

Article

Color and Texture of Wheat and Whole Grain Wheat Salty Crackers—Technological Aspects of Cricket Powder Addition

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Abstract

Salty wheat crackers prepared from wheat white (WF) and whole grain flour (WG) were enriched with 5, 10, and 15% cricket powder (CRPW). According to the content of dietary fiber and fat, two types of wheat flour and CRPW differed in terms of darkness “100 – L*” and redness *a**. The color of the baked products reflected these differences, but the darkening of the whole grain crackers was less intense; the shades of wheat–cricket 90:10 and whole grain 100:0 cracker variants were comparable. Within the WF subset, the hardness diminished insignificantly, with the reverse occurring in the WG group (from 25 to 22 N and from 31 to 35 N, respectively). The flexibility of the crackers was independent on type of wheat flour and the proportion of CRPW, as shown by a 90% confidence interval of 0.97–1.06 mm. By Principal Component Analysis, the primary role of wheat flour type in distinguishing the crackers was confirmed. As expected, the darkness “100 – L*” and the redness *a** of the cracker surface could be used to predict the results of the texture breaking test and fragility in general (*P* = 95%). The 90:10 WF–cricket crackers and 95:5 WG–cricket crackers had similar properties, and both could be adopted in baking practice without modification.

Keywords: wheat flour; whole grain flour; salty crackers; darkness “100 – L*”; redness *a**; texture; breaking test; stiffness; correlations; Principal Component Analysis



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1. Introduction

Regulation (EC) No. 258/97 of the European Union [1] defines the category of so-called ‘Novel Food’; it includes both food that had not been consumed to a significant extent by humans in the EU before May 1997, and food that has been manufactured using new technologies and production processes. For instance, seeds of Spanish sage (*Salvia hispanica* L.), known worldwide by their original Aztec name *chia*, were among the first items to be approved. Since 2017, white mushrooms (champion *Agaricus bisporus*), which were cultivated under ultraviolet light, could be considered as a representative example of a contemporary technological innovation. Consequently, they contain a significantly higher proportion of vitamin D₂. For human nutrition and livestock and pet feeding purposes, the category

Insect was established after the year 2020. In addition to the imagoes of the house cricket (*Acheta domesticus*) in frozen, dried, and powdered forms, the consumption of four additional species of insect is endorsed. In fact, hundreds of insect species are consumed worldwide [2].

The inclusion of insects in the *Novel Foods* was primarily motivated by their high nutritional value. The composition of members of the zoological class *Insecta* exhibits significant variation depending on the specie, its stage of metamorphosis (egg, larva, pupa, or imago), and breeding/growing conditions. It is evident that insect larvae or adults are a rich source of protein, fat, and of carbohydrate-derived fiber (chitin in most cases [3]); for crickets, the ranges could be 5–47% d.m., 7–29% d.m., and 1–12% d.m., respectively [4]. Most edible insects offer a unique opportunity to meet the recommended daily doses of several essential amino acids [5]. Animal fat is usually accompanied by cholesterol; its proportion could be between 45 and 195 mg/100 g [6], which is comparable to the values known for red meat. The mineral and vitamin content, mainly of the B group, is also significant. The second advantage is related to the minimal risk of allergies associated with the consumption of insects; however, some allergenic proteins [7] and chitin may be present. In addition, each alternative raw material of plant or animal origin has its own characteristic taste and smell, which, in the case of cricket powder, could be recognized as ‘strange’ or ‘additive’ [8]. Furthermore, commercial insect production appears to be a more sustainable option compared to traditional rearing of warm-blooded mammals and birds [9], utilizing industrial plant by-products.

In the context of bakery products enriched with edible insects, Amoah et al. [10] collated 44 original scientific papers. The review provided a comprehensive overview of recent advances in the field, focusing on the impact of the insect-based raw materials on the nutritional and physical characteristics of various baked goods, including bread and crackers, muffins, or biscuits and cookies. In testing a maximum replacement level of 30%, the acceptable dose of such dry powders was 10% for bread and 5% for the other listed bakery goods. In the case of crackers and cookies, the elevated fat content resulted in a softening of the product, leading to a partial loss of both hardness and crispness. On the contrary, a soft crumb received approval in the category of cupcakes and muffins. In any case, the objective of nutritional improvement was achieved for proteins and fat, as well as for dietary fiber.

The incorporation of 5% to 20% dried cricket powder (CRPW) into wheat flour formulations caused crackers to darken, accompanied by a notable rise in their hardness [11]. These observations were consistent with a negative trend in the preferences of consumers. The overall acceptability of the enriched crackers was found to be statistically dependent on the flavor perception—the sample containing 15% CRPW remained acceptable for 80% of the 150 assessors employed.

The present study focuses on the technological aspects of salty wheat and wheat whole grain crackers, substituted by 5, 10, or 15% dried powder from house crickets (*Acheta domesticus*). The objective was to determine consumer quality in terms of CIE *Lab* color and physico-mechanical properties by analyzing texture profile and to conduct a statistical comparison with the sensorial attributes of the crackers—fragility, hardness, sensorial score, and score-derived overall acceptability. In general, a darker shade of cracker could be indicative of a harder, probably less acceptable product, reflecting an actual protein-to-fiber ratio. The assumed relationships of both parameter groups were explored by multivariate statistical analyses. It was demonstrated that statistics could enable the identification of formulations possessing similar properties, which have the potential to be applied in bakery practices. This study continues the work of Hradecka et al. [12], who compared the dynamics of acrylamide production in the above-described foods.

2. Materials and Methods

2.1. Materials

Wheat white flour (WF) and its whole grain counterpart (WG) were produced by the Czech company MLÝN PERNER SVIJANY s.r.o. (Svijany, Czech Republic), and their fine granulation is defined in the Czech National Decree 18/2020 Coll. [13]. According to international norms, their basic nutritional composition was determined by Hradecka et al. [12] to be chemically as follows: fats 0.8/1.8%, carbohydrates 84.8/74.9%, and proteins 9.0/10.4%, respectively. In the whole grain flour, the portions of dietary fiber and minerals were found to be 2.5 times and 8.5 times higher. Dried cricket powder (CRPW) was produced by the Czech company GRIG Distribuce s.r.o. (Brno, Czech Republic). The basic composition of the CRPW was 55.6%, 5.5%, 19.3%, and 3.7%, respectively [12]. For such alternative types of flour and powders of plant and animal origin, granulation is not regulated in any Czech national decree—it depends on the consideration of each manufacturer. Visually and tactilely, the CRPW appeared close to fine wheat flour.

Other ingredients used were table rapeseed oil and non-iodized kitchen salt, purchased from the Czech retail market, and distilled water. The doses of water in the WF and WG dough were derived from a determination of the Solvent Retention Capacity of water (water-SRC, AACC Method 56-11.01 [14]) for WF, WG, and CRPW. For this determination, a rotational shaker PTR-35 (Grant Instruments, Royston, UK) and a centrifuge Eppendorf 5702 (Eppendorf SE, Hamburg, Germany) were used. Within the second step, the difference in water-SRC of WF and WG was checked precisely using a Farinograph-TS rheometer (Brabender Co. & KG, Duisburg, Germany; a branch of Anton Paar GmbH., Graz, Austria; AACC Method 54-21 [15]).

2.2. Cracker Manufacturing

The non-laminated cracker dough was manufactured from non-puff pastry, which primarily contained 200.0 g of WF or WG. This basic flour dose was later replaced stepwise by 10.0, 20.0, or 30.0 g of cricket powder. The proportions of rapeseed oil and salt were constant in all 8 cases (45.0 g and 3.0 g, respectively). The amount of water in the recipe was 56.0 g for the WF and 3 WF–CRPW mixtures, and 76.0 g for the WG and 3 WG–CRPW mixtures (details in Section 3.1).

The dough was mixed in a 4.5 L inox bowl of the KitchenAid mixer, using a flat beater paddle with a one-side silicone edge scraper (Kitchen Aid Company, Greenville, OH, USA; a brand of Whirlpool Corporation, Benton Harbor, MI, USA). To limit the development of wheat gluten in dough, wheat flour or a binary flour mixture was premixed with rapeseed oil for 0.5 min at speed 3. Then, an aqueous salt solution was poured into the bowl without the mixing interruption; it continued for another 1.5 min, until the developing dough became compact and silky. The dough mass was split into halves and using the own laboratory mechanical double-roll sheeter, the halves were rolled out forth and back on baking paper to a thickness of 5.0 mm first. To suppress asymmetric spread of the crackers during baking, the dough sheet was rotated by 90° and rolled forth and back to a final thickness of 3.5 mm. Using a manual double-wheel cutter with 3 partitions, the dough sheet was divided into 40 × 40 mm pieces; 16 representatives were regularly placed on the non-sticky baking sheet.

Without an initial steaming, the baking was carried out in electric mini oven Sencor SEO 2000BK (Sencor, a brand of FAST ČR a.s., Říčany, Czech Republic) in the middle vertical position; the oven was preheated to 180 °C in a forced air circulation regime. A baking time of 25 min was chosen since in the first part of the study [12], it was shown that this baking time provides the lowest levels of acrylamide without affecting other quality traits of the product. After 60 min of cooling the crackers on inox sieves under laboratory conditions

(temperature 21 °C, RH 56%, without a sunlight), instrumental evaluation of the surface color and texture properties was carried out. The coding of the cracker variants reflected the wheat flour type and an actual level of CRPW addition: WF-0 (control-1 cracker), WF-5, WF-10, and WF-15, and WG-0 (control-2 cracker), WG-5, WG-10, and WG-15 for their whole grain counterparts.

2.3. Determination of Crackers Physical Properties

2.3.1. Cracker Color

The color of the wheat crackers was determined in the CIE *Lab* color space ([16]). The vertical coordinate L^* called *lightness (luminosity)* was inverted into the *darkness (blackness)* “ $100 - L^*$ ” ($L^* = 100$ newly expresses the black and $L^* = 0$ the white). A further 2 basic color coordinates are the *redness* a^* ($+a^*$ for red, $-a^*$ for green) and the *yellowness* b^* ($+b^*$ for yellow, $-b^*$ for blue). Both coordinates are usually measured on scales $<-50; 50>$.

