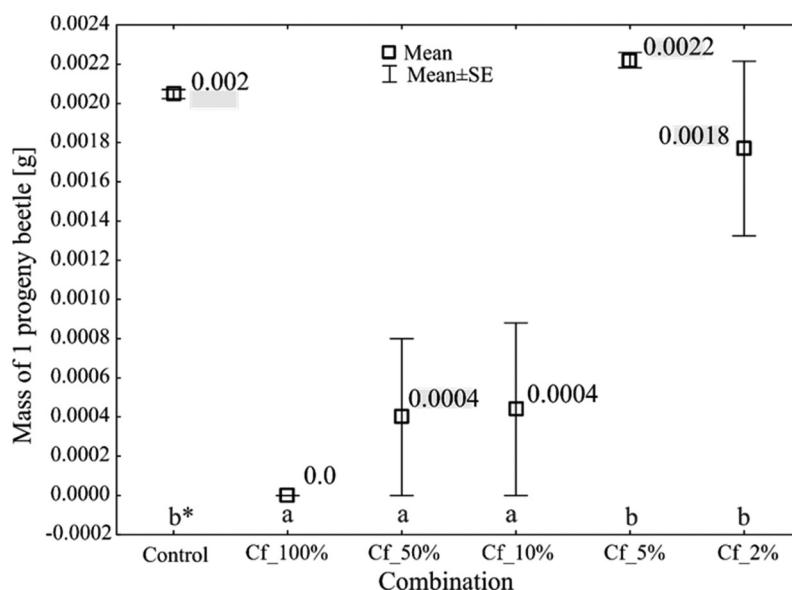


Figure 7. The average mass of 1 progeny beetle of *T. confusum* observed on the tested combinations with different shares of cricket flour in a free-choice test. (*means marked with the same letter index do not differ significantly, by Tukey's HSD test).

Table 3. Results of statistical significance tests (ANOVA) of the content of selected chemical substances contained in the tested wheat and cricket flour.

	df*	F values	p**
Dry matter	1	18,830.8	.00
Crude ash	1	3983.8	.00
Total protein	1	218,860.8	.00
Crude fat	1	192,392.4	.00
Crude fibre	1	68,709.3	.00

*Degrees of freedom; **test probability *p* value.

Table 4. Chemical composition and average amounts (\pm SD) of compounds detected in wheat and cricket flour.

	Wheat flour		Cricket flour	
Dry matter	88.54 \pm 0.10	a*	96.86 \pm 0.03	b
Crude ash	0.91 \pm 0.04	a	3.41 \pm 0.05	b
Total protein	10.12 \pm 0.02	a	68.05 \pm 0.45	b
Crude fat	0.41 \pm 0.01	a	16.78 \pm 0.16	b
Crude fibre	–		6.90 \pm 0.11	

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

food. This relationship was evident for the last two compounds. An inverse correlation was found for the content of dry mass in the tested food – its increase in the food affected the decrease in the number of progeny generations of the pest. The second distinguished parameter describing the development of *T. confusum* – loss of food mass, was strongly correlated with the combination of wheat flour. Beetles developing on this combination ate more significant amounts of food than during the development of cricket flour (Figure 9).

Crude fat can be a factor that significantly affects the development of storage pests (Nietupski et al. 2021; Ludwiczak et al. 2023). Therefore, the composition of fatty acids isolated from wheat flour and cricket flour was examined in more detail. The two types of flour differed in the content of the distinguished fatty acids. Cricket flour contains the fatty acids C12:0, C14:1, C20:2 and C20:4, which are not found in wheat flour. Cricket flour, compared to wheat flour, is characterized by a higher content of the following acids: myristic acid (C14:0), palmitic acid (C16:0), palmitoleic acid (C16:1), stearic acid (C18:0), oleic acid (C18:1) and araquinic

