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Development of High-Fiber Functional Cereal from Broken Black Rice, Corn, and Red Beans Using Mixture Design Approach

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ABSTRACT

Broken black rice (BBR) is a locally available cereal rich in macronutrients and bioactive compounds with reported health promoting properties. This study aimed to optimize a BBR based functional cereal blend with corn and red bean and evaluate its physicochemical and nutritional characteristics. A D optimal mixture design was used to identify the optimal proportions of BBR flour, corn flour, and red bean flour. The resulting formulations were prepared and characterized in terms of textural properties (crispiness, hardness), functional attributes (total phenolic content, resistance in milk, swelling degree), and proximate composition (moisture, ash, protein, fat, carbohydrates, and total dietary fiber). The optimal formulation comprised 29.107% BBR, 53.593% corn, and 8.300% red bean, with crispiness of 2.054 kgf, hardness of 5.821 kgf, total phenolic content of 18.350 mg GAE/g, resistance in milk of 44.326 minutes, and swelling degree of 275.216%. The product had a moisture content of 3.972%, ash of 2.519%, protein of 9.738%, total fat of 5.631%, carbohydrates of 71.078%, and total dietary fiber of 10.246%, with statistically significant model terms supporting the optimization (D optimal model). The optimized BBR–corn–red bean cereal exhibited balanced textural quality and enhanced functional properties, including high dietary fiber and phenolic content. These findings provide a basis for developing nutritionally enriched, ready to eat functional cereals from locally sourced ingredients.

1. INTRODUCTION

Breakfast is generally accepted to be the most important meal of the day because it affects energy intake, cognitive performance, and long term cardiometabolic health. In Indonesia, about 65% of school age children skip breakfast because of busy schedules (Kemenkes, 2024). Globally, most adults consume less dietary fiber than recommended, often below 20 g/day, owing to high intake of ultraprocessed foods and low consumption of whole grain cereals and plant based foods. This dietary pattern increases the risk of micronutrient deficiencies and non communicable diseases such as obesity, type 2 diabetes, and digestive disorders. Consequently, there is a need for convenient, nutrient dense, fiber rich breakfast products from local ingredients (Ramezani *et al*., 2024).

Cereal based breakfasts are well suited for ready to eat, yet conventional rice based cereals often rely on highly milled rice, which removes the bran and aleurone layers rich in protein, dietary fiber, lipids, and minerals. Studies show that progressive milling reduces these beneficial components, even though it improves appearance and palatability. This underlines the opportunity to develop functional cereals using less refined rice fractions, such as broken black rice, combined with whole grains and legumes to enhance nutritional quality while maintaining practicality. Polished rice in breakfast cereals should be partially substituted with broken black rice (BBR) to improve nutritional quality. BBR retains more protein, lipids, and dietary fiber than polished rice and provides γ oryzanol, phytosterols, phenolic acids, flavonoids, anthocyanins, vitamins, and minerals, which support antioxidant and metabolic health (Saleh *et al*., 2019). Combining BBR with corn and red beans further strengthens the nutritional profile of the cereal: corn contributes slowly digestible starch and high antioxidant activity compared with other common cereals, whereas red beans provide high quality plant protein, complex carbohydrates, and additional dietary fiber (Layli, 2019; Sheng *et al*., 2018; Li, 2025). This BBR–corn–red bean combination is therefore strategically chosen to simultaneously improve protein quality, fiber content, and antioxidant capacity while maintaining acceptable texture and processability for ready to eat cereal products. Cereal production generally uses extrusion technology, which is an HTST (High Temperature Short Time) process that produces puffed products while modifying dietary fiber. Extrusion at high temperatures is more effective in breaking the glycosidic bonds between fiber molecules, thus converting large-molecule IDF (Insoluble Dietary Fiber) into small-molecule SDF (Soluble Dietary Fiber) (Dang & Vasanthan, 2019; Qiao *et al*., 2021).

