

Research Article

Functional Characterization of Fiber-enriched Breakfast Cereals Blends

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Abstract

This study evaluated the functional properties of fiber-enriched breakfast cereals formulated from millet, malted mungbean and tigernut flours using quadratic response surface models. The data obtained were subjected to regression/statistical analysis as prescribed by the RSM. The regression coefficients were used to test the models. The linear, binary and ternary blends were generated and further highlighted by the response surface plot. The blend ratio '31.16g millet, 21.72g mungbean, 47.11g tigernut' with high desirability of 0.951 was selected after optimization and were validated. The blend will be suitable for production of high gluten-free fiber breakfast cereal and other food products such as bread, cake, sausage and biscuit. The developed regression models will enable food industries maximized/optimized the blending of these flours in production of aforementioned food products so as to increase the product quality. The results showed that blend composition significantly influenced bulk density (BD), water absorption capacity (WAC), oil absorption capacity (OAC), solubility (S), emulsification capacity (EC), and foam stability (FS) ($p < 0.05$), while wettability, viscosity, swelling index, gelatinization temperature, and foam capacity were not significantly affected. Malted mungbean flour played a key role in reducing BD and improving WAC and OAC, indicating its suitability for producing lighter cereals with improved hydration and flavor retention. Significant ($p < 0.05$) interaction effects among the flours, particularly for WAC and EC, highlighted the importance of optimized blend combinations. Foam stability exhibited the highest model predictability (Adj. $R^2 = 0.8596$), mainly enhanced by millet inclusion. However, these findings support the development of nutritionally enhanced, consumer-acceptable breakfast cereals with improved reconstitution, texture, and stability, suitable for children, adults, and the elderly, and valuable for commercial cereal formulation and product optimization.

Keywords

Functional Properties, Breakfast Cereals, Response Surface Models

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1. Introduction

Breakfast cereals serve as an essential component of human nutrition, providing critical nutrients that contribute to overall health and well-being. They are typically rich in carbohydrates, vitamins, and minerals, making them a convenient source of energy, especially in busy lifestyles. In recent years, dietary fiber has gained increasing attention for its various health benefits, including improved digestive health, reduced risk of chronic diseases such as cardiovascular diseases and diabetes, and better weight management [26, 5]. However, many conventional breakfast cereals are refined, which involves processing that often removes beneficial nutrients and fiber. This refinement typically leads to a product that is lower in essential nutrients and may not support optimal health outcomes [6, 21].

However, the use of alternative ingredients such as millet, malted mungbean, and tigernut presents a feasible approach for developing fiber-enriched breakfast cereals. Millet is a gluten-free grain that provides an excellent energy source and is also rich in dietary fiber, vitamins, and minerals [2, 10]. Its inherent health properties make it an ideal candidate for enhancing the nutritional profile of breakfast cereals. Malted mungbean improves protein quality and digestibility; the malting process enhances nutrient availability by breaking down anti-nutritional factors, thereby making proteins more accessible [12, 25]. Tigernut, which is not a nut but a tuber, adds not only dietary fiber but also natural sweetness and healthy fats, complementing the overall composition of these composite cereals [23, 7]. Despite the potential of these ingredients, there is a significant gap in the literature regarding the functional properties of composite cereals made from millet, mungbean, and tigernut. Existing studies primarily focus on individual components or other grain-legume combinations, leaving a deficiency in information on how these specific blends perform nutritionally and functionally [4, 22]. The aim of this study is to evaluate the functional properties of fiber-enriched breakfast cereals from blends of millet, malted mungbean, and tigernut. Thus, the functional characterization of these composites is thus a critical step toward innovative and health-oriented food development.

2. Materials and Methods

Source of Millet, Mungbean, and Tigernut

Green pearl millet (*Pennisetum glaucum*) and brown tigernut (*Cyperus esculentus*) were purchased from Relief Market, Imo State, Nigeria, while whole green mungbean (*Vigna radiata*) was obtained from Kingsway Market, Apapa, Lagos State, Nigeria. All raw materials were authenticated at the Crop Science and Technology Department, Federal University of Technology Owerri (FUTO), Imo State, Nigeria.

Chemicals and Reagents

All chemicals and reagents used in this study were of analytical grade. Laboratory equipment and facilities utilized for

sample preparation and analysis were sourced from the Department of Food Science and Technology, Federal University of Technology Owerri (FUTO), Imo State, Nigeria; Imo state Polytechnic, Umuagwo-Ohaji, Imo state, Nigeria; University of Ilorin; University of Jos; and the National Root Crops Research Institute (NRCRI), Umudike, Abia State, Nigeria.

Production of Millet Flour

Millet flour was produced following the method described by Jideani [16]. Two kilograms (2 kg) of millet grains were cleaned and sorted to remove dirt and other extraneous materials. The grains were washed and soaked in distilled water for 12 h at ambient temperature, after which they were thoroughly rinsed. The soaked grains were oven-dried at 65°C for 6 h using a laboratory oven (DHG-9023A, Zenith Laboratory, China). The dried millet was milled using an attrition mill and sieved through a 300 µm sieve to obtain fine millet flour. The resulting flour was packaged in an airtight container and stored for subsequent analyses.