Color measurement was carried out using a CR-5 chromameter (Konica Minolta Inc., Japan) equipped with an aperture of 8 mm and pre-set to daylight as illuminant ($D65$) and the *SCI* regime (specular component included). The instrument was calibrated once before each day of measurement, using an internal white reference tile ($[L^*; a^*; b^*] = [97.52; -5.06; 3.57]$). For all 8 variants of the wheat crackers, the color was scanned directly on the upper surface in a regime 8×5 —from 8 baked pieces and 5 points on each cracker (4 corners plus the center).

To evaluate the effect of CRPW addition on the color of the final baked product, 2 common color indexes were calculated:

$$\Delta E = \sqrt{(L^* - L^*_{control})^2 + (a^* - a^*_{control})^2 + (b^* - b^*_{control})^2} \quad (1)$$

$$\text{Darkness Index} = \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad (2)$$

The ΔE index, alternatively the *Total Color Difference* (Equation (1)), is a measure of the Euclidean distance between the sample and the control in the CIE *Lab* space. In addition, Shevell [17] mentioned the *Just Noticeable Difference* index (distance) ≈ 2 as the minimal color contrast between 2 samples, just distinguishable by human vision. The ΔE index was calculated 4 times for different purposes:

- As ΔE_F , to compare the color of wheat WG flour and the CRPW per contra the WF one.
- As ΔE_{C4+4} , to quantify the color change within a pair of 4-member cracker subsets separately (that is, for WF-5, WF-10, and WF-15 versus WF-0, and for WG-5, WG-10, and WG-15 versus WG-0).
- As ΔE_{C8} , to quantify the color similarity within an 8-member set of crackers independently on the wheat flour type used (WF-5, WF-10, and WF-15 together with WG-0, WG-5, WG-10, and WG-15 versus WF-0 solely).
- As $\Delta E_{\text{pairwise}}$, to quantify the color difference in recipe-related pairs WF-0–WG-0, WF-5–WG-5, WF-10–WG-10, and WF-15–WG-15. In general, the $\Delta E_{\text{pairwise}}$ index could be calculated according to Equation (1), but also simply as a difference “ $\Delta E_{\text{pairwise}}(\text{WG-}i) - \Delta E_{\text{pairwise}}(\text{WF-}i)$ ”, where i is the CRPW addition level 0, 5, 10, or 15%.

The Darkness Index (DI, Equation (2)) was derived from the Hunter Whiteness [18] as its counterpart:

$$\text{HW} = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad (3)$$

The parameter DI quantifies contributions of the basic color components L^* , a^* , and b^* to the overall darkness of the sample.

2.3.2. Crackers Texture

The hardness and other common rheological properties of baked crackers were determined by a fracture test. For the testing, the TA-XTplus texturometer (Stable Micro Systems Ltd., Godalming, UK) and the company software Exponent 6.1.16 were used. The texturometer was equipped with a small 3-point bend rig ‘HDP/3PB’ and a single aluminum blade. Due to the fact that the crackers were cut-off in size 40×40 mm, the distance between 2 side supports was fixed at 32 mm (−16 mm to the left and +16 mm to the right of the centered breaking blade). The profile setting for the TPA test was as follows:

- Test mode ‘*Compression*’;
- Trigger ‘*Auto (Force)*’, and trigger force 0.049 N;
- Support gap 40 mm (the initial as well as post-test position of the blade edge above the inserted cracker);
- Distance 20 mm (final positions of the blade under the edge of the side supports, to break a sample surely);
- Probe test speed 3 mm/s;
- Calibration by weights of 5000 g before each day of measurement.

The measurement in the Exponent software was simplified using an internal macro. For all 8 variants of crackers, the fracture test was performed in 8 repetitions; on the side supports, each cracker was placed in the 2D-centered position upper side up (“as baked”). From the recorded deformation curves, the software Exponent derived the following physical and texture parameters of the crackers:

- *Thickness* (height);
- *Hardness* (force $1 \approx \text{peak-1 height}$);
- *Flexibility* (distance-1 $\approx \text{time} < t_0; t_{\text{peak } 1} >$);
- *Breaking work* (defined as the area ‘Force Distance 1:2’).

Later, a further characteristic called *stiffness* was calculated as the *hardness-to-flexibility ratio* [19]. On a common laboratory scale, the weight of the object was determined with precision ± 0.01 g, too, directly before the cracker breaking.

2.4. Summary Data of Sensory Analysis

In the Sensory Laboratory of the UCT Prague, Hradecka et al. [12] organized and conducted the sensory analysis of all 2×4 cracker variants. The list of the 13 statistical attributes considered is as follows:

- *Overall appearance*;
- *Intensity of flavor*;
- *Pleasantness of flavor*;
- *Fragility*;
- *Hardness*;
- *Pleasantness of texture*;
- *Pleasantness of overall taste*;
- *Intensity of fatty taste*;
- *Pleasantness of fatty taste*;
- *Intensity of salty taste*;
- *Pleasantness of salty taste*;
- *Intensity of bitter taste*;
- *Off-flavor intensity*.

Fourteen qualified assessors were asked to score on the non-divided scale ‘0–100 pts.’, which means ‘the worst/less intensive’ and ‘the best/most intensive’, respectively. Fragility and

hardness were selected as the representative sensory attributes of the consumer quality of the cracker as directly contrastable to the texturometer parameters.

For the Principal Component Analysis, the summary sensory scores were calculated to expand the proprietary dataset of the color and rheological parameters of wheat and wheat–cricket crackers. The sensory score represents the sum of points of 13 listed sensorial attributes, as scored by each assessor. The minimum and maximum score is equal to 0 and 1300 pts., respectively, meaning the unacceptable and best consumer quality of the cracker. Based on maximum of this range, 112 scores in total were recalculated to cracker’s overall acceptability as a percentage of the score maximum in the interval 0–100%.

The goal of implementing the sensorial fragility and hardness, as well as the sensory score, was to explore the relationship of human perception with the determined physical parameters of the crackers.

2.5. Statistical Analysis

2.5.1. Analysis of Variance (ANOVA)

The data gained underwent a statistical pre-treatment; each data octet was ordered and a pair ‘*minimum*’–‘*maximum*’ was excluded. Using Statistica 13.0 software (TIBCO Inc., Palo Alto, CA, USA), data scatter was described using Tukey’s HSD test. The factors considered were *F1—Wheat flour type* (WF or WG) and *F2—CRPW addition level* (0%, 5%, 10%, or 15%) plus their interaction. The variation in each qualitative parameter could be quantified by a calculation of the own original parameter, called *Samples Distinguishing Rate* (SDR). There are 2 border cases of the sample distinguishing, based on the count of evaluated samples and count of homogenous groups:

- SDR = 0%: Samples are statistically similar (the arithmetic means of the analyzed items are signed by 1 letter solely).
- SDR = 100%: The samples are completely statistically different (a count of the ANOVA letters is equal to the total number of items under evaluation).

A quantification of the ANOVA results is summarized in the Appendix A part, namely in Tables A1–A3.

2.5.2. Correlation Analysis

At the likelihood level $P = 95, 99, \text{ or } 99.9\%$, the correlation analysis was calculated in 2 directions:

- As a linear Pearson correlation coefficient $r(r_{X.Y})$, including both variance factors, *Wheat flour type* and *CRPW addition level*, into the color, texture, and sensory dataset.
- As a multiple linear Galton–Pearson correlation coefficient $R_{Z/(X.Y)}$, which combines linear regression and linear correlation for 3 selected variables [20]. The cracker texture parameters of hardness, flexibility, stiffness, and breaking work have been correlated to 3 pairs of the CIE colors: (a) darkness “ $100 - L^*$ ” – redness a^* ; (b) darkness “ $100 - L^*$ ” – yellowness b^* ; and (c) redness a^* – yellowness b^* . The significance of the relationships among 3 tested variables was expressed by the ‘calculated likelihood p ’.

In the case of the *Wheat flour type* factor, the positive or negative value of the correlation coefficient is related to the abbreviations of the types of WF and WG flour used. In the Statistica software, the abbreviations were automatically recoded as ‘101’ and ‘102’, respectively, with the mathematical meaning “WG” > “WF”. Coincidentally, that coding reflects different contents of fat and dietary fiber, higher in the former wheat flour type.

2.5.3. Principal Component Analysis (PCA) and the Euclidean Distances

Reciprocal relationships among all determined physical parameters of the cracker, as well as quality of the cracker variants, were explored in terms of the Principal Component

Analysis. In the line plot of variables, an inner circle representing 70% data variability was newly drawn; the percentage represents the minimal portion of the explained data variability for a successful PC model. A percentage of explained variability of the each of 18 active and 4 supplementary variables by the first three principal components are presented into Table A4 (Appendix A). Additionally, using the procedure invented by Chabanet [21], the importance of variables was distinguished by decrease in letter sizes. The PCA scatter plot of samples was generated by the calculation of the Euclidean distances to the WF-0 sample (control-1 cracker) in the PC1 and PC2 plane, and by the drawing of concentric circles centered on this control-1.

3. Results and Discussion

In the food industry, each specific product possesses distinctive rheological and organoleptic properties, which could fluctuate to a minimal extent. For biscuits, crackers, and other types of food, such as extruded bread, the predominant rheological properties are typically hardness and brittleness; in sensory analysis, both could be recognized together as crispness [22]. In the case of the surface color, it is of principle importance that the product is attractive to the potential buyer, corresponding to receiving of 80% of sensory impressions by visual stimuli [23]. The shade of the crust and crumb of the baked product may range from light golden beige to dark brown in the case of rolls or biscuits and rye bread on the other side, respectively. The resulting shade arises from the natural constituents presented in the ingredients used; the crust is formed during baking, and a complex reaction between free amino acids and reducing sugars (the Maillard reaction) participates in its final appearance.