To produce functional cereals with high nutritional value, formula optimization are needed. No study has optimized BBR, corn, and red bean cereal by D optimal design or evaluated its extrusion based, high fiber formulation. This study aimed to obtain the optimal formula of functional cereals based on BBR, corn, and red beans, and determine the physicochemical characteristics and nutrition facts of functional cereals based on BBR, corn, and red beans. The development of functional cereal products based on BBR, corn, and red beans is expected to meet daily nutritional requirements of the productive age group.

2. MATERIALS AND METHODS

2.1. Tools and Materials

The tools used in this study were twin screw extruder (model puffing 2256 Berto Company), UV-Vis spectrophotometer (UVmini 1240 shimadzu), texture analyzer (Lloyd TA1), soxhlet, kjeldahl flask, water bath, sonicator, incubator, desiccator, centrifuge, kjeldahl flask, oven, husker, disc mill, sieve, mixer, caliper, analytical balance, whatman paper, erlenmeyer, beaker glass, and other glassware. The materials used in this study were cempo ireng broken black rice (BBR) variety (Cigudeg, Bogor), corn (*Zea mays* L.) and adzuki red beans (Bogor Market), sesame seeds, water, salt, milk, and chemicals for analysis.

2.2. Design of Experiments

The formula for functional cereal products was optimized using Design Expert 12. Optimization was performed on the independent variables consisted of BBR flour, corn flour, and red bean flour. The lower and upper limits of independent variables were determined based on trial and error results by observing the texture response that resembled commercial products of Kellog's brand. The lower and upper limits of BBR flour, corn flour, and red bean flour are presented in Table 1. After obtaining the lower and upper limits of the independent variables, a formula design was carried out using the Design Expert 12.

Table 1. The lower and upper limits of independent variables

Variables	Lower Limit	Upper Limit
BBR	10.0	40.0
Corn	46.0	66.0
Red beans	5.0	15.0

2.3. Methods

2.3.1. Preparation of Ingredients

Ingredients preparation consisted of making BBR flour, corn flour, and red bean flour. The steps of BBR flour preparation consisted of: BBR grain was sorted and then milled using a husker. The milled BBR then stored at a temperature of -20 °C until the next day. The BBR grain was then ground into flour using a disc mill with an 80-mesh sieve to produce BBR flour (Boulemkahel *et al*., 2021). The steps of corn flour preparation consisted of: corn was shelled from the cob, then dried. The dried corn was ground into grits using a hammer mill. Next, it was milled using a disc mill with a 40-mesh sieve (Alcântara *et al*., 2020). The steps of red bean flour preparation consisted of: the red beans was sorted, then washed and roasted for 10 minutes and cooled. Next, it was grounded with a disc mill and 80-mesh sieve (Boulemkahel *et al*., 2021; Sukarno *et al*., 2021).

2.3.2. Optimization Formulas of Functional Cereal

a. Formula design

The formula design for functional cereals based on BBR, corn, and red beans using D-optimal mixture design in Design Expert 12. The control variables were sesame, water, and salt; the independent variables were BHPK flour, corn flour, and red bean flour expressed as relative proportions (%) of the total formula used; and the dependent variable were crispiness, hardness, milk resistance, swelling degree, and total phenolic content (TPC). Texture properties (hardness and crispiness) were measured using a Lloyd TA1 Texture Analyzer equipped with a 1/4" cylindrical probe. Milk resistance determined by adding 70 mL of milk (29 °C) to 1.5 g of sample, measuring the floatation time until crispness was lost. Swelling degree were measured using a caliper with the following formula:

$$\text{Swelling degree (\%)} = \frac{\text{product diameter (mm)}}{\text{extruder diameter (mm)}} \times 100 \tag{1}$$

Total phenolic content (TPC) was measured by UV-Vis spectrophotometer at a wavelength of 765 nm. The lower and upper limits of the independent variables were determined based on trial and error results. The Design Expert 12 program generated several formula designs as a reference for making functional cereals and responses testing.