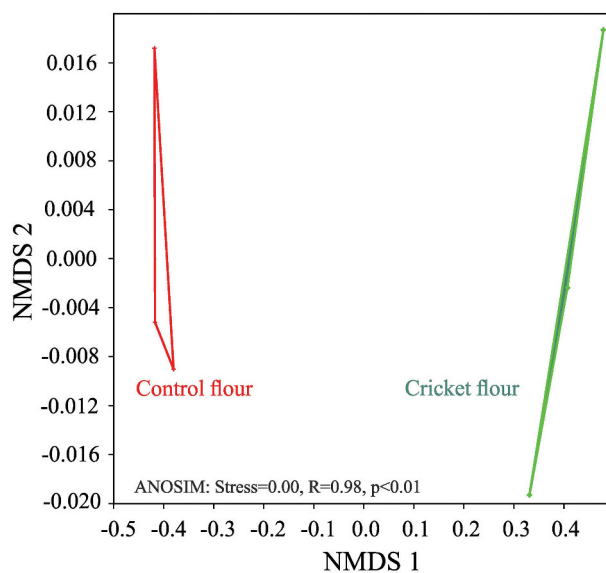


Figure 8. NMDS diagram describing similarities of the tested wheat flour and cricket flour with respect to the tested chemical compounds.

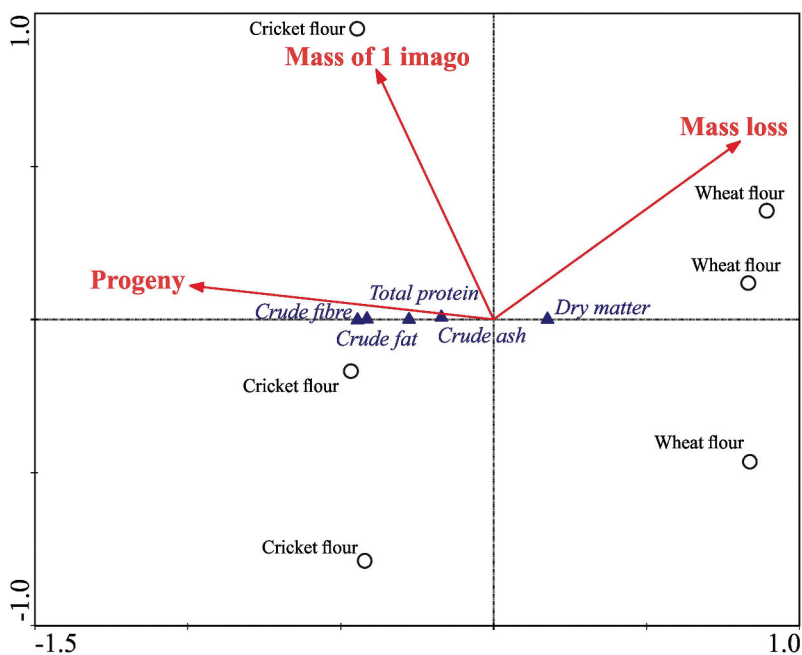


Figure 9. Relationship (CCA) between chemical compounds of flour (wheat and cricket) and development parameters of *T. confusum*.

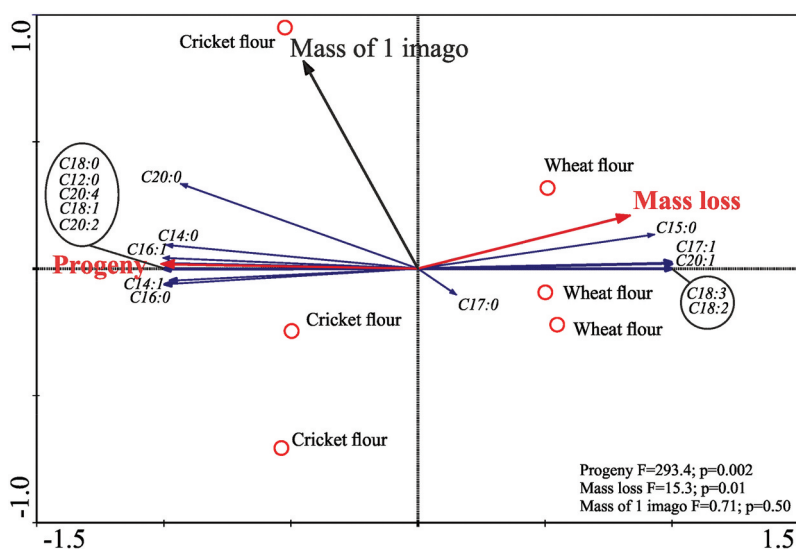
acid (C20:0). Wheat flour contained significantly more of the following acids: pentadecanoic acid (C15:0), margaroleic acid (C17:1), inoleic acid (C18:2), α -linoleic acid (C18:3) and godoleic acid (C20:1) (Table 5).