Processing of Malted Mungbean Flour

Malted mungbean flour was prepared according to the method of Mubarak [18]. Two kilograms (2 kg) of mungbean seeds were cleaned, sorted, and washed with distilled water before being soaked in distilled water for 12 h at ambient temperature in a transparent container. The soaked seeds were drained and spread on a sterile jute bag, covered with a muslin cloth, and allowed to germinate at ambient temperature for 24 h. During germination, distilled water was sprinkled on the muslin cloth at 6-h intervals to maintain moisture. After germination, the sprouted seeds were cleaned and oven-dried at 60 °C for 9 h using a laboratory oven (DHG-9023A, Zenith Laboratory, China). The dried sprouts were milled into flour, packaged in airtight containers, and stored for further analysis.

Production of Tigernut Flour

Tigernut flour was produced following the method described by Adejuyitan [1]. Two kilograms (2 kg) of fresh tigernut tubers were cleaned, sorted, and thoroughly washed to remove adhering impurities. The cleaned tigernuts were milled into a paste, homogenized with boiled water at 100 °C, and filtered through a muslin cloth to extract the milk. The residual tigernut mash was oven-dried at 60 °C for 8 h using a laboratory oven (DHG-9023A, Zenith Laboratory, China). The dried mash was packaged in airtight containers and stored for subsequent analyses.

Production of Breakfast Cereals

Breakfast cereals were produced from composite blends of millet flour, malted mungbean flour, and tigernut spent mash flour (Table 1) following the method described by Okafor and Usman [20]. The formulated composite flour blends were thoroughly mixed and toasted in a hot air oven (DHG-9023A, Zenith Laboratory, China) at 150°C for 10 min until dried, ready-to-eat cereal granules were obtained. Control samples were prepared separately using 100% millet flour, 100% malted mungbean flour, and 100% tigernut spent mash flour

under the same processing conditions. The toasted cereal products were cooled to room temperature, packaged in air-tight containers, and stored for subsequent functional property analyses.

Experimental design

A Box-Behnken design (BBD) under Response Surface Methodology (RSM) was used to evaluate the effects of millet

flour (x_1), mungbean flour (x_2), and tigernut flour (x_3) on the functional properties of fibre-enriched breakfast cereals. The independent variables were studied at three levels: low (50g), centre (75g), and high (100g). A total of 14 experimental runs, including two centre point replications, were generated and fitted to a quadratic model.

Table 1. Three component augmented simplex centroid experimental design.

Run	Experimental variable		
	Millet flour (x_1)	Mungbean flour (x_2)	Tiger nut flour (x_3)
1	100	0	0
2	0	100	0
3	0	0	100
4	50	50	0
5	50	0	50
6	0	50	50
7	33.3	33.3	33.3
8	66.6	16.7	16.7
9	16.7	66.6	16.7
10	16.7	16.7	66.6
11	100	0	0
12	0	100	0
13	0	0	100
14	50	50	0

11-14 are replicates runs

Quadratic model used

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 \quad (1)$$

Statistical analysis

The experimental data obtained from the Box-Behnken design were analysed using Response Surface Methodology (RSM) to evaluate the effects of millet flour (x_1), mungbean flour (x_2), and tigernut flour (x_3) on the functional properties of the breakfast cereal products. Statistical analyses were performed using Design-Expert software (version 13).

A second-order quadratic polynomial model was fitted to the experimental data for each response. Analysis of variance (ANOVA) was used to assess the significance of the model terms, including linear, interaction, and quadratic effects. The adequacy of the fitted models was evaluated using the F-value, p-value, and coefficient of determination (R^2). Model terms with p-values less than 0.05 were considered statistically sig-

nificant. Model fitness was further examined using the adjusted R^2 , with adequate agreement between the two indicating good predictive ability of the model. The lack-of-fit test was used to determine the suitability of the model, where a non-significant lack of fit ($p > 0.05$) confirmed that the model adequately represented the experimental data.

Determination of Functional Properties of Flour Samples

The functional properties of the flour samples were determined using standard methods as described by Onwuka [24]. The properties evaluated included bulk density, water absorption capacity, oil absorption capacity, emulsification capacity, viscosity, wettability, gelatinization temperature, swelling index, foam capacity, foam stability and solubility. All determinations were carried out in triplicate, and mean values were reported.

3. Results and Discussion

Table 2. Regression equation coefficients for functional characterization of fiber-enriched breakfast cereals from millet, malted mungbean, and tigernut blends.