b. Manufacture of functional cereal and responses testing

Manufacture of functional cereals refers to the research of Boulemkahel *et al*. (2021). The composition of ingredients in manufacturing functional cereals consisted of 91% independent variables (BBR flour, corn flour, and red bean flour), 5% sesame, 3% water, and 1% salt. All ingredients were mixed in a mixer for 5 minutes, then added 3% water and mixed again for 5 minutes. Each mixture of ingredients was extruded using a twin screw extruder at a temperature of 127 ℃ (T3) with an auger speed of 28.1 Hz and a screw speed of 28.8 Hz. Then cooled at room temperature for 3 minutes. The functional cereal that had been obtained was then tested for crispiness and hardness (Sobukola *et al*., 2021), milk resistance (Campuzano *et al*., 2018), swelling degree (Abilmazhinov *et al*., 2023), and total phenolic content (TPC) (Nisa *et al*., 2019).

c. Responses analysis

All responses were conducted in quintuplicate, and the results of the responses testing were entered into Design Expert 12 program for analysis to obtain a mathematical model and analysis of variance (ANOVA). In response analysis, several criteria must be fulfilled, including the model must be significant ($p<0.05$), the lack of fit value must be insignificant ($p>0.05$), the difference between adjusted R^2 and predicted R^2 was less than 0.2, and the adequate precision value must be more than 4.

d. Determination of the optimal formula of functional cereal

All analyzed responses were optimized. Responses criteria were determined based on benchmarking results with commercial cereal products of Kellog's brand. The criteria goal of crispiness, hardness, milk resistance, and swelling degree was targeted of 2.045 kgf, 5.908 kgf, 43.9 minutes, and 279% and the criteria goal of total phenolic content (TPC) was maximize. The best formula was obtained with a maximum desirability value (~1.0).

e. Verification of the best functional cereal formula

The functional formula with a highest desirability value was validated through response testing, and the results were compared with the response value predicted by the Design Expert 12 program. The verification was deemed successful when the actual response test value was still in the range of 95% Confident Interval (CI) and 95% Prediction Interval (PI).

2.3.3. Characterization of the best functional cereal

The functional cereal characterization was carried out on the best functional cereal formulas selected based on the maximum desirability value (~1.0). Proximate analysis, nutrition facts and %DV calculations were performed.

3. RESULTS AND DISCUSSION

3.1. Optimization Formulas of Functional Cereal

The total formula generated by the Design Expert 12 was 17 formulas. The combination of the formula design and optimization response is presented in Table 2. The results of the analysis of variance for each optimization responses were presented in Table 3. The entire model was significant (p<0.05) for the response and the selected model, and all responses had a lack of fit value that was not significant (p>0.05), which meant that the selected model had a good fit to the response data and was not significant for incompatibility model.

Table 2. Formula and optimization responses of functional cereal based on BBR, corn, and red beans

Run	A : BBR flour (%)	B : Corn flour (%)	C : Red bean flour (%)	Response				
				Crispiness (kg_f)	Hardness (kg_f)	TPC (mg GAE/g)	Milk resistance (min)	Swelling degree (%)
1	11.500	66.000	13.500	2.253	4.808	9.119	35.600	297.300
2	19.054	66.00	5.946	2.598	4.473	10.829	34.300	300.000
3	30.868	55.132	5.000	2.237	5.943	18.454	42.100	276.300
4	23.030	57.983	9.987	2.226	5.559	14.541	38.100	283.000
5	19.054	66.000	5.946	2.583	4.473	10.73	34.700	301.700
6	23.030	57.983	9.987	2.203	5.559	14.541	39.600	285.400
7	23.030	57.983	9.987	2.134	5.559	14.531	40.200	288.400
8	26.975	49.386	14.639	1.695	6.251	18.004	47.300	263.500
9	38.650	46.000	6.350	1.907	6.275	21.815	50.300	260.700
10	23.023	57.983	9.987	2.038	6.212	19.578	45.000	267.300
11	30.767	50.946	9.288	1.926	5.961	18.416	43.500	274.000
12	25.369	60.631	5.000	2.435	5.378	14.449	36.700	291.300
13	21.304	54.696	15.000	1.788	5.787	14.971	40.300	280.100
14	32.520	46.000	12.480	1.614	6.168	19.446	44.200	271.200
15	16.420	60.330	14.250	2.036	5.010	11.783	36.400	293.500
16	32.520	46.000	12.480	1.531	6.343	20.257	53.300	257.300
17	35.378	50.622	5.000	1.986	6.276	20.004	50.500	258.600