3.1. Water Absorption of WF, WG, and CRPW

The absorption abilities of both the wheat flour types and the CRPW were determined in two replications as the water-SRC. The determined values were $58.8 \pm 0.1\%$, $74.9 \pm 1.7\%$, and $148.4 \pm 0.5\%$, respectively, reflecting mainly different fiber and dry matter contents. For the WF and WG samples, farinograph water absorption (WAB) reached levels of 53.8 ± 0.2 and $68.3 \pm 0.2\%$ on the flour basis, respectively. In the pair WF and WG, differences in the water-SRC and the WAB were roughly comparable—16.1 and 14.5 percentage points, respectively. Based on the values presented, the doses of the water in the cracker dough were rounded to 56.0 g for the WF and 3 WF–CRPW mixtures, and to 76.0 g for the WG and 3 WG–CRPW mixtures.

3.2. Color of Wheat Flour, Cricket Powder, and Non-Enriched Wheat Control Crackers

As anticipated, a marked variation in color was observed between the two types of wheat flour, WF and WG. This variation was evident primarily in the darkness “ $100 - L^*$ ” and the redness a^* —the latter was approximately 10 times higher (−0.16 and 1.54, respectively; Table 1). In whole grain wheat flour, a higher percentage of light orange bran particles was verified indirectly. Unlike wheat flour, the CRPW was evidently darker, most likely falling within the mid-brown shade. This shade could be compared with that of crackers baked from whole grain wheat flour only (WG-0 sample as the control-2 cracker; Figure 1).

The color of wheat flour is contingent partly on the botanical specie of the milled wheat and the milling scheme—simplified, on the granulation, and on contents of the ash and natural colorants. The finer the flour, the whiter it appears due to the reduced surface area for light scattering. Fine semolina, produced from golden grains of durum wheat (*Triticum durum* Desf.), represents the medium-coarse milling fraction (mean particle size between 300 and 400 μm). Compared to WF, semolina could be similar in darkness (11.92),

but its redness a^* (1.48) and yellowness b^* (22.91) are multiplied due to a verifiably higher carotenoids content [24].

Table 1. Comparison of CIE *Lab* color of wheat white flour, wheat whole grain flour, and cricket powder.

Flour Sample ¹	Darkness “100 – L^* ”	Redness a^*	Yellowness b^*	ΔE_F ²	Darkness Index ³
WF	11.01 ± 0.09 ^A	−0.16 ± 0.02 ^A	7.17 ± 0.13 ^A	0 ± 0 ^A	13 ± 0 ^A
WG	17.77 ± 0.14 ^B	1.54 ± 0.04 ^B	8.80 ± 0.10 ^B	7 ± 0 ^B	20 ± 0 ^B
CRPW	48.70 ± 0.35 ^C	3.79 ± 0.05 ^C	17.52 ± 0.33 ^C	39 ± 0 ^C	52 ± 0 ^C

Data presented as average ± standard deviation. ¹ WF, WG—wheat white flour and wheat whole grain, respectively; CRPW—cricket powder. ² ΔE_F —Total Color Difference (Equation (1)) between flour types; that is, for WG and CRPW versus the WF. ³ Darkness Index—a ratio of the relative darkness of the flour layer surface (Equation (2)). ^{A–C} the same superscript in columns denotes statistically similar averages of six-member groups of WF, WG, and CRPW ($P = 95\%$).

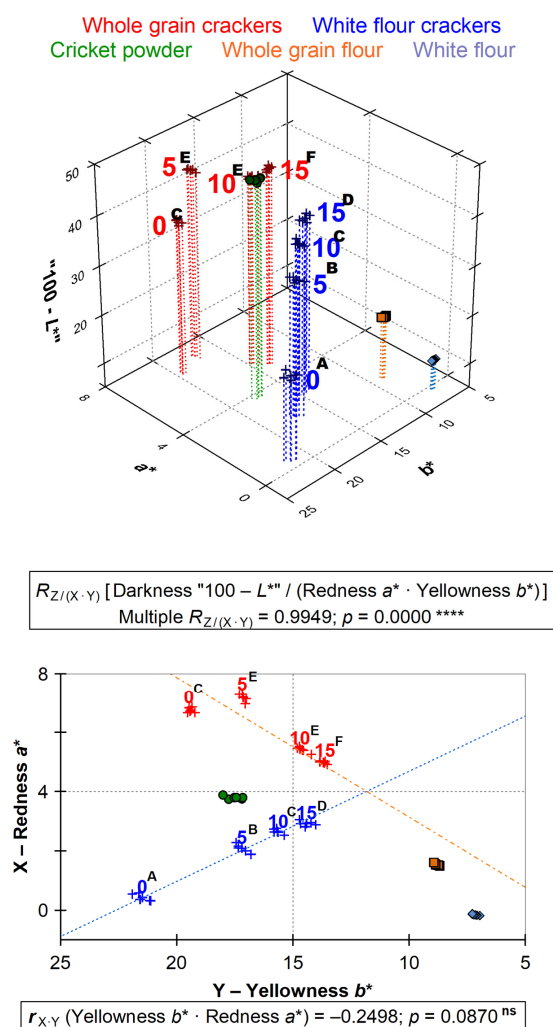


Figure 1. Comparison of CIE *Lab* color of three basic raw materials with the surface color of eight wheat cracker variants—effects of wheat flour type and addition level of cricket powder. L^* —color coordinate luminosity (lightness) as the variable Z; $R_{Z/(X \cdot Y)}$ —multiple correlation coefficient; $r_{X \cdot Y}$ —Pearson’s pair correlation coefficient; p —calculated probability; ns—non-significant correlation ($P > 95\%$); ****—significant correlation ($P = 99.99\%$). ^{A–F} on basis of the ΔE_{C8} index (Equation (1)) against the WF-0 cracker (control-1), samples marked by the same letter are not statistically different ($P = 95\%$). The color of three basic raw materials—wheat white flour (♦), wheat whole grain flour (■), and cricket powder (●)—was not included in two-factor ANOVA.

The heat transformation of the flour pair WF and WG into the control cracker pair WF-0–WG-0 magnified twice the Total Color Difference ($\Delta E_F = 7.16$, $\Delta E_{C8} = 15.33$, respectively). According to the Darkness Index, a color change “flour $\rightarrow$ non-enriched cracker” showed somewhat more intensive overall darkening in the case of the white flour samples ($DI_{WF-0}/DI_{WF} = 31/13 \approx 2.4$ versus $DI_{WG-0}/DI_{WG} = 41/20 \approx 2.1$; Tables 1 and 2). In the study published by Ardoin et al. [11], ‘wholewheat’ crackers clearly baked to a darker color than the control-2, because their recipe was richer in soybean oil, sugar, and baking soda (darkness 41.6, redness 12.3, and yellowness 24.1 versus 36.02, 1.54, and 19.39 for the own crackers WG-0, respectively).

Table 2. CIE *Lab* color of wheat crackers—effect of wheat flour type and addition level of cricket powder.

Cracker Sample ¹	Darkness “100 – L*”	Redness <i>a*</i>	Yellowness <i>b*</i>	ΔE_{C4+4} ²	ΔE_{C8} ³	$\Delta E_{\text{pairwise}}$ ⁴	Darkness Index ⁵
WF-0 (control-1)	22.22 ± 0.53 ^A	0.42 ± 0.11 ^A	21.48 ± 0.30 ^F	0 ± 0 ^A	0 ± 0 ^A	–	31 ± 0 ^A
WF-5	32.74 ± 0.39 ^B	2.08 ± 0.13 ^B	17.19 ± 0.24 ^D	11 ± 1 ^E	11 ± 1 ^B	–	37 ± 0 ^B
WF-10	37.07 ± 0.44 ^D	2.65 ± 0.08 ^C	15.67 ± 0.16 ^C	16 ± 1 ^F	16 ± 1 ^C	–	40 ± 0 ^C
WF-15	40.19 ± 0.46 ^E	2.92 ± 0.08 ^D	14.42 ± 0.27 ^B	19 ± 1 ^G	19 ± 1 ^D	–	43 ± 0 ^E
WG-0 (control-2)	36.02 ± 0.26 ^C	6.74 ± 0.08 ^G	19.39 ± 0.11 ^E	0 ± 0 ^A	15 ± 0 ^C	15 ± 0 ^D	41 ± 0 ^D
WG-5	43.25 ± 0.10 ^F	7.17 ± 0.12 ^H	17.14 ± 0.10 ^D	8 ± 0 ^B	23 ± 1 ^E	12 ± 0 ^C	47 ± 0 ^G
WG-10	43.22 ± 0.20 ^F	5.41 ± 0.09 ^F	14.59 ± 0.21 ^B	9 ± 0 ^C	23 ± 1 ^E	7 ± 1 ^B	46 ± 0 ^F
WG-15	44.92 ± 0.40 ^G	4.98 ± 0.04 ^E	13.69 ± 0.12 ^A	11 ± 0 ^D	24 ± 0 ^F	5 ± 1 ^A	47 ± 0 ^G
WF-set average (N = 24)	33.1 ± 7.0	2.02 ± 1.00	17.19 ± 2.73	12 ± 8	12 ± 8	–	38 ± 5
WG-set average (N = 24)	41.9 ± 3.5	6.07 ± 0.93	16.20 ± 2.28	7 ± 4	21 ± 4	–	45 ± 2

Data are presented as average ± standard deviation. ¹ WF-0, WG-0—non-enriched control-1 and control-2 crackers, prepared from wheat white flour (WF) and wheat whole grain flour (WG), respectively. Numbers 5, 10, and 15 identify the addition levels of the cricket powder as the wheat flour replacement (*w/w*). ² Total Color Difference (Equation (1)) in color of wheat–cricket crackers WF-5, WF-10, and WF-15 versus color of non-enriched cracker WF-0 (control-1), and similarly in the WG subset (with the WG-0 cracker as the control-2). ³ Total Color Difference (Equation (1)) in color of WG-0 cracker and 2 × 3 wheat–cricket cracker variants versus color of the cracker WF-0 (control-1) solely. ⁴ Total Color Difference (Equation (1)) between color of pairs WG-0–WF-0, WG-5–WF-5, WG-10–WF-10, and WG-15–WF-15 (a difference between the proper ΔE_{C8} values). ⁵ Darkness Index—a ratio of relative darkening of the cracker’s surface (Equation (2)). ^{A–H} in columns, the same superscript denotes statistically similar averages (of six-member groups of each sample; *P* = 95%).