Coefficient	BD	WAC	OAC	WE	V	S	SI	GT	EC	FC	FS
Intercept	0.6357	1.4907	1.2821	71.695	32.1607	18.472	16.48	6.9757	5.4278	6.9285	78.105
A (p-value)	0.03 (0.2390)	-0.015 (0.8278)	0.0187 (0.7626)	-5.5675 (0.4869)	1.0275 (0.8187)	0.2537 (0.6960)	6.0412 (0.3998)	0.0425 (0.9594)	0.9862 (0.1097)	6.3637* (0.0263)	-0.0587 (0.9782)
B (p-value)	0.1687* (< 0.0001)	0.285* (0.0036)	0.2037* (0.0071)	12.195 (0.1691)	0.5425 (0.9036)	1.1987 (0.0958)	-6.5137 (0.3654)	0.5 (0.5530)	1.0987 (0.0807)	-2.3287 (0.3631)	-0.1225 (0.9546)
C (p-value)	0.00125 (0.9594)	-0.0875 (0.2293)	-0.055 (0.3838)	0.6675 (0.9313)	-3.63 (0.4253)	-1.13 (0.1127)	0.555 (0.9372)	-0.7925 (0.3535)	-1.065 (0.0885)	-1.9075 (0.4532)	-0.8737 (0.6881)
AB	-	-0.3675* (0.0058)	-	-21.867 (0.1008)	-	-3.31* (0.0071)	-	-	-2.4925* (0.0136)	-	3.8075 (0.2541)
AC	-	-0.0775 (0.4366)	-	-12.102 (0.3048)	-	-1.8125 (0.0788)	-	-	-2.05* (0.0310)	-	20.87* (0.0019)
BC	-	0.2625* (0.0268)	-	7.9325 (0.4838)	-	-0.1275 (0.8891)	-	-	2.47* (0.0142)	-	0.1625 (0.9574)
A ²	-	-	-	6.8487 (0.5837)	-	-	-	-	-	-	-9.585* (0.0401)
B ²	-	-	-	-20.161 (0.1546)	-	-	-	-	-	-	13.392* (0.0139)
C ²	-	-	-	-18.951 (0.1749)	-	-	-	-	-	-	-1.74 (0.6154)
Model (p-value)	0.0003*	0.0095*	0.0387*	0.3003	0.8569	0.0398*	0.6536	0.7280	0.0124*	0.0972	0.0209*
Lack of Fit	0.6783	0.7429	0.6943	0.3688	0.8351	0.2500	0.9424	0.8698	0.4072	0.6356	0.5421
Fit statistics											
Adj R ²	0.7875	0.7450	0.4173	0.3553	-0.2080	0.6001	-0.1131	-0.1478	0.7228	0.2895	0.8596
CV (%)	10.66	12.61	13.32	38.65	38.41	9.54	117.91	33.02	28.06	99.77	7.22
Standard deviation	0.0678	0.1879	0.1708	20.58	12.35	1.76	19.43	2.30	1.52	6.91	5.72
Mean	0.6357	1.49	1.28	53.26	32.16	18.47	16.48	6.98	5.43	6.93	79.29

* Significant at the 5% level ($p < 0.05$); BD- Bulk density; WAC- Water absorption capacity; OAC- Oil absorption capacity; V- Viscosity; SI- Solubility Index; GT- Gelatinization Temperature; WE- Wettability; FC- Foam Capacity; FS- Foam Stability; EC- Emulsification Capacity

The quadratic response surface models as shown in Table 2 adequately described several functional properties of the cereal blends. The overall model p-values were significant ($p < 0.05$) for bulk density (BD), water absorption capacity (WAC), oil absorption capacity (OAC), solubility (S), emulsification capacity (EC), and foam stability (FS), indicating that the independent variables significantly influenced these responses. In contrast, models for wettability (WE), viscosity

(V), swelling index (SI), gelatinization temperature (GT), and foam capacity (FC) were not statistically significant ($p > 0.05$), suggesting that the compositional variations within the studied range had limited influence on these properties (Table 1). The lack-of-fit values were non-significant ($p > 0.05$) for all responses, confirming that the fitted models adequately represented the experimental data without systematic deviation. The adjusted R² values ranged from 0.4173 to 0.8596, with

particularly high values observed for FS (0.8596), BD (0.7875), WAC (0.7450), and EC (0.7228), indicating good explanatory power. Low coefficients of variation ($CV < 15\%$) for BD, WAC, OAC, S, and FS further demonstrate good experimental precision, whereas very high CV values for SI and FC suggest greater variability and lower model reliability for these responses (Table 1).

Bulk density (BD)

Table 2 and Figure 1 show that bulk density was significantly affected by the model ($p = 0.0003$), with a strong adjusted R^2 of 0.7875. Among the linear terms, mungbean flour

(B) exerted a significant negative effect ($p < 0.0001$), indicating that increasing malted mungbean content reduced bulk density (Figure 1). This reduction may be attributed to the lighter structure and higher protein-fiber content of mungbean flour, which can increase porosity in cereal matrices [12]. Millet (A) and tigernut (C) did not significantly ($p > 0.05$) influence BD individually. Lower bulk density is desirable in breakfast cereals because it improves rehydration characteristics and digestibility, particularly for children and elderly consumers [12, 19]. Thus, incorporation of malted mungbean flour appears beneficial in producing lighter cereal products.