Table 3. Analysis of variance for optimization response of functional cereal based on BBR, corn, and red beans

Responses	Model	Signification (p<0.05)	Lack of fit (p<0.05)	R^2	Adj. R^2	Pred. R^2	Adeq. Precision
Crispiness (kg_f)	Linear	<0.0001	0.883	0.972	0.968	0.961	42.013
Hardness (kg_f)	Linear	<0.0001	0.403	0.824	0.799	0.756	14.395
TPC (mg GAE/g)	Linear	<0.0001	0.975	0.886	0.867	0.862	21.679
Milk resistance (minutes)	Linear	<0.0001	0.941	0.808	0.781	0.717	14.561
Swelling degree (%)	Linear	<0.0001	0.914	0.829	0.804	0.764	15.243

3.1.1. Crispiness Response Analysis

Crispiness is the ease with which a product can break, snaps, or crack at low energy (Sukarno *et al*., 2021). Crispiness is affected by extrusion temperature, water content, and ingredients. The combination of components that mutually affected the crispness value was shown in Figure 1(a). The lowest crispiness value was 1.531 kgf, obtained with the formula containing 32.5% BBR flour, 46% corn flour, and 12.5% red bean flour, represented by the blue color. The highest crispiness value was 2.598 kgf, obtained with the formula containing 19.1% BBR flour, 66% corn flour, and 5.9% red bean flour, represented by the red color. Crispiness lack of fit value was 0.883 and R^2 was 0.972. In Design-Expert, a model are classified as good lack of fit if the lack of fit value is not significant (p > 0.05) and R^2 value is close to 1 (~1.0), so this model is accurate. The equation used to interpretation the crispiness response was presented in Equation (2).