3.3. Crackers’ Physical Properties

3.3.1. Cracker Color

The change in the color of the wheat crackers under a rising dose of CRPW reflected the shades of the WF, WG, and non-fortified cracker pair WF-0 and WG-0 (Figure 1). A more pronounced darkening in the WF subset of crackers was found to be statistically significant (*P* = 95%). Regarding control-1 and control-2 as the non-fortified crackers, the darkness “100 – L*” of the most enriched crackers WF-15 and WG-15 increased by approximately 180% and 120% (from 22.22 for WF-0 to 40.20 for WF-15 and from 36.02 for WG-0 to 44.92 for WF-15, respectively; Table 2). The yellowness *b** exhibited an expected reverse tendency, decreasing by approximately 48% and 44%. In the redness *a**, as the third color coordinate, the three fortified crackers baked from wheat white flour exhibited a gradual darkening, but a significant change was only observed in the pair WF-0 and WF-5 (perhaps due to the first verifiable increase in proportions of non-cereal protein and fat).

The baking of the whole grain counterparts caused a partial shift to the green half-space. The redness *a** of the WG-0 cracker was reduced by approximately one third, from 7.17 to 4.98, by incorporating 5% and 15% of CRPW. Furthermore, the darknesses “100 – L*”

of the crackers WG-5, WG-10, and WG-15 were similar to that of cricket powder (Table 2, Figure 1). By the three calculated color indexes, ΔE_{C4+4} , ΔE_{C8} , and DI, there was verified the statistical significance of the variation in the color of both subsets of crackers. By the ΔE_{C4+4} index, it was established that darker whole grain flour could not produce a darker shade of crackers to the same extent as the white flour did (ΔE_{C4+4} 19 for the WF-15 item and 11 for the WG-15 product). Taking the WF-0 cracker as a unique standard, the results of the statistical analysis indicated a high degree of shade similarity for the WF-10, WF-15, and WG-0 crackers, as quantified by ΔE_{C8} index and also by the DI (Table 2). By the $\Delta E_{\text{pairwise}}$ index, the color in a foursome of cracker couples (WF-0–WG-0, . . . , WF-15–WG-15) was compared. The tendency of the gradual decrease in reciprocal distances observed in Figure 1 was quantified; the index values decreased verifiably in a row of 15 ± 0 , 12 ± 0 , 7 ± 1 , and 5 ± 1 , respectively (Table 2).

Ardoin et al. [11] confirmed the observed stepwise darkening of crackers manufactured from their ‘wholewheat’ flour, in agreement with the cricket powder portions incorporated (0, 5, 10, 15, and 20%). The ΔE index values between their non-enriched ‘wholewheat’ control and enriched crackers were 0, 6, 12, 20, and 21 units, respectively, while the Darkening Index varied improbably (49, 49, 48, 46, and 46 units). Due to the baking sweet cracker variant, a shift in the CIE *Lab* color space reached a more diverse range than the pure WF and WG crackers. At the same time, the authors verified the strong impact of the color of the cracker on its sensory acceptability. On a 9-point hedonic scale, the visually perceived color of their ‘wholewheat’ control reached 6.9 points, while the scores of their variants enriched by 5, 10, 15, and 20% cricket powder fell into the ‘dislike’ region (6.4, 5.9, 5.0, and 4.7 points, respectively; $P > 99.9999\%$).

As outlined in Table A1 for the calculated SDR parameter, all four WF crackers could be 100% distinguished according to the factor *CRPW addition level* in the five determined color parameters (darkness “ $100 - L^*$ ”, redness a^* , yellowness b^* , and both ΔE_{C4+4} and DI indexes). Whole grain counterparts were depicted by shades somewhat close together; this fact was demonstrated by the crackers WG-0, WG-5, WG-10, and WG-15 receiving scores of 75% in terms of darkness “ $100 - L^*$ ” as well as in the index DI. The complete set of eight salty cracker modifications, prepared both from WF and WG, received scores of 75% in yellowness b^* and in total color change ΔE_{C8} . In terms of the remaining three color parameters, the complete cracker set differed by 88%.

Within the first part of this study of the CRPW effect on chemical composition and properties of wheat crackers [12], there was published photo of the eight wheat and wheat–cricket crackers, arranged for the sensory analysis. In both cracker subgroups, majority of color differences described above were clearly noticeable ($\Delta E_{\text{pairwise}} \gg \text{JND} \approx 2$, Table 2).

3.3.2. Crackers Weight and Thickness

As can be seen in Table 3, the weight and the thickness of the eight variants of baked cracker oscillated in narrow ranges of 10.05–10.39 g and 5.67–6.66 mm, respectively. Among the data averages, a small, likewise insignificant, decreasing trend could be observed. This tendency could be related to the rising fat proportion in the dough corresponding to the actual CRPW dose, which slightly reduced the cohesiveness of the gluten skeleton of the wheat dough. Among the whole grain counterparts, weight and thickness were observed in the ranges 6.96–10.08 g and 5.58–5.97 mm, respectively. The thickness of the crackers, measured by the Exponent software on the texturometer, corresponded tightly to their weight; however, the mean of the WF subset was similar to the WG only (6.27 ± 0.53 mm versus 5.51 ± 0.65 mm).

Table 3. Physical and texture parameters of wheat crackers—effects of wheat flour type and addition level of cricket powder.

Cracker Sample ¹	Weight (g)	Thickness (mm)	Stiffness ² (N/mm)	Breaking Work ³ (N.mm)
WF-0 (control-1)	10.39 ± 0.28 ^{BC}	6.66 ± 0.43 ^E	20.77 ± 2.07 ^A	19.54 ± 2.63 ^{AB}
WF-5	10.20 ± 0.25 ^B	6.26 ± 0.47 ^{CDE}	25.24 ± 2.49 ^{AB}	14.29 ± 3.32 ^A
WF-10	10.81 ± 0.19 ^C	6.49 ± 0.39 ^{DE}	22.14 ± 2.40 ^A	12.92 ± 1.84 ^A
WF-15	10.05 ± 0.28 ^B	5.67 ± 0.26 ^{BC}	25.61 ± 2.03 ^{AB}	11.56 ± 2.43 ^A
WG-0 (control-2)	6.96 ± 0.19 ^A	5.58 ± 0.20 ^B	30.86 ± 2.46 ^{CD}	19.95 ± 5.32 ^{AB}
WG-5	7.05 ± 0.30 ^A	4.56 ± 0.47 ^A	28.28 ± 2.10 ^{BC}	16.02 ± 4.79 ^A
WG-10	10.01 ± 0.43 ^B	5.93 ± 0.25 ^{BCD}	34.85 ± 1.41 ^D	26.21 ± 3.90 ^B
WG-15	10.08 ± 0.24 ^B	5.97 ± 0.25 ^{BCD}	33.71 ± 1.26 ^D	25.09 ± 4.34 ^B
WF-set average (N = 24)	10.36 ± 1.70	6.27 ± 0.53	23.44 ± 3.43	14.58 ± 4.14
WG-set average (N = 24)	8.53 ± 1.58	5.51 ± 0.65	31.93 ± 3.51	21.82 ± 6.80

Data are presented as average ± standard deviation. ¹ WF-0, WG-0—non-enriched control-1 and control-2 crackers, prepared from wheat white flour (WF) and whole grain flour (WG), respectively. Numbers 5, 10, and 15 identify the addition levels of the cricket powder as the wheat flour replacement (*w/w*). ² Stiffness = Hardness/Flexibility [19]. ³ Breaking work = Area “Force Distance 1:2”. ^{A–E} in columns, the same superscript denotes statistically similar averages of six-member groups of each sample (*P* = 95%).

3.3.3. Cracker Textural Properties

Food texture refers to the visual, olfactory, tactile, and gustatory perceptions of humans of food properties during the sensory analysis, which form a food experience. In the category ‘*Snack food*’, there is a defined class of ‘*Biscuits and cookies*’, to which crackers can also be sorted as a special salty type. The typical characteristics are fragility and crispness, reflecting higher contents of dry matter, fat, and sugar or salt. For reference purposes of the U.S. Department of Agriculture, for example, Kweon designed a sweet cracker recipe containing 12.00 g of fat (shortening), 9.00 g of sugar, and 0.75 g of salt per 100.00 g of wheat flour [25]. Fragility and crispness is usually enhanced by baking soda or a similar chemical leavening agent incorporated into the cracker’s formula, which, like fat, erodes the gluten skeleton.

A comparison of the texture profiles—the force-time curves of eight produced samples is presented in Figure 2a–d. For the four whole grain products considered, the mean hardness as the peak-1 height was approximately one-fourth higher, corresponding to the higher dietary fiber content. Consequently, the elevated water content in the recipe was not a substantial contributing factor. As the peak values recorded earlier show, whole grain crackers demonstrated a higher level of brittleness. The hardness was verified as the primary texture parameter, and the entire eight-member sample set was distinguished by 50% due to reciprocal close values of 30.77 N for WG-0 and 34.62 N for WG-15 (no perceptible trend was registered). In paper [11], the hardness values of a similar pair of their ‘wholewheat’ snack crackers were 43.2 N and 72.0 N (that is, approximately about 29% and 52% higher, respectively). For their sample containing 20% cricket powder, they even measured the value at 75.8 N. In the flexibility as the curve peak-1 width, all the own crackers tested shown a greater degree of independence from the formula tested, and the samples were rather statistically similar (SDR parameter in Table A2). Food hardness usually correlates with its sensory score tightly, but, unlike stiffness, the crucial impression of fracture and deformation is missing when a bite is bitten off and a mouthful is chewed.