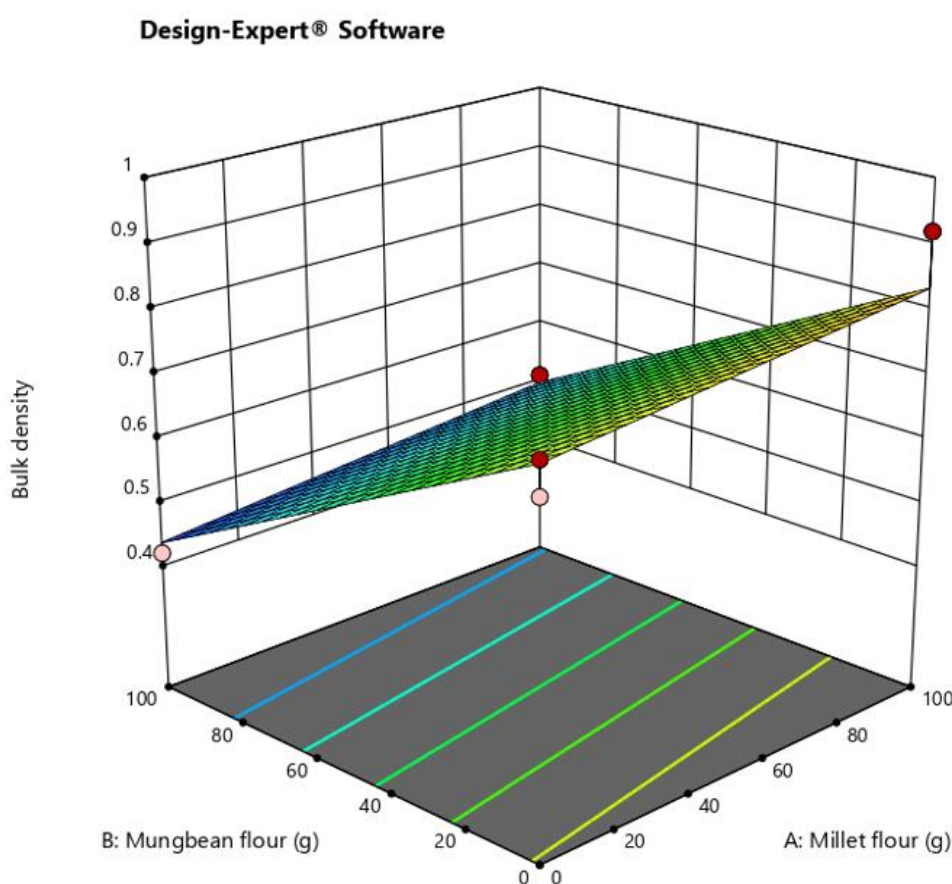


Figure 1. Bulk density of fiber-enriched breakfast cereals.

Water absorption capacity (WAC)

The WAC model was significant ($p = 0.0095$) with an adjusted R^2 of 0.7450, indicating good predictability (Table 2, Figure 2). Malted mungbean flour (B) had a significant positive effect on WAC ($p = 0.0036$), while the interaction terms AB ($p = 0.0058$) and BC ($p = 0.0268$) were also significant. These interactions suggest synergistic effects between millet-mungbean and mungbean-tigernut blends in enhancing water absorption suggesting that combinations of these ingredients can further promote WAC beyond individual contributions [11,

5]. The increase in WAC with mungbean inclusion is likely due to its higher protein and soluble fiber content, which possess hydrophilic functional groups capable of binding water. High WAC is advantageous for breakfast cereals as it improves bowl life, mouthfeel, and consumer acceptability [7]. Interaction of millet-mungbean blends significantly decreased ($p < 0.05$) the WAC (Figure 2) while the interaction of mungbean-tigernut blends significantly increased ($p < 0.05$) the WAC (Figure 3).

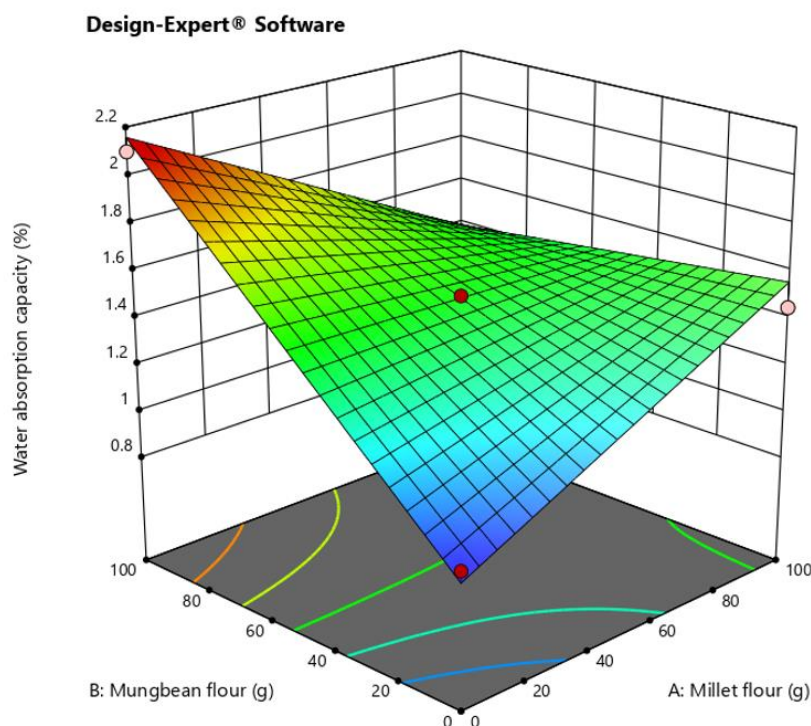


Figure 2. Interaction of millet-mungbean blends of WAC of fiber-enriched breakfast cereals.