To determine which of the fatty acids in the types of flour studied could affect the development of *T. confusum*, a redundancy analysis (RDA) was performed. The graphical interpretation of the results is presented in Figure 10. Three factors determining the intensity of the development of the flour beetle were distinguished (progeny, mass loss, and mass of 1 imago). A significant correlation was noted between the axis describing the number of the progeny generation of the pest (progeny) and the content of fatty acids

Table 5. Results of the statistical significance test (ANOVA) for the content (as a % of the sum of fatty acids) of fatty acids present in tested wheat and cricket flour.

Fatty acid	Name of acid	Wheat flour	Cricket flour	df*	ANOVA F value	p**
C12:0		0	0.02 ± 0.00	–	–	–
C14:0	Myristic acid	0.21 ± 0.01	0.37 ± 0.02	1	315.4	.00
C14:1	Myristoleic acid	0	0.03 ± 0.01	1	–	–
C15:0	Pentadecanoic acid	0.10 ± 0.01	0.06 ± 0.01	1	28.8	.01
C16:0	Palmitic acid	19.48 ± 0.09	24.02 ± 0.37	1	512.2	.00
C16:1	Palmitoleic acid	0.14 ± 0.01	0.57 ± 0.02	1	1821.6	.00
C17:0	Margaric acid	0.11 ± 0.01	0.11 ± 0.02	1	0.1	.77
C17:1	Margaroleic acid	0.12 ± 0.00	0.04 ± 0.01	1	576.5	.00
C18:0	Stearic acid	1.87 ± 0.01	8.95 ± 0.14	1	21,859.0	.00
C18:1	Oleic acid	15.72 ± 0.12	28.5 ± 0.24	1	8075.4	.00
C18:2	Inoleic acid	58.48 ± 0.03	35.60 ± 0.10	1	100,705.0	.00
C18:3	α-linoleic acid	2.90 ± 0.03	0.91 ± 0.04	1	3901.0	.00
C20:0	Araquinic acid	0.19 ± 0.00	0.30 ± 0.04	1	27.92	.01
C20:1	Godoleic acid	0.68 ± 0.01	0.06 ± 0.00	1	53,090.02	.00
C20:2		0	0.02 ± 0.00	1	–	–
C20:4	Arachidonic acid	0	0.43 ± 0.00	1	–	–

*Degrees of freedom; **test probability *p* value.

**Figure 10.** Relationship (RDA) between fatty acids of flour (wheat and cricket) and development parameters of *T. confusum*.

with the length of carbon chains: C12:0, C18:0, C18:1, C20:2, and C20:4. The second developmental parameter (mass loss) was significantly correlated with a higher content of pentadecanoic acid (C15:0) in the flour. No significant correlation was noted between the content of the determined fatty acids in both types of flour and the mass of 1 progeny beetle.

Discussion

Due to the growing importance of cricket flour as a sustainable alternative to plant flour, it is necessary to identify the potential threats that may affect the quality and quantity of stored insect protein. Understanding the influence of cricket flour properties on the food preferences of storage pests will enable the development of detailed methods for protecting processed insect protein in the new agriculture sector, insect farming. The dynamics of *T. confusum* development strictly depend on the type and degree of fragmentation of the food it feeds (Trematerra et al. 2000; Laszczak-Dawid et al. 2010a, 2010b). The experiment conducted (no-choice test) showed that fragmented insect protein creates conditions for its development. Moreover, *T. confusum* developed most abundantly in combinations with a high content of insect flour (Cf_100%, Cf_50%). Inverse relationships were shown in the multi-choice biotest, during which the analysed insect had the opportunity