$$\text{Crispiness} = 0.005015\ (A) + 0.040932\ (B) - 0.035498\ (C) \quad (2)$$

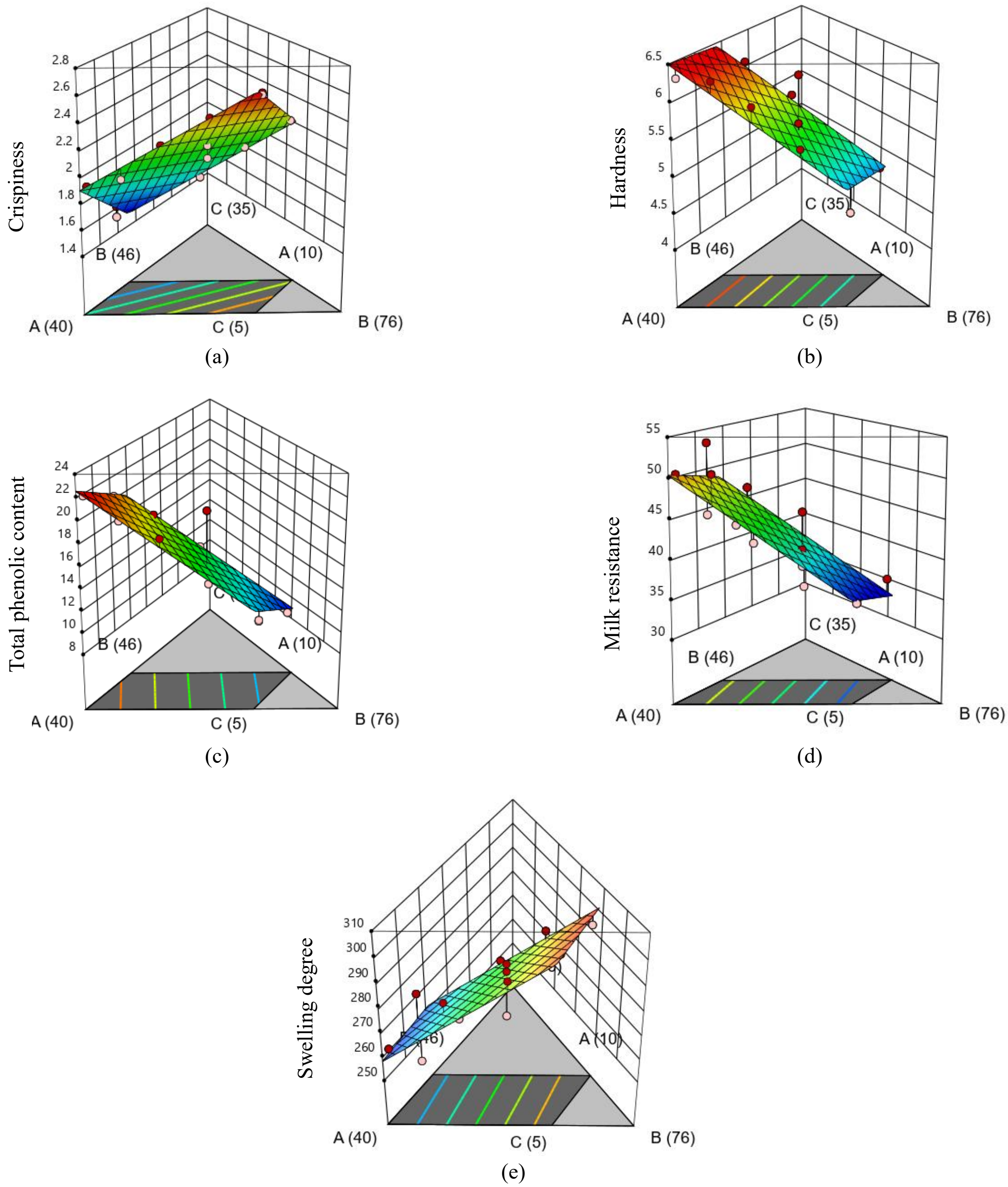

Figure 1. 3D graph of: (a) crispiness response, (b) hardness response, (c) total phenolic content response, (d) milk resistance response, and (e) swelling degree response

The Equation (2) showed that the crispiness response was affected by the concentration of BBR flour (A), corn flour (B), and red bean flour (C). Corn flour had a greater effect on the crispiness of functional cereal than BBR flour and red bean flour. The higher the corn flour used in the functional cereal formula, the higher crispiness was obtained. This is in line with research by Sukarno *et al*. (2021), which found that the higher the corn flour content, the higher the crispiness. This is caused by corn contains approximately 70–75% starch, with the composition of amylose and amylopectin significantly affecting its texture. During the extrusion process, starch gelatinizes, which means it expands due to heat and pressure, then hardens quickly after leaving the mold due to reduced pressure. This process produces a porous and crispy structure.

3.1.2. Hardness Response Analysis

Hardness is one of the factors in the acceptance of food products. The combination of components that mutually affected the hardness value was shown in Figure 1(b). The lowest hardness value was 4.473 kgf, obtained with the formula containing 19.1% BBR flour, 66% corn flour, and 5.9% red bean flour, represented by the blue color. The highest hardness value was 6.343 kgf, obtained with the formula containing 32.5% BBR flour, 46% corn flour, and 12.5% red bean flour, represented by the red color. Hardness lack of fit value was 0.403 and R^2 was 0.824, so this model is accurate. The equation used to interpretation the hardness response was presented in Equation (3).

$$\text{Hardness} = 0.114108\ (A) + 0.030203\ (B) + 0.109209\ (C) \quad (3)$$

The Equation (3) showed that the BBR, corn, and red bean flours all affected hardness, with BBR exerting the strongest effect. This can be explained mechanistically: BBR’s coarser particle size and retained bran increase insoluble fiber content, which interrupts the continuous starch matrix and limits bubble growth during extrusion, producing a denser product. In addition, BBR’s higher amylose fraction promotes stronger retrogradation and forms firmer, more ordered gel networks during starch gelatinization; amylose tends to leach, realign, and retrograde into rigid structures that reduce matrix extensibility. During extrusion, restricted starch swelling and limited amylopectin-driven expansion lower cell expansion and increase cell wall thickness, both of which raise hardness (Nandiyanto *et al*., 2022; Boakye *et al*., 2023).