During the breaking test on the texturometer, the user can recognize a different intensity of the sound as the breaking occurs, but a person is not able to quantify it as precisely. The narrow variation observed in the flexibility of the crackers meant higher stiffness for the whole grain subset, approximately 40% on average (31.93 versus 23.44 N/mm). The higher the stiffness, the higher the cohesiveness, likely resulting in a less favorable sensory score.

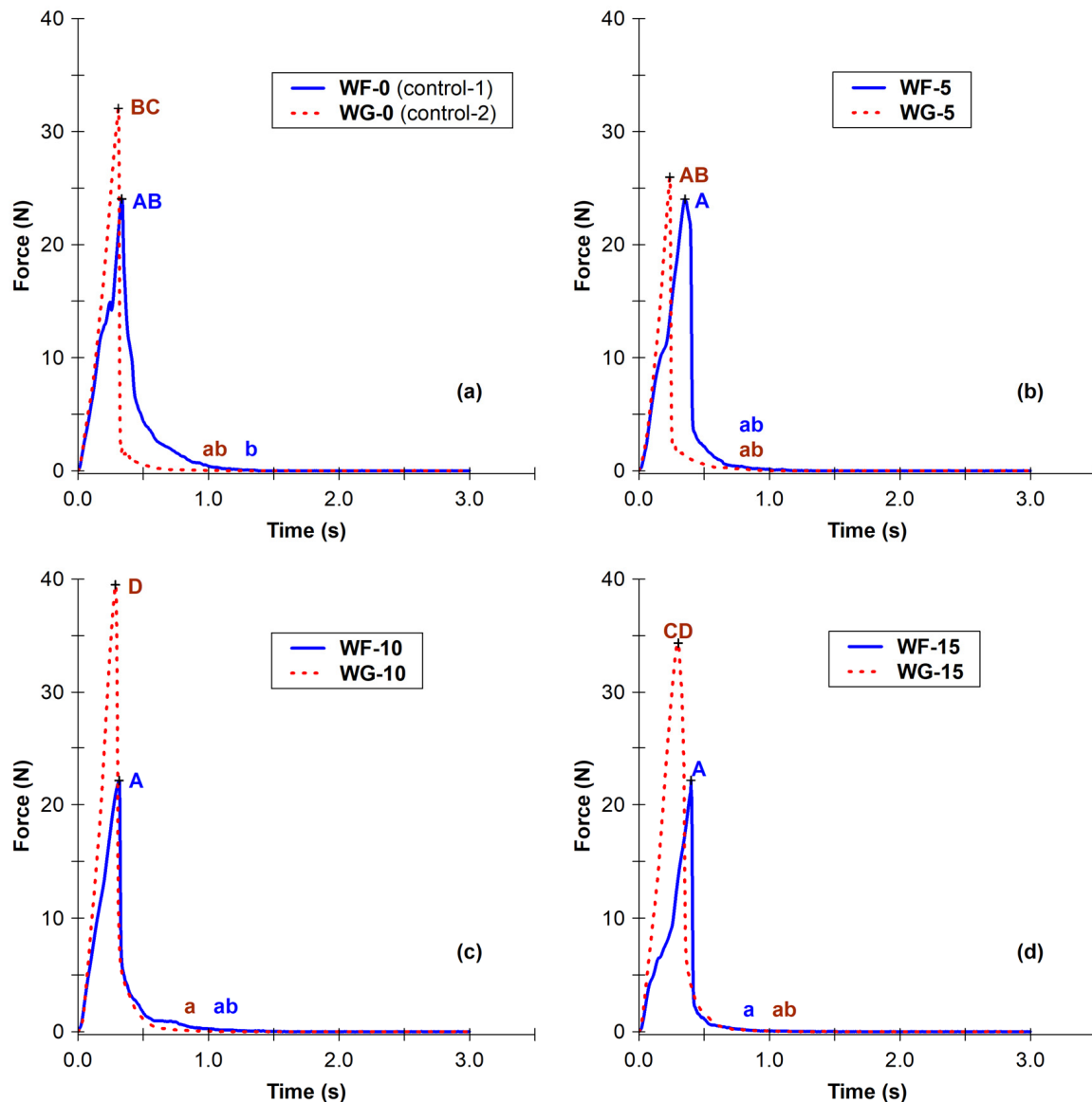


Figure 2. Texture force–time curves of wheat crackers—effect of wheat flour type and addition level of cricket powder (CRPW), recorded on the TA-XTplus texturometer. (a) non-enriched wheat white (WF) and wheat wholegrain (WG) crackers (control-1, control-2); (b) WF and WG crackers with 5% of CRPW as replacement of wheat flour; (c) WF and WG crackers with 10% of CRPW; (d) WF and WG crackers with 15% of CRPW. A–D, a–b: the same letters denote statistically similar values of the cracker hardness and the flexibility, respectively ($P = 95\%$).

In Table A2, a weak effect of the CRPW addition level on the texturometer parameters was shown in both parallel subsets of WF and WG crackers—the SDR index most often reached 50%. The complete set of eight members was also characterized by small statistically provable differences—this finding could be a motivation for semi-industrial producers to process whole grain wheat flour in this way. The thickness of the crackers, which re-

versely demonstrated a higher variability (SDR 63%), must be maintained consistently in bakeries, owing to the non-complicated running of the automated packing line.

3.4. Statistical Analysis of Summary Sensory Data

As written above, results of the sensory evaluation of salty wheat crackers and wheat-cricket crackers published by Hradecka et al. [12], considered 13 sensory attributes and applied a scale '0–100 pts.', which means 'the worst/less intensive' and 'the best/most intensive', respectively. Based on 112-point evaluations given by all employed assessors, the minimal and maximal values as the averages of a two-factor ANOVA are as follows:

- Overall appearance (64^A–78^A pts.);
- Intensity of flavor (14^A–60^C pts.);
- Pleasantness of flavor (59^A–70^A pts.);
- Fragility (33^A–68^B pts.);
- Hardness (45^A–74^D pts.);
- Pleasantness of texture (55^A–80^B pts.);
- Pleasantness of overall taste (50^A–78^B pts.);
- Intensity of fatty taste (22^A–35^A pts.);
- Pleasantness of fatty taste (55^A–72^A pts.);
- Intensity of salty taste (32^A–55^A pts.);
- Pleasantness of salty taste (59^A–74^A pts.);
- Intensity of bitter taste (4^A–37^C pts.);
- Off-flavor intensity (4^A–30^B pts.).

To fully describe the scatter of the sensory data, the ranges of the calculated pair of the additional sensory parameters were as follows:

- Sensory score (534^A–631^B pts.);
- Overall sensory acceptability (43^A–50%^B).

Within the WF-subset, the stepwise darker shade was quantified (for WF-15, $\Delta E_{C8} = 19$; Table 2); Hradecka et al. [12] confirmed that a change from yellowish to medium-beige improved the perception of the color by the evaluators within the series of products. The introduction of a partially bitter taste and off-flavor was also caused by higher doses of CRPW, less so in the WG cracker subset. On the contrary, the higher fat and chitin contents contributed to the well-accepted sensorial fragility and crispness of the crackers—mainly the WG ones, for which the peak-1 times of the texturometer breaking test were visibly shorter (Figure 2). However, the attribute of hardness only demonstrated a statistically higher dependence on the cracker recipe (range 29 pts., variance A–D supra). The ranges of intensity of the flavor and bitter taste (46 and 33 pts., respectively) and the fragility (35 pts.) highlighted the importance of these attributes in the differentiation of the crackers. From a general perspective, personal experiences and preferences of the assessors could not have a uniform tendency, and because of this, a narrowing of the statistical provability of the mentioned attributes was observed. Hradecka et al. [12] summarized that, in agreement with the conclusions of the other studies, the preference test has shown the highest acceptability of crackers containing 5% CRPW in WF and WG (appreciated by 64% and 50% of assessors, respectively).

Crispness is defined by rapid fracture accompanied by an audible sound and fragility as quality of being easily broken; hardness is the resistance to deformation (up to the material breaking); crispy food needs to be hard to a certain extent, but its fragility must dominate. Crunchiness lies somewhere between both [26]. For crispness and hardness (Table 4), representing the consumer quality of the crackers, a significant span was recorded between the control-1 and the three resting WF samples as well as the WG counterparts. That observation is similar to the distances in the CIE *Lab* space (Figure 1). For the former

attribute, potentially significant differences were suppressed by a higher data scatter, indicating a wide range in the perception of this parameter by the assessors. Conversely, the evaluators were more uniform (self-confident) in the case of the cracker hardness evaluation (variance *A–D* versus *A–B*). Using ANOVA (and especially by the subgroup ones), a reversal relationship between the fragility and the hardness was indicated; the following correlation analysis, however, did not validate this trend. For sweet short-dough biscuits, Mieszkowska and Marzec [27] quantified a positive bound.

Table 4. Selected results of the sensory analysis of wheat crackers—effects of wheat flour type and addition level of cricket powder (adopted from paper [12]).

