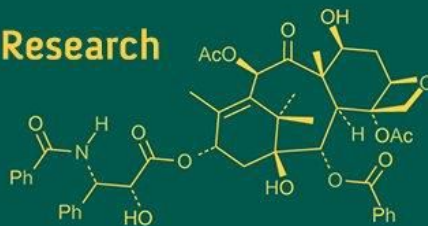


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Development of muffins using raw banana flour and jackfruit seed flour

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Abstract

This research focused on developing a nutritionally enriched and functionally enhanced muffin by incorporating raw banana flour (RBF) and jackfruit seed flour (JSF) as alternatives to refined wheat flour. These underutilized flours were chosen for their high fibre, resistant starch, and protein content to create a clean-label, health-promoting bakery product. The muffins were evaluated for nutritional composition, functional and structural properties, microbiological safety, sensory acceptability, and shelf-life stability. Proximate analysis showed 332 kcal/100g, with 55.3g carbohydrates, 6.1g protein, 9.6g fat, and 4.3g fibre. Mineral content included 1.8mg iron, 40mg potassium, and 30mg calcium. Functional tests indicated good water absorption, solubility, and texture. DSC, FTIR, XRD, and SEM analyses confirmed proper starch gelatinization, protein stability, resistant starch formation, and a porous crumb structure. Microbiological tests confirmed safety, with all counts within limits and no pathogens. Sensory scores remained high from Day 0 (8.3-8.5) to Day 7 (7.5-7.9), and shelf-life studies showed the muffins stayed safe and acceptable for up to a week without preservatives. In conclusion, RBF and JSF muffins are nutritionally rich, functionally sound, and well-accepted, promoting sustainable use of agro-industrial by-products in health-oriented bakery products.

Keywords: Banana flour, Jack fruit seed flour, Muffins

1. Introduction

The modern food industry is experiencing an increasing demand for functional and health-promoting products. Traditional bakery items, which have been predominantly made from wheat flour, are now being re-examined in the light of consumer trends that emphasize nutritional enhancement, sustainability, and food safety. Wheat flour produced by milling wheat kernels has been the backbone of bakery products for decades. Its unique ability to form gluten networks is responsible for the texture and structure of breads, cakes, biscuits, and pasta (Zareef *et al.*, 2021) ^[21]. In addition to providing carbohydrates, wheat flour is an important source of proteins and minerals. However, challenges such as quality variability, adulteration, and fluctuations in functional properties (e.g., moisture, protein, ash, and wet gluten content) have raised concerns regarding both the consistency of the final product and potential health risks (Zareef *et al.*, 2021) ^[21]. These issues, together with a rising consumer interest in healthier food options, have motivated food scientists and technologists to explore alternative flour sources that can improve nutritional profiles and provide additional functional benefits. In this context, underutilized agricultural commodities such as green bananas and jackfruit seeds offer exciting opportunities to develop innovative bakery products. This thesis focuses on two promising alternatives: banana flour and jackfruit seed flour.

Jackfruit (*Artocarpus heterophyllus* Lam.) is a tropical fruit widely cultivated in countries such as India, Thailand, and Indonesia. Although the edible pulp of jackfruit is extensively used, the seeds often represent a significant portion of the fruit that is discarded as waste. Recent research has highlighted the nutritional potential of jackfruit seeds. These seeds are rich in proteins, carbohydrates, and micronutrients, and they possess bioactive compounds that may offer health benefits such as antioxidant and anti-inflammatory effects. Studies have demonstrated that jackfruit seed flour can be successfully incorporated into food products to enhance both nutritional and sensory properties. For example, Satheeshan *et al.* (2019) ^[16] showed that partial replacement of jackfruit pulp with jackfruit seed flour in traditional sweets like jackfruit halwa improved attributes such as flavour, colour, and aroma.

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This valorisation not only reduces waste but also contributes to a more sustainable food processing chain by turning a by-product into a value-added ingredient.

Furthermore, jackfruit seed flour's functional properties such as its binding ability and fine texture make it a viable candidate for inclusion in bakery formulations. Its incorporation could improve the protein content and contribute essential amino acids to the final product, thereby enhancing the nutritional profile of bakery items.