3.1.3. Total Phenolic Content (TPC) Response Analysis

Total phenolic content (TPC) are the total phenolic content found in a sample, generally measured as gallic acid equivalents (GAE). The combination of components that mutually affected the TPC value was shown in Figure 1(c). The lowest TPC value was 9.119 mg GAE/g, obtained with the formula containing 11.5% BBR flour, 66% corn flour, and 13.5% red bean flour, represented by the blue color. The highest TPC value was 21.815 mg GAE/g, obtained with the formula containing 38.7% BBR flour, 46% corn flour, and 6.4% red bean flour, represented by the red color. TPC lack of fit value was 0.975 and R^2 was 0.886, so this model is accurate. The equation used to interpretation the TPC response was presented in Equation (4).

$$\text{Total phenolic content} = 0.532613\ (A) + 0.000428\ (B) + 0.246972\ (C) \quad (4)$$

The Equation (4) showed that the TPC response was affected by the concentration of BBR flour (A), corn flour (B), and red bean flour (C). BBR flour had a greater effect on the TPC of functional cereal than corn flour and red bean flour. The higher the BBR flour used in the functional cereal formula, the higher TPC was obtained. BBR has an endosperm that produces anthocyanins, which contribute to the rice's deep purple, almost black color. Pigmented rice has a higher content of phenolic compounds and higher antioxidant activity than non-pigmented rice. The concentrations of phenolic content in broken black rice, broken white rice, and broken red rice are 4.38 mg/g, 2.33 mg/g, and 3.27 mg/g (Suarti, 2024). Therefore, BBR greatly affected the increase of TPC in functional cereal.

3.1.4. Milk Resistance Response Analysis

Milk resistance is the ability of functional cereals to maintain their texture in milk. The combination of components that mutually affected the milk resistance value was shown in Figure 1(d). The lowest milk resistance value was 34.4 minutes, obtained with the formula containing 19.1% BBR flour, 66% corn flour, and 5.9% red bean flour, represented by the blue color. The highest milk resistance value was 53.3 minutes, obtained with the formula containing 32.5% BBR flour, 46% corn flour, and 12.5% red bean flour, represented by the red color. Milk resistance lack of fit value was 0.941 and R^2 was 0.808, so this model is accurate. The equation used to interpretation the milk resistance response was presented in Equation (5).

$$\text{Milk resistance} = 0.957053\ (A) + 0.178125\ (B) + 0.782742\ (C) \quad (5)$$

The Equation (5) showed that the milk resistance response was affected by the concentration of BBR flour (A), corn flour (B), and red bean flour (C). BBR flour had a greater effect on the milk resistance of functional cereal than corn flour and red bean flour. The higher the BBR flour used in the functional cereal formula, the longer milk resistance of functional cereal was obtained. Based on hardness, crispiness, and swelling degree value, functional cereal F16 showed a low swelling degree, was less crispy, and had the hardest texture. This condition made the functional cereal difficult to absorb milk because its dense and less expanded structure leaves only a small cavity for milk absorption. This is due to the high content of protein, dietary fiber, and phenolic content in BBR, which results in a denser and tighter extrudate structure (Boakye *et al*., 2023). As a result, milk absorption is slower, so that the functional cereal has a longer shelf life before softening.

3.1.5. Swelling Degree Response Analysis

Sweeling degree is an important factor in determining expansion product (puffing). When the material exits the extruder, increased pressure in the die causes rapid water evaporation, causing the product to expand. The combination of components that mutually affected the swelling degree value was shown in Figure 1(e). The lowest swelling degree value was 257.3%, obtained with the formula containing 32.5% BBR flour, 46% corn flour, and 12.5% red bean flour, represented by the blue color. The highest milk resistance value was 301.7%, obtained with the formula containing 19.1% BBR flour, 66% corn flour, and 5.9% red bean flour, represented by the red color. Swelling degree lack of fit value was 0.914 and R^2 was 0.829, so this model is accurate. The equation used to interpretation the swelling degree response was presented in Equation (6).