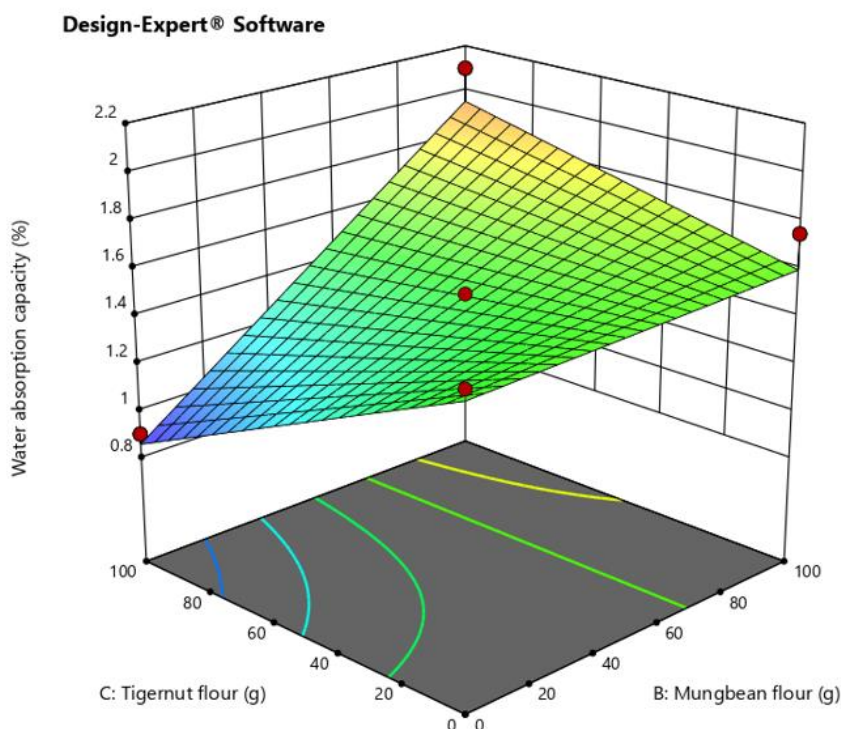


Figure 3. Interaction of mungbean-tigernut blends of WAC of fiber-enriched breakfast cereals.

Oil absorption capacity (OAC)

Table 2 and Figure 4 showed that the OAC model was significant ($p = 0.0387$), though with a moderate adjusted R^2 of 0.4173. Mungbean flour (B) again showed a significant positive linear

effect ($p = 0.0071$), indicating enhanced oil retention with increased mungbean content (Figure 4). This may be linked to protein–lipid interactions and the presence of non-polar amino acid side chains. The presence of non-polar amino acid side

chains is particularly important for promoting these protein-lipid interactions, allowing the flour to effectively trap oil [3]. Such interactions not only increase OAC but also improve emulsifying capabilities, which are critical during cooking

processes and can enhance the sensory attributes of the finished product [27]. Higher OAC is technologically important because it enhances flavor retention and palatability, making the cereal more appealing [9].

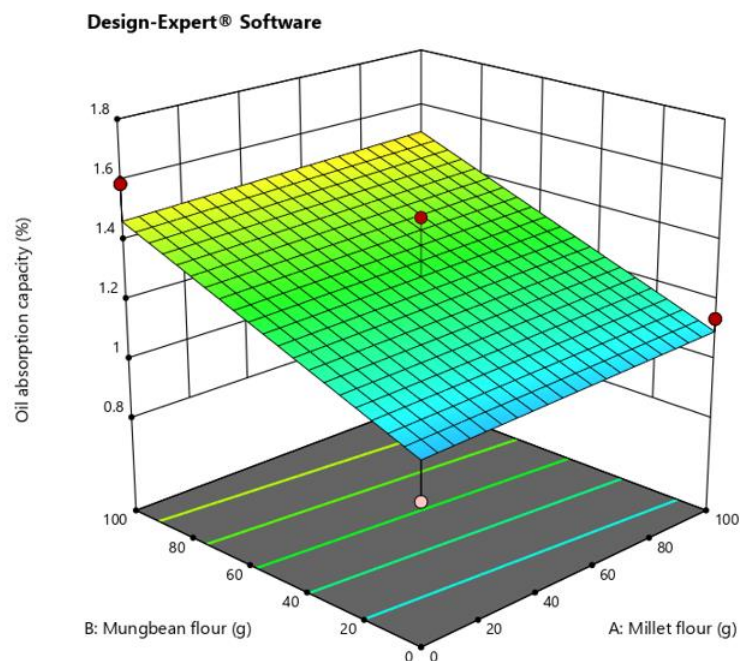


Figure 4. Oil absorption capacity of fiber-enriched breakfast cereals.

Solubility (S)

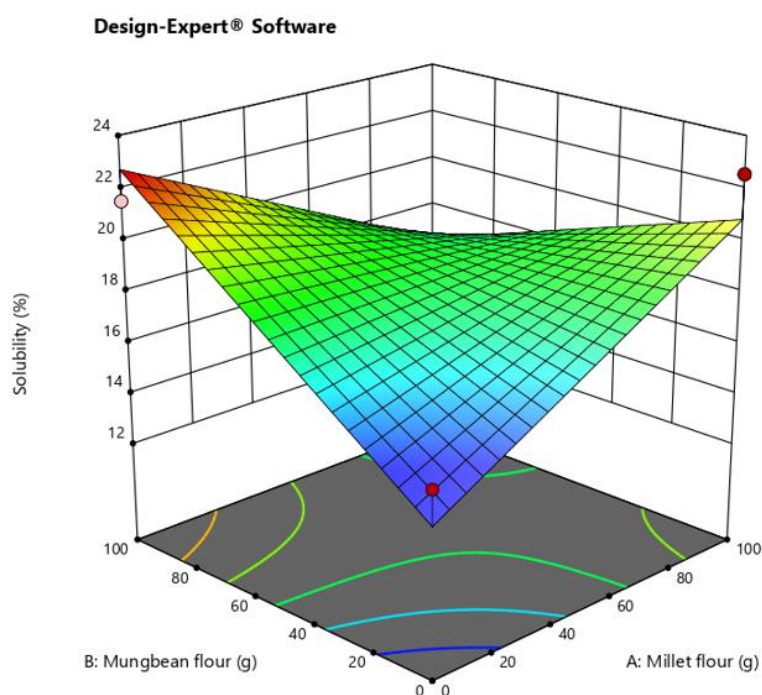


Figure 5. Interaction of millet-mungbean blends of solubility of fiber-enriched breakfast cereals.