to choose its preferred type of food. In conditions of free access to a varied diet, the flour beetle laid eggs in the highest numbers on wheat flour (Control) and in combinations with a low content of cricket flour (Cf_2% and Cf_5%). In an analysis of the behavioural responses of *Sitophilus zeamais* Mots. on semolina pasta and semolina pasta with cricket flour added, this pest was more likely to inhabit products without added insect protein (Trematerra et al. 2024). The impact of insect feeding on quantitative losses is a key threat during food storage. The loss of mass of food products causing direct losses is included in the basic parameters describing the development of storage pests. Our previous studies showed that the development of *Sitophilus granarius* L. and *Rhyzopertha dominica* F. was strongly correlated with this parameter (Nietupski 2020; Nietupski et al. 2021; Ludwiczak et al. 2024). However, our entomological experiment on *T. confusum* showed that the physical parameter tested is not always linearly correlated with the intensity of the beetle's development, and this may be influenced by the type of food inhabited. In the case of storage of pure insect protein (Cf_100%), the lowest mass losses were observed, which may be useful when organizing the storage system for this product. Among the factors determining the effectiveness of long-term storage of cricket flour, the most important include temperature, humidity, packaging type, and storage time (Kamau et al. 2018). In addition to physical properties, chemical parameters have a significant impact on the occurrence and development of storage pests, which can act both as a deterrent and an attractant on insects (Wong & Chow-Yang 2011; Nietupski et al. 2021; Sabier et al. 2022; Kordan et al. 2023). The chemical composition of plant flour and flour as a source of insect protein is statistically significantly different. Digestive enzymes contained in the digestive tract of the tested pests allow for the effective use of protein-rich food substrates (Vinokurov et al. 2009). Previous studies have shown that the development of storage pests closely depends on the protein content in the products they feed on (Nietupski et al. 2006; Mebarkia et al. 2010; Astuti et al. 2020). Cricket flour is characterized by a high content of this component (up to 70%), which can stimulate the development of the flour beetle (Food Bugs 2024). This was confirmed by our observations, which showed that in combinations with a high protein content (wheat flour 10.12%; cricket flour 68.05%) *T. confusum* developed more intensively (average number of the progeny generation of *T. confusum* Control = 109.1 indiv.; Cf100% = 202.8 indiv.; Cf50% = 204.8 indiv.). The effect of protein on the development of the tested pest on insect flour was also demonstrated by CCA.

Our previous observations showed that the development of *T. confusum* on millet depended on the degree of grinding and fatty acids (Nietupski et al. 2021; Ludwiczak et al. 2023). The influence of acids on the development of the flour beetle was also demonstrated by, among others, Niewiada et al. (2003) and Mebarkia et al. (2010). The analysis showed that the tested flours (wheat and cricket flour) differ in terms of fatty acid content, where insect flour is characterized by its higher content. Cricket flour, on which the insect developed in greater numbers, contained fatty acids that were not recorded in plant flour (C12:0; C14:1; C20:2; C20:4) and higher contents of other fatty acids (C14:0; C16:0; C16:1; C18:0; C18:1; C20:0). The presence of these substances, or their higher concentration, could have influenced the intensive development of *T. confusum* in the experiment in which the pest had no ability to choose other food. Cereals, by emitting volatile organic compounds (including terpenoids, fatty acids, alkanes, alkenes, esters, aldehydes, and ketones), modify the chemical odour signals released into ones that are repellent to pests (Maffei 2010; Tamiru & Khan 2017). The ability to detect odours determines most of insects' physiological and behavioural responses (Conchou et al. 2019). Olfactory signals received by insects are key determinants influencing the search for and settlement on food (Gadenne et al. 2016; Badji et al. 2021). Therefore, the food preferences of storage pests are significantly determined by the odour stimuli emitted by stored food products. Astuti et al. (2020) showed in their study that volatile odorous substances of wheat flour are considered the dominant factor attracting and stimulating storage pests to continue feeding. Trematerra et al. (2024) showed that the lower attractiveness of products containing insect protein for *S. zeamais* results from their properties masking the smell of food. In the case of the free-choice experiment, the flour beetle in our study inhabited products that were identified using the sense of smell (pure wheat flour or combinations with a high content of it). This may indicate that cricket flour does not contain volatile substances that attract *T. confusum*, and at high concentrations, it drowns out the attractants of vegetable flour.

Summary

Cricket flour is a habitat enabling the development of *T. confusum*, whose reproductive potential is significantly higher on this material than on plant (wheat) flour, which may depend on the chemical

composition, especially the protein content. However, insect flour probably does not contain compounds attracting (food attractants) the tested insect or compounds with a food deterrent character (repelling beetles). Therefore, the composition of volatile substances emitted by flour from *A. domesticus* may increase its safety during its storage. This topic requires further research, especially on the nature of proteins and their impact on food selection by imagines and their larvae. This research may become crucial in developing recommendations for the sustainable and safe storage of food products produced from insects.

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Data availability statement

The development data for *T. confusum* presented in this study are available on request from the corresponding author.

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