Cracker Sample ¹	Sensory Fragility (pts.) *	Sensory Hardness (pts.) *	Sensory Score (pts.)	Sensory Acceptability ² (–)
WF-0 (control-1)	57 ± 26 ^{AB}	45 ± 12 ^A	534 ± 91 ^A	43 ± 7% ^A
WF-5	65 ± 28 ^B	48 ± 7 ^{AB}	610 ± 47 ^{AB}	49 ± 4% ^{AB}
WF-10	68 ± 21 ^B	47 ± 5 ^{AB}	606 ± 98 ^{AB}	49 ± 8% ^{AB}
WF-15	66 ± 16 ^B	54 ± 7 ^{AB}	626 ± 63 ^{AB}	50 ± 5% ^{AB}
WG-0 (control-2)	33 ± 24 ^A	74 ± 17 ^C	553 ± 88 ^{AB}	44 ± 7% ^{AB}
WG-5	43 ± 22 ^{AB}	63 ± 15 ^{CD}	631 ± 80 ^B	50 ± 6% ^B
WG-10	52 ± 26 ^{AB}	61 ± 15 ^{BCD}	616 ± 76 ^{AB}	49 ± 6% ^{AB}
WG-15	50 ± 31 ^{AB}	63 ± 14 ^{CD}	612 ± 100 ^{AB}	49 ± 8% ^{AB}
WF-set average (N = 24)	64 ± 23	44 ± 26	594 ± 84	48 ± 7% [†]
WG-set average (N = 24)	50 ± 31	65 ± 17	603 ± 89	48 ± 7% ^{††}

Data are presented as average ± standard deviation. * Sensory analysis conducted and selected data provided by Hradecka et al. [12]. ¹ WF-0, WG-0—non-enriched control-1 and control-2 crackers, prepared from wheat white flour (WF) and whole grain flour (WG), respectively. Numbers 5, 10, and 15 identify the levels of the cricket powder addition as the wheat flour replacement (*w/w*). ² Sensory acceptability (%) = 100 × sensory score/sensory score maximum = 100 × sensory score/1300 (§ 2.4); [†] 47.5 ± 6.7%, ^{††} 48.2 ± 7.1%. ^{A–D} In columns, the same superscript denotes statistically similar averages of six-member groups of each sample (P = 95%).

Within the original data, 112 sensory scores ranged from 382 pts. for the WF-0% cracker to 843 pts. for the WG-15% one; that is, the overall acceptability began at 31% and ended at 67%, respectively. By pooling out over the assessors, the arithmetic means of eight cracker variants showed closer ranges of <534; 631> pts. and <43; 50> %, respectively (Table 4). Such results could be interpreted as ‘neither like nor dislike’, independently of *Wheat flour type* and *CRPW addition level* factors. Even for the 14 qualified evaluators involved in the sensory panel, the rating of the insect powder-enriched wheat crackers appears to still be a less common task.

In Table A3, the SRD parameter confirmed the narrow ranges of the fragility, hardness, sensory score and overall acceptability. Only in the case of the compete eight-member cracker set were the samples distinguished by 25%.

3.5. Statistical Exploration of Data

3.5.1. Correlation Analysis

A linear correlation matrix is calculated to reveal a correspondence or disparity in the course of each pair of variables involved. As the color measurement belongs among non-destructive methods, determination of CIE *Lab* coordinates may be used for a prediction of the texture parameters (the TPA results).

For the darkness component “ $100 - L^*$ ” of the cracker color and the $\Delta E_{C8} - DI$ indexes, the factors *Wheat flour type* and *CRPW addition level* interacted positively (r between 0.588 and 0.731, $P = 99.9\%$). As predicted, the baking graduated the stepwise darkening of the binary premixes from wheat flour and CRPW, reflected in an unequivocal loss of the yellowness b^* of baked goods ($r = -0.942$; Table 5 (part a)). When focusing on the links among the color and texture characteristics of the crackers, the most promising prediction could be found for the cracker stiffness as a function of the darkness, redness, and less of the yellowness. In this case, five of the six correlations in total were significant at the likelihood level 99.9% ($|r|$ between $<0.442; 0.687>$, $N = 48$). The definition of stiffness is the hardness-to-flexibility ratio. It implies that this parameter of food texture could potentially closely related to human perception during sensory evaluation (a response to action ‘to bite a mouthful’; that is, with the characteristics crispness and fracturability [28]). Conversely, the complex character of the texture parameter breaking work resulted in a difficult prediction of the color of the cracker (five of the six correlations were insignificant; Table 5 (part b)). Sensory scores were positively influenced by the *CRPW addition level*, which was reflected simultaneously in the darkness and yellowness of the cracker ($P = 99.9\%$) and in its hardness too ($P = 95\%$; Table 5 (part b)).

As indicated above, the statistical dependence of the summary sensory data on the cracker composition, covered by the both observed factors, was corroborated by linear correlation analysis. The fragility of the crackers was medium–strongly influenced by both the *Wheat flour type* and *CRPW addition level* factors ($r = -0.392$, $P = 99\%$ and 0.366 , $P = 95\%$; Table 5 (part c)), mainly due to the dietary fiber and fat, respectively. The sensorial hardness of the cracker demonstrated a relationship to the former factor, while the sensory score to the latter ($P = 99.9\%$). As assumed, the factors had to act against each other. The weight and thickness verifiably participated in both sensory fragility and hardness, but in the scores, clear tendencies were lost.

No one of four objective texturometer parameters were characterized by a distribution of 112 values similar to that of sensory fragility and the cracker score. In the scores, the stiffness of the crackers could be potentially reflected ($r = 0.320$, $P = 95\%$). Therefore, significant correlations were thus confirmed between the sensory and instrumental hardness of the crackers and further to the instrumental hardness-related features stiffness and breaking work (r between 0.348 and 0.462, Table 5 (part c)). In paper [26], the sensorial hardness1 in the first bite of biscuit, hardness2 in the first compression, and hardness3 in the chewing down of the mouthful correlated with the instrumental hardness, with $r \geq 0.85$ at $P = 99.999\%$.

A novel insight into the relationships between the color components and the textural parameters of the wheat–cricket crackers could provide a three-variable correlation analysis, represented by the multiple correlation coefficient $R_{Z/(X.Y)}$. In Table 6, the predicted Z-variables gradually represent the hardness, elasticity, stiffness of the texture, and the breaking work, while the X- and Y-predictors represent three pairs of combinations of darkness “ $100 - L^*$ ”, redness a^* , and yellowness b^* . Within the complete set of 4 + 4 crackers, the combination of darkness and redness logically had a higher prediction potential of cracker hardness and stiffness ($P = 99\%$ at least). The flexibility and breaking work of the product seemed to be independent of the composition of the crackers; that is, on the *Wheat flour type* as well as on the *CRPW addition level*.

Table 5. (a) Correlation analysis of color coordinates and indexes, physical and textural parameters, and sensory attributes of the crackers with wheat flour type and addition level of cricket powder. (b) Correlation of physical and texture parameters of the crackers with their basic color parameters and color indexes. (c) Correlation of sensory fragility, hardness, and score with physical and texture parameters of crackers.

(a)							
Variance Factor ¹	Color Component, Index				Physical Traits		
	Darkness "100 – L*"	Redness a*	Yellowness b*	deltaE _{C8}	Darkness Index	Weight	Thickness
WFT	0.632 ***	0.907 ***	−0.196 ^{ns}	0.634 ***	0.731 ***	−0.633 ***	−0.547 ***
CRPW%	0.682 ***	0.025 ^{ns}	−0.942 ***	0.677 ***	0.588 ***	0.458 **	−0.017 ^{ns}
Variance factor	Texture parameters				Sensory attribute		
	Hardness	Flexibility	Stiffness	Breaking work	Fragility	Hardness	Score
WFT	0.691 ***	0.051 ^{ns}	0.781 ***	0.549 ***	−0.392 **	0.625 ***	0.223 ^{ns}
CRPW%	0.126 ^{ns}	−0.218 ^{ns}	0.273 ^{ns}	0.002 ^{ns}	0.366 *	−0.053 ^{ns}	0.498 ***
(b)							
Variable	Weight	Thickness	Hardness	Flexibility	Stiffness	Breaking work	
Darkness "100 – L*"	−0.240 ^{ns}	−0.543 ***	0.386 **	−0.291 *	0.652 ***	0.170 ^{ns}	
Redness a*	−0.785 ***	−0.727 ***	0.456 **	−0.164 ^{ns}	0.676 ***	0.270 ^{ns}	
Yellowness b*	−0.302 *	0.138 ^{ns}	−0.252 ^{ns}	0.258 ^{ns}	−0.442 **	−0.073 ^{ns}	
deltaE _{C4+4}	0.482 **	−0.023 ^{ns}	−0.287 *	−0.373 **	−0.092 ^{ns}	−0.386 **	
deltaE _{C8}	−0.242 ^{ns}	−0.530 ***	0.399 **	−0.281 ^{ns}	0.658 ***	0.177 ^{ns}	
Darkness Index	−0.355 *	−0.613 ***	0.432 **	−0.254 ^{ns}	0.687 ***	0.222 ^{ns}	
(c)							
Sensory Attribute	Weight	Thickness	Hardness	Flexibility	Stiffness	Breaking work	
Fragility	0.457 **	0.270 ^{ns}	−0.124 ^{ns}	0.048 ^{ns}	−0.169 ^{ns}	−0.236 ^{ns}	
Hardness	−0.519 ***	−0.328 *	0.428 **	0.083 ^{ns}	0.462 ***	0.348 *	
Score ²	0.045 ^{ns}	−0.112 ^{ns}	0.237 ^{ns}	−0.035 ^{ns}	0.320 *	0.146 ^{ns}	

¹ WFT—wheat flour type (white, wholegrain), CRPW%—cricket powder addition level (0, 5, 10, 15% as the wheat flour replacement). ² For the sensory overall acceptability as a function of the sensory score (§ 2.4), the same correlations are valid. Significance of correlations: ^{ns}—non-significant ($P > 95\%$; $r_{crit} = 0.293$); *, **, ***—significant at $P = 95\%$ ($r_{crit} = 0.293$), 99% ($r_{crit} = 0.368$), or 99.9% ($r_{crit} = 0.460$), respectively ($N = 48$).