As shown in Table 2 and Figure 5, the solubility model was significant ($p = 0.0398$) with a reasonable adjusted R^2 of 0.6001. The interaction between millet and mungbean (AB) had a significant negative effect ($p = 0.0071$), indicating that combined increases in these two flours reduced solubility (Figure 5). Such a reduction is likely due to starch–protein interactions that limit the ability of the mixture to disperse uniformly in water. The proteins from mungbean may form complexes with the starches from millet, impacting the overall dispersion [8]. Controlled solubility is particularly desirable in breakfast cereals to balance textural integrity and consumer appeal. An optimal solubility level can prevent excessive disintegration while also ensuring adequate dispersion, contributing to a uniform texture in the final product. If solubility is too low, products may exhibit grainy textures, which are less appealing to consumers, whereas overly soluble formulations can lead to a dilapidated product upon rehydration [14].

Emulsification capacity (EC)

The EC model was significant ($p = 0.0124$) with a strong adjusted R^2 of 0.7228 (Table 2, Figure 6). Significant interaction effects (AB, AC, and BC) indicate that emulsification properties were highly dependent on blend combinations rather than single components. AB and AC significantly decreased ($p < 0.05$) the emulsification properties (Figure 6 and 7)

while BC significantly increased ($p < 0.05$) the emulsification properties of the breakfast cereals (Figure 8). The decrease observed with the millet-mungbean and millet-tigernut blends resulted from the competitive interaction between the proteins and lipids, which can hinder effective stabilization of the oil-water interface due to overlapping hydrophobic regions or steric hindrance. Conversely, the mungbean-tigernut blend appears to enhance emulsification capacity, suggesting a synergistic mechanism where the proteins from mungbean work effectively with the lipids in tigernuts to stabilize emulsions, thereby improving product texture and stability [15]. This behavior reflects the complex role of proteins from mungbean and lipids from tigernut in stabilizing oil-water interfaces, which is important for texture and stability of reconstituted cereal products. High EC led to better mouthfeel, improved flavor retention, and increased shelf stability. Products with effective emulsification properties are less prone to separation, thereby ensuring that consumers experience a uniform texture upon rehydration [7]. Additionally, the quadratic terms A^2 ($p = 0.0401$) and B^2 ($p = 0.0139$) were significant, confirming curvature effects. This denotes that at certain levels of incorporation, the emulsification capability can significantly change, pointing to an optimal balance of each flour for maximization of emulsification properties [12].

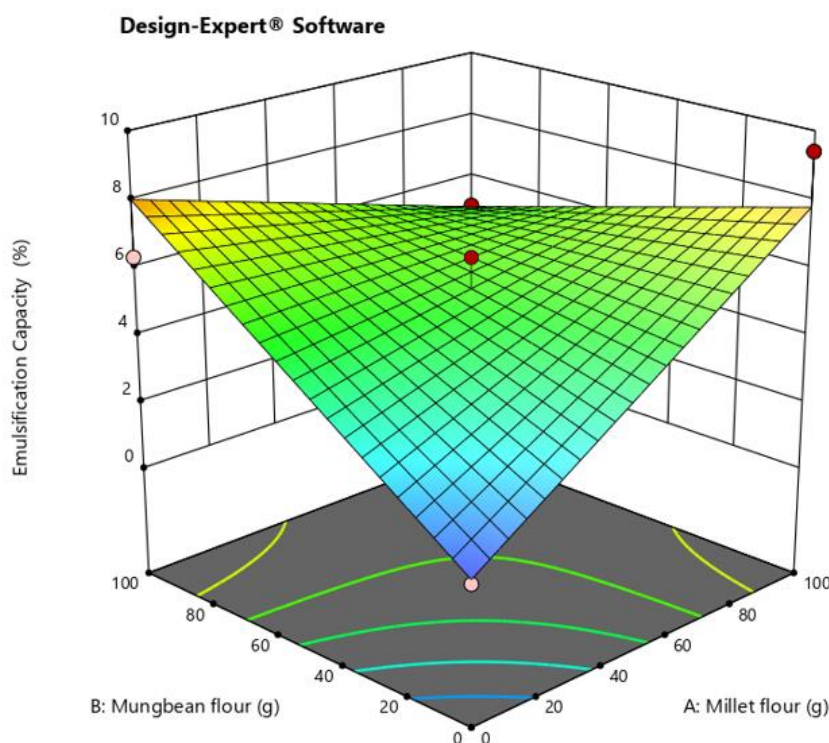


Figure 6. Interaction of millet-mungbean blends of emulsification capacity of fiber-enriched breakfast cereals.