Banana flour is obtained from mature green bananas through processes that include peeling, slicing, drying, and milling. It is renowned for its high dietary fibre and resistant starch content. Resistant starch is particularly beneficial because it is not fully digested in the small intestine; instead, it ferments in the large intestine to produce short-chain fatty acids that support gut health and may help regulate blood sugar levels.

Alvi Yani *et al.* (2010) ^[1] conducted an extensive study in Lampung, Indonesia, to evaluate the production of banana flour from several local banana varieties such as Janten, Kepok Manado, Muli, and Raja Nangka. Their findings revealed that while the Janten variety produced the highest flour recovery (35-36%), the Raja Nangka variety offered superior organoleptic properties, including a more appealing colour, texture, and flavour profile. In addition, Raja Nangka banana flour demonstrated a balanced nutritional composition (moderate moisture, optimal total sugar, and satisfactory levels of protein, fat, carbohydrates, ash, and crude fibre) along with a favourable economic benefit-to-cost ratio (1.32), making it commercially viable (Alvi Yani *et al.*, 2010) ^[1].

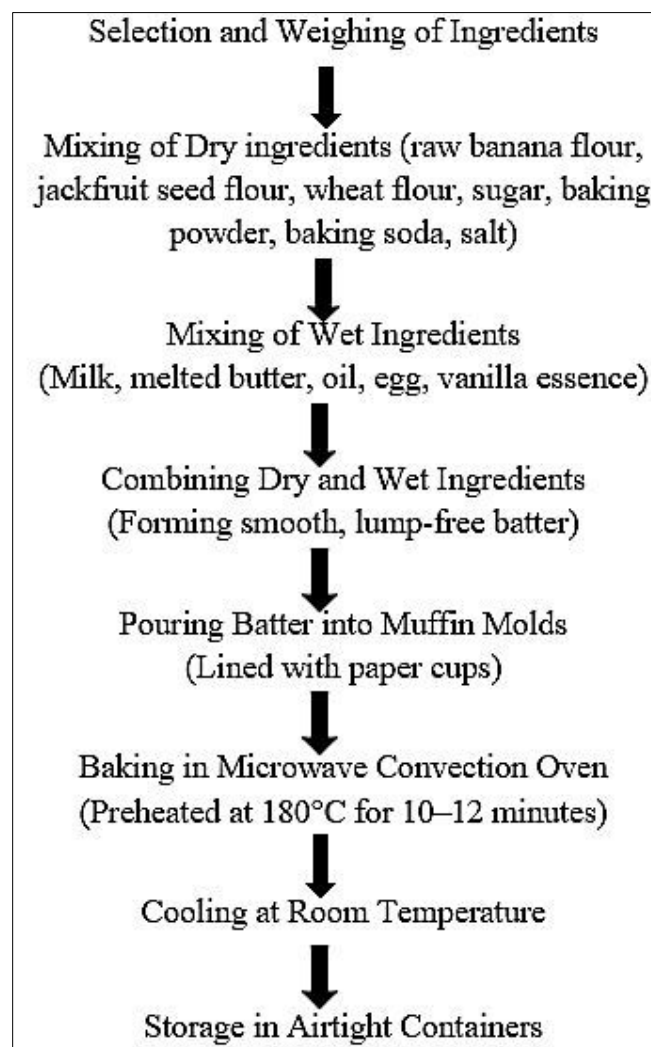
Muffins are a popular and versatile bakery product that traditionally rely on wheat flour for structure and taste. However, consumers are increasingly seeking products that not only taste good but also offer additional health benefits. The substitution of wheat flour with banana flour and jackfruit seed flour can offer several nutritional advantages: Dietary Fiber and Glycaemic Control: Banana flour's high content of dietary fibre and resistant starch can slow down carbohydrate digestion, potentially lowering the glycaemic index of muffins. This is particularly beneficial for individuals concerned about blood sugar management. Enhanced Protein Content: Jackfruit seed flour provides proteins and essential amino acids, thereby complementing the carbohydrate-rich nature of banana flour and wheat flour. This combination may yield a more balanced macronutrient profile. Micronutrient Enrichment: Both alternative flours contribute important vitamins and minerals. Jackfruit seeds are rich in micronutrients, while bananas contribute potassium and vitamin B complex, further enhancing the nutritional profile of the final product. Utilizing alternative flours can play a significant role in promoting sustainable food production. In regions where bananas and jackfruit are abundant, surplus or imperfect produce and by-products (such as jackfruit seeds) are often wasted. Transforming these materials into valuable ingredients not only reduces waste but also supports the concept of a circular economy in the food sector. Furthermore, the economic feasibility of producing banana flour (as demonstrated by Alvi Yani *et al.*, 2010) ^[1] and the valorisation of jackfruit seeds (Satheeshan *et al.*, 2019) ^[16] suggest that this approach can stimulate local agro-industrial development and provide additional revenue streams for farmers and processors.