Table 6. Multiple correlation analysis $R_{Z/(X \cdot Y)}$ —potential prediction of the texture parameters of wheat–cricket crackers on basis of pairs of the basic color components: darkness, redness, and yellowness.

Predicted Z-Variable (Texture Parameter)	X- and Y-Variable Multiplication ‘X · Y’ (Predictors—Color Components)	Multiple Correlation Coefficient $R_{Z/(X \cdot Y)}$	Calculated Probability p
Hardness	(Redness a* · Yellowness b*)	0.4782 **	0.00290
Flexibility		0.2779 ^{ns}	0.16380
Stiffness		0.7321 ***	0.00000
Breaking work		0.2701 ^{ns}	0.18180
Hardness	(Darkness “100 – L**” · Redness a*)	0.4629 **	0.00440
Flexibility		0.2995 ^{ns}	0.12080
Stiffness		0.7143 ***	0.00000
Breaking work		0.2731 ^{ns}	0.17470
Hardness	(Darkness “100 – L**” · Yellowness b*)	0.4073 *	0.01690
Flexibility		0.2921 ^{ns}	0.13440
Stiffness		0.6790 ***	0.00000
Breaking work		0.2108 ^{ns}	0.35960

Significance of the multiple correlation coefficient $R_{Z/(X \cdot Y)}$: ^{ns}—non-significant ($P > 95\%$); *, **, ***—significant at $P = 95, 99$, or 99.9% , respectively ($N = 48$).

3.5.2. Principal Components Analysis (PCA)

Based on the correlation matrix, the collected data were transformed into a space of 17 principal components (PC) in total. The *Wheat flour type* factor plus the color parameters lightness L^* and Darkness Index were considered as the supplementary (passive, explaining) variables, because each of them covers or is incorporated in other primary characteristics. The modeling was processed with a satisfactory accuracy—the first 3 PCs covered 42, 24, and 17% of the data scatter on average of all 17 active variables. The sum is equal to 83% of the variability in total (communalities in Table A4). For variables (Figure 3a), the importance of the 16 qualitative parameters for the PC model is primarily characterized by their positions to the outer circle, which expresses 100% of the explained variability covered by PC1 and PC2; the closer the position, the more important variable. In this regard, the properties of crackers inside the inner circle (thickness, flexibility, breaking work, sensory score) could be potentially excluded in the case of calculation of the refined PCA model; they played a minor role in the differentiation of the primary samples.

In part, PC1 covered most of the measured characteristics, so it could hardly be interpreted. This principal component axis was potentially formed on a basis of the *Wheat flour type* as well as the *CRPW addition level* factors, which affected the basic chemical composition of crackers, the instrumental hardness, and the darkness/lightness of baked goods. The second PC also reflected the chemical composition of the crackers and the cracker redness, yellowness, weight, and thickness. The third PC absorbed more than 50% of the scatter of texture characteristics (hardness, flexibility, and breaking work; communalities summarized in Table A4). As shown in Figure 3a, the technological quality of two wheat crackers and six wheat–cricket crackers could be in the PC1 $\times$ PC2 plane described by four groups of variables as follows:

- I + II. quadrants: Connection between chemical composition (fat and protein content, and the CRPW addition level) and surface darkness “ $100 - L^*$ ” (or the lightness L^* in the IV. quadrant), together with texture parameters; these bio-components, fat and proteins, are responsible for the fragility of the cracker in general, and the CRPW elevated proportion of both.
- Border of the I. and II. quadrant: Darkness “ $100 - L^*$ ”, influenced by or connected with all the primary variables located on the positive PC1 semi-space.
- III. quadrant: Thickness, weight, and the product’s surface lightness L^* , dependent on the moisture content in baked crackers.
- IV. quadrant: Pair of lightness–yellowness as an antipode of the CRPW addition level, dependent also on moisture content in baked goods.

In the I. and II. quadrant, three representative sensory attributes—fragility, hardness, and sensory score—were connected to the product’s chemical composition and to a course of baking, i.e., to the rate of overall darkening:

- Fragility reflected mainly the cracker’s weight and thickness;
- Sensory hardness corresponded with the fiber content and the product redness as well as with the instrumental hardness;
- The sensory score, as a complex quality indication, depended on the dose of the CRPW presented in the piece just tested (probably interacting with the personal preferences of each assessor).

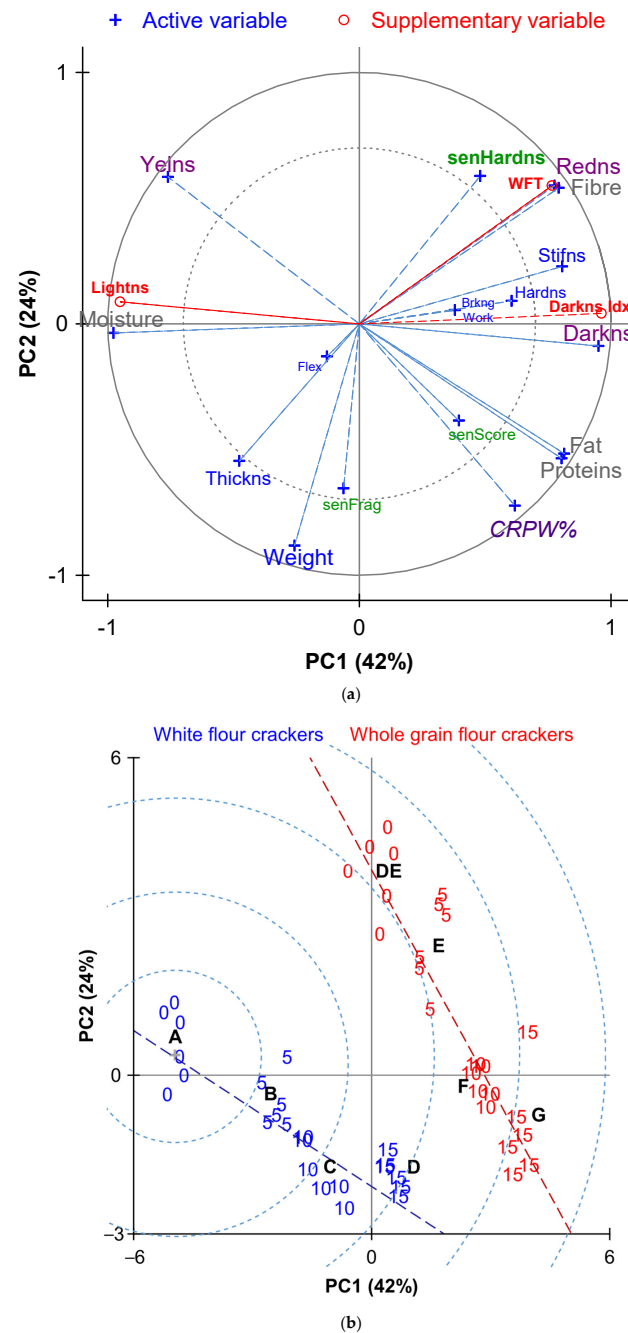


Figure 3. (a) Principal component (PC) plot of variable loadings—analysis of color, texture, and selected sensory attributes of wheat crackers as affected by the wheat flour type (WFT) and the cricket powder addition level (CRPW%). Cracker's surface color components: Darkns—darkness “100— L^* ”; Redns—redness a^* ; Yelns—yellowness b^* . Cracker physical and texture parameters: Thickns—thickness; Hardns—hardness; Flex—flexibility; Stifns—stiffness; Brkng Work—Breaking work. Cracker sensory attributes: senFrag—fragility; senHardnes—hardness; senScore—sensory score (profile). Supplementary (passive) variables (WFT, CRPW%, Lightns—Lightness L^* , and Darkns Idx—Darkness Index (Equation (2)) were not integrated into the PC model. As the sum of PC1 and PC2, inner and outer circle indicate 70% or 100% of the explained scatter of variables. (b) Principal components (PC) score plot of samples, based on color, texture properties, and summary sensory data of wheat and wheat–cricket crackers (part (a)). Numbers 5, 10, and 15 express wheat flour replacement level (w/w), while “0” identifies the non-enriched wheat crackers WF-0 (control-1) and the WG-0 counterpart. A–G—based on the Euclidean distance to the cracker WF-0 (control-1), as indicated by blue dashed lines, averages of six-member groups of crackers signed by the same capital letter are not statistically different ($P = 95\%$).

In the PCA cases plot (Figure 3b), the *Wheat flour type* factor played a primary role in the positioning of the crackers in the PC1 $\times$ PC2 plane. The lower slope of the regression line through the WF set of crackers reflected a weaker effect of the CRPW additions, equal to a smaller extent of overall changes in color and texture. A stepwise shorter distance could be observed between the wheat and wheat–cricket cracker couples WF-0–WF5, WF5–WF-10, and WF-10–WF-15 and similarly between the WG counterparts, quantified by the ΔE_{C8} and $\Delta E_{\text{pairwise}}$ indexes above. As corroborated in numerous studies, for example, in articles [10,11], each such reformulation of the wheat flour-based product rarely exceeds the replacement level of 10% to manufacture a still acceptable product. In line with the inserted circles centered on the control cracker WF-0, the final products were grouped as follows:

- Cracker group WF-0 and WF-5: The addition of 5% CRPW in the WF shortened the distance to WG-0 cracker almost to a half, and the texture parameters have been gently modified; this is potentially the most preferred cracker formulation for common consumers (statistical similarity in this pair of products 64%).
- Cracker group WF-10, WG-0, and WG-5: This is likely a compromise of the nutritional enrichment of the WF and the quality of cracker; these two modified formulations would be suitable for semi-industrial production directly (similarities with the WF-0 sample 47%, 30%, and 25%, respectively).
- Cracker group WF-15, WG-10, and WG-15: These formulations are potentially applicable in bakery practice, but a partial modification of the recipe is necessary (similarities to the WF-0 specimen 35%, 13%, and 0%, respectively).