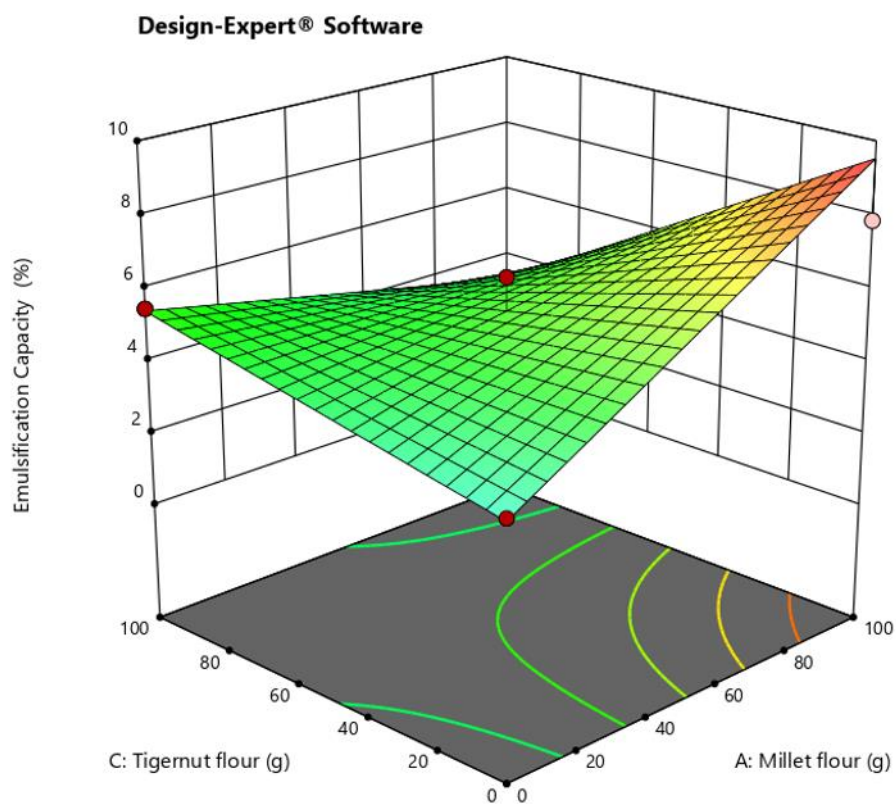


Figure 7. Interaction of millet-tigernut blends of emulsification capacity of fiber-enriched breakfast cereals.

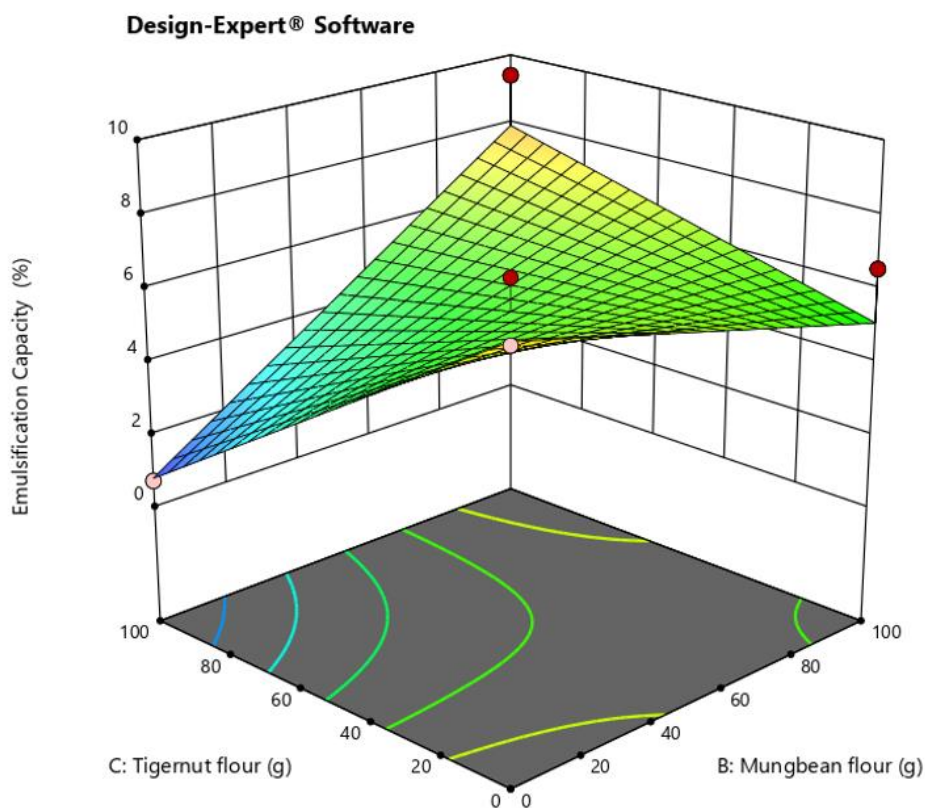


Figure 8. Interaction of mungbean-tigernut blends of emulsification capacity of fiber-enriched breakfast cereals.

Foam capacity (FC) and foam stability (FS)

Table 2 and Figure 9 showed that the foam capacity was not significantly affected by the model ($p = 0.0972$) and showed high variability ($CV = 99.77\%$), indicating inconsistent foaming behavior. The FC of the breakfast cereals displayed high variability ($CV = 99.77\%$), suggesting inconsistent foaming behavior across different samples. This variability may stem from the complex interactions among the components and the processing conditions employed during formulation [12]. Proteins in the cereal matrix are primarily responsible for foam formation due to their ability to stabilize air cells during mixing; however, the lack of consistent results implies that optimizing conditions for FC is challenging. This inconsistency can also be correlated with findings from other studies showing that protein composition significantly affects the foaming behavior of flour blends, where denaturation or over-processing can lead to varying FC outcomes [17].