$$\text{Swelling degree} = 1.82221\ (A) + 3.79886\ (B) + 2.14657\ (C) \tag{6}$$

The Equation (6) showed that the swelling degree response was affected by the concentration of BBR flour (A), corn flour (B), and red bean flour (C). Corn flour had a greater effect on the milk resistance of functional cereal than BBR flour and red bean flour. The higher the corn flour used in the functional cereal formula, the higher swelling degree was obtained. Corn is rich in starch with a high amylopectin content, so it is easily gelatinized so that the product expands more (Bayomy *et al*., 2024).

3.1.6. Formula Optimization and Verification of Functional Cereal

All analyzed responses were optimized to get the best formula of functional cereal. Responses criteria were determined based on benchmarking results with commercial cereal products. The criteria for each variable were presented in Table 4. The goal criteria for BBR, corn, and red beans were in range because the optimal formula was expected to be in the concentration interval used. The goal criteria for crispiness, hardness, milk resistance, and swelling degree was targeted of 2.045 kgf, 5.908 kgf, 43.9 minutes, and 279% based on criteria from cereal commercial. The goal criteria for total phenolic content were to maximize because it was expected that functional cereal based on BBR, corn, and red beans had a high phenolic for a health.

From the optimization results, three optimal formulas were obtained, as shown in Table 5. Formula 1 with the highest desirability value (~1.0) was selected. This formula has composition of BBR 29.11%, corn 53.59%, and red beans 8.30%. The selected formula was then verified to determine the ability of the model to predict optimal values.

Table 4. Criteria for determining the optimum formula for functional cereal based on BBR, corn, and red beans

Variables	Goal	Lower Limit	Upper Limit	Importance
BBR (%)	In range	10.0	40.0	3 (+++)
Corn (%)	In range	46.0	66.0	3 (+++)
Red beans (%)	In range	5.0	15.0	3 (+++)
Crispiness (kgf)	Target → 2.045	1.5	2.6	3 (+++)
Hardness (kgf)	Target → 5.908	4.5	6.3	3 (+++)
TPC (mg GAE/g)	Maximize	9.1	21.8	3 (+++)
Milk resistance (minutes)	Target → 43.9	34.3	53.3	3 (+++)
Swelling degree (%)	Target → 279.0	257.3	301.7	3 (+++)

Table 5. Optimal formulas for functional cereal based on BBR, corn, and red beans

Formula	BBR (%)	Corn (%)	Red beans (%)	Desirability
1	**29.11**	**53.59**	**8.30**	**0.87**
2	32.18	53.82	5.00	0.82
3	22.12	53.88	15.00	0.71

Table 6. Verification of the optimal formula of functional cereal based on BBR, corn, and red beans

Responses	Prediction	Verification	95% CI low	95% CI high	95% PI low	95% PI high
Crispiness (kg_f)	2.04	2.05	2.01	2.07	1.98	2.10
Hardness (kg_f)	5.84	5.82	5.67	6.01	5.52	6.16
TPC (mg GAE/g)	17.57	18.35	16.74	18.41	16.00	19.15
Milk resistance (min)	43.90	44.32	42.25	45.55	40.78	47.01
Swelling degree (%)	274.44	275.21	270.52	278.36	267.05	281.84

The verification results of the optimal formula are shown in Table 6. The response test results are within the range of the 95% Confidence Interval (CI) and 95% Prediction Interval (PI). This condition indicates the response of optimal formula in line with the predictions from the Design Expert 12. The Confidence Interval (CI) represents the estimated range for the average value of the next measurement, while the Prediction Interval (PI) represents the estimated range for the next response measurement under the same conditions.