4. Conclusions

Following the current trend of using of non-traditional food raw materials, referred to in the European Union as *Novel Food*, the powder of house cricket (*Acheta domesticus*) was used for the laboratory preparation of salty crackers from wheat white flour and wheat whole grain flour at levels of 5, 10, or 15%. At the stage of the preparation of the wheat cracker dough, the different fiber contents in these three basic ingredients were taken into account. The quality of these two parallel lines of cricket-enriched crackers was described in terms of the CIE *Lab* color and the rheological properties during the texturometer breaking test, and the later data were statistically contrasted to the sensory crispiness, hardness, and to a cumulative sensorial score.

As the three aforementioned raw materials differed significantly in basic chemical composition (proteins, fat, fiber, and minerals), the properties of the final products corresponded to the actual binary wheat flour–cricket powder mixture under evaluation. Alongside the increasing proportion of fat-rich brown cricket powder in cracker dough, the properties of single cracker variants in those two parallel lines slowly narrowed together, both in CIE *Lab* color and in texturometer parameters. Due to a partially nutritionally deficient base, a larger extent of stepwise changes was quantified within the white wheat flour production line compared to its wholegrain counterpart. Increasing the fat content in the cracker dough that interacts with the fiber-weakened gluten skeleton supported its flow properties. It could represent a potential risk in semi-industrial production during baking, because the crackers may exceed the tolerable size necessary for fluid continuous packing. A better sensory fragility of the whole grain crackers was confirmed during the fracture test, as these cracker variants were broken completely in shorter times. A higher content of dietary fiber could support such product fragility, but the mouthful could be too dense and unpleasantly chewy. Employing multivariate Principal Component Analysis accompanied by distance quantification on the basis of the Euclidean metrics, laboratory modeling has shown a possible way by which to arrive at an optimally manufacturable

and sensory acceptable innovated cereal product, characterized by nutritional benefit. The general quality closeness of the salty crackers was determined for variants of wheat–cricket (90:10), whole grain–cricket (95:5), and non-fortified whole grain (100:0), and all of these variants could be recommended in bakery practice. To suppress the extreme hardness of the crackers, as well as a cereal taste and fatty off-flavor, higher doses of cricket powder in whole grain wheat flour need to be further tested.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Quantification of ANOVA results—Sample Distinguishing Rate (SDR) of wheat crackers according to CIE *Lab* colors and indexes, as affected by wheat flour type and addition level of cricket powder. (a) White flour (WF) crackers (4 variants); (b) Whole grain flour (WG) crackers (4 variants); (c) Conjoined WF and WG subsets (8 cracker variants).

(a)					
Variability descriptor	Darkness “100 − L*”	Redness a*	Yellowness b*	deltaE _{C4+4} ¹	Darkness Index ³
Count of different samples (variability)	4 (A, B, D, E)	4 (A, B, C, D)	4 (B, C, D, F)	4 (A, E, F, G)	4 (A, B, C, E)
Total count of samples			4		
SDR	100%	100%	100%	100%	100%
(b)					
Variability descriptor	Darkness “100 − L*”	Redness a*	Yellowness b*	deltaE _{C4+4}	Darkness Index
Count of different samples (variability)	3 (C, E, G)	4 (E, F, G, H)	4 (A, B, D, E)	4 (A, B, C, D)	3 (C, E, F)
Total count of samples			4		
SDR	75%	100%	100%	100%	75%
(c)					
Variability descriptor	Darkness “100 − L*”	Redness a*	Yellowness b*	deltaE _{C8} ²	Darkness Index
Count of different samples (variability)	7 (A–G)	7 (A–G)	6 (A–F)	6 (A–F)	7 (A–G)
Total count of samples			8		
SDR	88%	88%	75%	75%	88%

¹deltaE_{C4+4}: Total Color Difference (Equation (1)) of wheat–cricket WF-5, WF-10, WF-15 crackers versus color of non-enriched WF-0 cracker (control-1; within the WG-subset with WG-0 cracker as control-2 similarly).

²deltaE_{C8}: Total Color Difference (Equation (1)) of WG and 6 wheat–cricket cracker variants versus color of the WF-0 cracker (control-1) solely. ³ Darkness Index—a ratio of relative darkening of the cracker’s surface (Equation (2)).

A–H in Table 3, identification of homogenous groups within the conjoined WF and WG subsets of crackers.

Table A2. Quantification of ANOVA results—Sample Distinguishing Rate (SDR) of wheat and wheat–cricket crackers according to physical and texture parameters, as affected by wheat flour type and addition level of cricket powder: (a) white flour (WF) crackers (four variants); (b) whole-grain flour (WG) crackers (four variants); (c) conjoined WF and WG cracker subsets (eight variants).

(a)						
Variability descriptor	Weight	Thickness	Hardness	Flexibility	Stiffness ¹	Breaking work ²
Count of different samples (variability)	2 (B, C)	2 (BC, DE)	1 (AB)	2 (A, B)	1 (AB)	1 (AB)
Total count of samples				4		
SDR	50%	50%	0%	50%	0%	0%
(b)						
Variability descriptor	Weight	Thickness	Hardness	Flexibility	Stiffness	Breaking work
Count of different samples (variability)	2 (A, B)	2 (A, B)	2 (AB, D)	1 (AB)	2 (BC, D)	2 (A, B)
Total count of samples				4		
SDR	50%	50%	50%	0%	50%	50%
(c)						
Variability descriptor	Weight	Thickness	Hardness	Flexibility	Stiffness	Breaking work
Count of different samples (variability)	3 (A–C)	5 (A–E)	4 (A–D)	2 (A–B)	2 (A–B)	4 (A–D)
Total count of samples				8		
SDR	38%	63%	50%	25%	25%	50%

¹ Stiffness = Hardness/Flexibility [19]. ² Breaking work = area “Force · Distance 1:2”. A–E in Table 3 and Figure 2—identification of homogenous groups within the conjoined WF and WG subsets.

Table A3. Quantification of ANOVA results—Sample Distinguishing Rate (SDR) of wheat and wheat–cricket crackers according to summary sensory data, as affected by wheat flour type and addition level of cricket powder: (a) white flour (WF) crackers (four variants); (b) whole-grain flour (WG) crackers (four variants); (c) conjoined WF and WG cracker subsets (eight variants).

(a)				
Variability descriptor	Sensory Fragility	Sensory Hardness	Sensory Score	Sensory Acceptability ¹
Count of different samples (variability)	1 (AB)	1 (AB)	1 (AB)p	1 (AB)
Total count of samples			4	
SDR	0%	0%	0%	0%
(b)				
Variability descriptor	Sensory Fragility	Sensory Hardness	Sensory Score	Sensory Acceptability
Count of different samples (variability)	1 (AB)	1 (BCD)	1 (AB)	1 (AB)
Total count of samples			4	
SDR	0%	0%	0%	0%
(c)				
Variability descriptor	Sensory Fragility	Sensory Hardness	Sensory Score	Sensory Acceptability
Count of different samples (variability)	2 (A, B)	2 (A, BCD)	2 (A, B)	2 (A, B)
Total count of samples			8	
SDR	25%	25%	25%	25%

¹ Stiffness = Hardness/Flexibility [19]. A–D in Table 3 and Figure 2—identification of homogenous groups within the conjoined WF and WG subsets.

Table A4. Communalities (%), a portion of the data scatter of wheat and wheat–cricket cracker properties, explained by first three principal components (PC).

Cracker Characteristics		Principal Component			
– property	– active variable	– PC1	– PC2	– PC3	– Sum PC1–3
Composition	Moisture	<u>95</u> ***	<u>0</u> ns	<u>1</u> ns	97
	Fat	<u>66</u> ***	<u>27</u> **	<u>4</u> ns	97
	Proteins	<u>65</u> ***	<u>29</u> **	<u>3</u> ns	97
	Fiber	<u>63</u> ***	<u>29</u> **	<u>3</u> ns	95
	CRPW%	<u>38</u> ***	<u>52</u> ***	<u>5</u> ns	96
Weight Thickness		<u>7</u> ns	<u>78</u> ***	<u>4</u> ns	89
		<u>23</u> **	<u>30</u> **	<u>30</u> **	82
Texture	Hardness	<u>37</u> ***	<u>1</u> ns	<u>56</u> ***	93
	Flexibility	<u>2</u> ns	<u>2</u> ns	<u>75</u> ***	78
	Breaking work	<u>14</u> *	<u>0</u> ns	<u>76</u> ***	90
	Stiffness	<u>65</u> ***	<u>5</u> ns	<u>3</u> ns	73
Surface color	Darkness “100 – L*”	<u>90</u> ***	<u>1</u> ns	<u>5</u> ns	96
	Redness a*	<u>60</u> ***	<u>30</u> **	<u>0</u> ns	91
	Yellowness b*	<u>58</u> ***	<u>34</u> **	<u>4</u> ns	96
Sensory crispness		<u>0</u> ns	<u>43</u> **	<u>1</u> ns	44
Sensory hardness		<u>23</u> **	<u>35</u> **	<u>1</u> ns	59
Sensory score		<u>16</u> *	<u>15</u> *	<u>13</u> *	43
Average of active variables		42	24	17	83
– supplementary variable		– PC1	– PC2	– PC3	– Sum PC1–3
WFT		<u>59</u> ***	<u>30</u> ***	<u>5</u> ns	94
Whiteness L*		<u>90</u> ***	<u>1</u> ns	<u>5</u> ns	96
Darkness Index		<u>93</u> ***	<u>0</u> ns	<u>3</u> ns	96
Average of supplementary variables		81	10	4	95

WFT—wheat flour type processed into crackers; that is, the white or the whole-grain flour. CRPW%—percentage of wheat white flour or whole-grain flour replaced by the cricket powder (*w/w*). Significance of the pair correlation “variable—PC”: ns—non-significant; *, **, ***—significant at P = 95, 99, or 99.9%. Underlined values (for example, 95 ***) identifies a negative paired correlation between the variable and the actual PC.

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