In contrast, foam stability (FS) was highly significant ($p = 0.0209$) with the highest adjusted R^2 (0.8596) and the lowest CV (7.22%). The linear effect of millet (A) significantly increased FS ($p = 0.0263$), while interaction effects (AC) and the quadratic term B^2 were also significant ($p < 0.05$).

Interaction of millet-tigernut significantly decreased the foam stability (Figure 9). However, FC and FS was significantly

influenced by the formulation, particularly from the linear effect of millet ($p = 0.0263$), which showed an ability to enhance the stability of foam once formed. The interaction effects among the flour blends and the quadratic terms of mungbean flour also contributed to this phenomenon. The strong significance of FS implies that while initial foam formation might be inconsistent, the ability of the foam to withstand destabilizing forces is considerably enhanced by appropriate blend combinations [19]. Protein-starch interactions are fundamental to this behavior; proteins from both mungbean and millet contribute to the formation of a stable interfacial film around air bubbles, which is crucial for maintaining foam structure over time [29]. This stabilization is vital in preventing the coalescence of bubbles, thus prolonging foam persistence and maintaining desirable textural characteristics in food products [13].

The contrasting behaviors of FC and FS have significant implications for the development of breakfast cereals. While achieving a high FC is important for creating a desirable mouthfeel and texture, the stability of the foam during storage and preparation significantly affects consumer acceptance and perception [17]. High foam stability can lead to improved sensory properties, providing a lighter, airy texture that is often preferred in breakfast cereals [28].

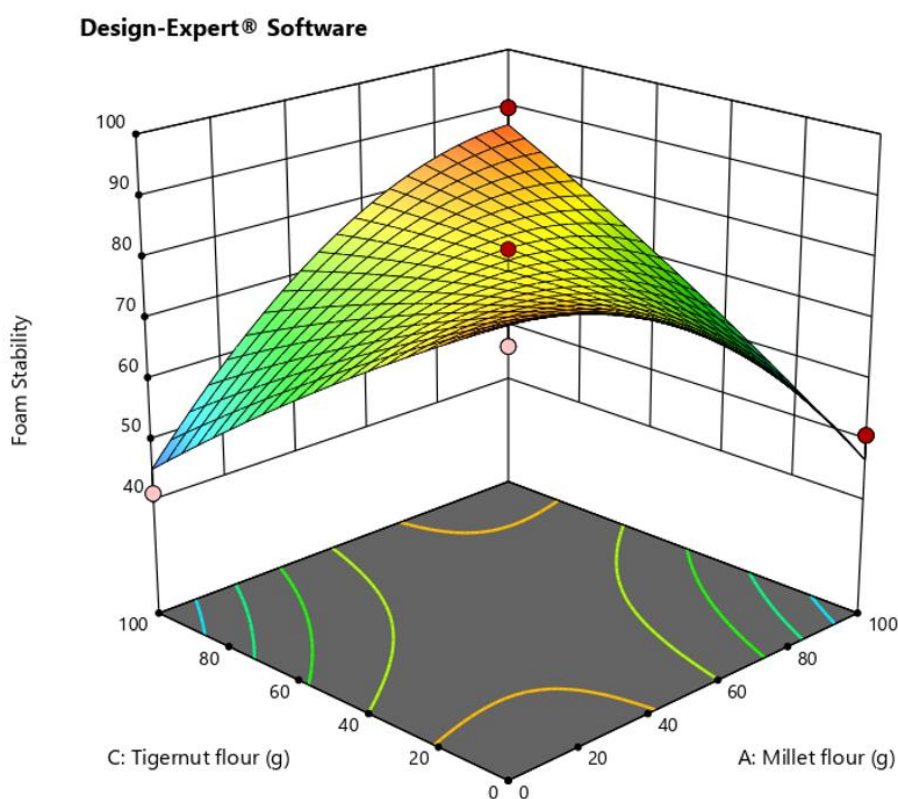


Figure 9. Interaction of millet-tigernut blends of foam stability of fiber-enriched breakfast cereals.

4. Conclusion

This study demonstrated that the functional properties of fiber-enriched breakfast cereals produced from millet, malted mungbean and tigernut flours are significantly influenced by blend composition. The quadratic models were adequate for predicting bulk density, water absorption capacity, oil absorption capacity, solubility, emulsification capacity, and foam stability. Malted mungbean flour had the most pronounced effect, reducing bulk density and improving water and oil absorption, while interaction effects among the flours were critical in determining emulsification and foam stability. Generally, the results confirm that appropriate blending of these flours can produce breakfast cereals with desirable functional characteristics suitable for instant and ready-to-eat products.

Abbreviations

RSM Respose Surface Methododology

Author Contributions

Ann Uchechi Eweama: Formal Analysis, Funding acquisition, Project administration, Visualization

Blessing Chibuzo Nwokeke: Conceptualization, Data curation, Investigation, Methodology

Solomon Onyeka Obeleagu: Software, Resources, Validation

Emmanuela Chinonye Ogugua: Resources, Supervision

Conflicts of Interest

The authors had no conflicts of interests.

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