3.2. Characteristics of the Best Functional Cereal

3.2.1. Chemical Characteristics of Functional Cereal

The chemical characteristics tested consisted of moisture content, ash content, protein, carbohydrates, total fat, and fiber, are shown in Table 7. Moisture content is an important factor in functional cereals because moisture content affects texture, microbiological stability, and shelf life. According to SNI 2886:2015 on Extruded Snack Foods, the maximum moisture content requirement for extruded products is 4% (BSN, 2015). The optimal formula moisture content is 3.972%, which under the maximum moisture content requirement for extruded products as stipulated by SNI 2886:2015. Ash, protein, fat, and fiber content contribute to nutritional value, and carbohydrate content determines energy contribution.

Table 7. Chemical composition of functional cereal based on BBR, corn, and red beans

Parameters	Result
Moisture content (% bb)	.972
Ash content (% bb)	2.52
Protein content (%)	9.74
Total fat (%)	5.63
Carbohydrate content (%)	71.08
Dietary fiber (%)	10.25

3.2.2. Nutrition Facts and %DV of Functional Cereal

According to BPOM (2023), Nutritional Information is a list of nutritional and non-nutritional content of processed foods as sold in accordance with a standardized format. Meanwhile, the %DV is how much a nutrient in a single serving of an individual packaged food or dietary supplement contributes to your daily diet. The %DV calculation refers to BPOM Number 9 of 2016 concerning Nutrition Labeling Standards (BPOM, 2016). This functional cereal product based on BBR, corn, and red beans is categorized as Food Category No. 6 was Cereals and Cereal Products, which has a serving size of 30 g.

The optimal formula for functional cereal products based on BHPK, corn, and red beans per serving provides a total energy of 110 kcal, energy from fat of 15 kcal, total fat of 2%, protein of 5%, and total carbohydrates of 7%. This nutritional content is not much different from commercially available products with a serving size of 30 g, which provide a total energy of 120 kcal, energy from fat 5 kcal, total fat 1%, protein 3%, and total carbohydrates 8%. The advantage of this functional cereal product based on BBR, corn, and red beans was there is no added sugar, sweeteners, or preservatives in its ingredients. The dietary fiber content in this functional cereal based on BBR, corn, and red beans is higher than the dietary fiber content in commercial cereals. The dietary fiber content in commercial functional cereals ranges from 1 to 2 g per serving (average of 30 g per serving). When compared to functional cereal products based on BBR, corn, and red bean flour, the dietary fiber content is higher. Food products are classified as high-fiber if they contain at >6 grams of fiber per 100 grams (BPOM, 2022) and this functional cereal has a fiber content of 10.246%, so it can be claimed as a high-fiber processed food (BPOM, 2022).

This study developed and optimized a ready-to-eat functional cereal based on broken black rice (BBR), corn, and red beans using a D-optimal mixture design and extrusion technology. The resulting product provides higher dietary fiber content and is formulated without added sugar, sweeteners, or preservatives, offering a healthier alternative to commercial cereals while promoting the utilization of Indonesian local food resources.

4. CONCLUSIONS

Optimization of functional cereal products from BBR, corn, and red bean flours using a D-Optimal mixture design (Design-Expert 12) evaluated 17 formulations and produced a linear model linking ingredient proportions to responses. Increasing BBR, corn, and red bean flours improved crispiness, hardness, total phenolic content (TPC), milk resistance, and expansion. The optimal blend (29.107% BBR, 53.593% corn, 8.300% red bean; desirability = 0.872) showed proximate values of 3.972% moisture, 2.519% ash, 9.738% protein, 5.631% fat, 71.078% carbohydrates, and 10.246% dietary fiber. A 30 g serving supplies ~10% of an adult's daily fiber requirement, supporting a high-fiber claim. Scientifically, the formulation demonstrates ingredient synergy enhancing texture and antioxidant potential. Industrially, the blend is viable for high-fiber snack or cereal products. Recommended next steps include glycemic index and in vivo studies, sensory evaluation, shelf-life and packaging trials, ensure consumer acceptance, and enable commercialization.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION

Not applicable. The authors did not use any generative AI tools or services in the preparation of this manuscript. All content is entirely the intellectual work of the authors.

AUTHOR CONTRIBUTION

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
SMS	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
SB	✓			✓			✓			✓		✓	✓	✓
ABS	✓			✓			✓			✓		✓	✓	✓

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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