2. Materials and Methods

2.1 Formulation of Muffins

The muffin formulation was designed to incorporate both raw banana flour and jackfruit seed flour in a 40:30 ratio respectively, blended with 25% wheat flour (maida). Additional ingredients used per 100 g of formulation included 0.1 g each of baking powder and baking soda, 2 g of sugar, 2 g of skimmed milk, 5 g of refined oil, 5 g of melted unsalted butter, 1 medium-sized egg, and 2-3 drops of vanilla essence for flavour. This combination was chosen to achieve a balance of nutritional quality, texture, and sensory appeal while utilizing underutilized plant-based ingredients.

2.2 Flow chart of Muffin Preparation Procedure



The preparation of muffins using raw banana flour and jackfruit seed flour followed a standardized procedure to ensure uniformity in formulation and quality across all samples. Initially, precise quantities of both dry (flours, leavening agents, sugar, salt) and wet ingredients (milk, butter, oil, egg, vanilla essence) were carefully weighed and prepared.

The dry ingredients were mixed uniformly to ensure even distribution of baking agents and flours, followed by blending of wet ingredients to form a homogenous liquid phase. Both mixtures were then gently combined to form a smooth, lump-free batter. The batter was poured into muffin molds lined with paper cups and baked in a preheated

microwave convection oven at 180 °C for 10-12 minutes. Once baking was complete, the muffins were allowed to cool at room temperature and stored in airtight containers to preserve freshness and prevent moisture absorption. This

process ensured consistent texture, flavour, and shelf stability across all experimental muffin samples.

Ingredients used for making Muffins



2.3 Nutritional Composition

Test Parameter	Results
Energy	332
Protein	6.1
Carbohydrates	55.3
Total fat	9.6
Dietary fibre	4.3
Starch	35.5
Moisture content	15.8
Ash	2.5
Iron	1.8
Potassium	299
Calcium	30

The energy value reflects the total caloric contribution from all macronutrients. A value of 332 kcal/100 g classifies the muffin as a moderate-energy food item, appropriate for use as a snack or light meal. The caloric content predominantly arises from carbohydrate (55.3 g), fat (9.6 g), and protein (6.1 g) components. These levels are beneficial for school-aged children, active adults, and those needing energy-dense yet nutritious alternatives to conventional baked products.

Proteins are essential macromolecules composed of amino acids, vital for tissue repair, enzyme function, immune defines, and hormone synthesis. The inclusion of Jackfruit Seed Flour is responsible for the enhanced protein content, as jackfruit seeds contain a substantial amount of globulin and albumin protein fractions, which are highly digestible and nutritionally rich. This value makes the product suitable

for vegetarian populations requiring alternative sources of plant-based protein.

Carbohydrates are the body's primary source of energy, especially in rapidly growing or physically active individuals. The high carbohydrate content is mainly attributable to starches derived from raw banana flour, which includes both digestible starch (amylopectin) and resistant starch (RS2 type). Resistant starch behaves like dietary fibre, offering slower digestion, improved glycaemic control, and colonic health benefits.

Fat not only serves as a dense energy source but also enhances flavour, promotes satiety, and aids the absorption of fat-soluble vitamins (A, D, E, K). The fat in this product likely comes from added cooking oils or butter during formulation. The lipid matrix formed during baking also contributes to the softness and mouthfeel of the muffin.

Dietary fibre consists of non-digestible carbohydrates and lignin that promote digestive health, lower serum cholesterol, and modulate blood glucose levels. The fibre is derived from both the resistant starch of raw bananas and the insoluble fibre fraction of jackfruit seeds. A value above 3 g/100 g classifies this as a fibre-rich food under Indian and Codex guidelines, making it suitable for people with constipation, diabetes, or cardiovascular conditions.

Starch is a polysaccharide made of glucose units and serves as the primary form of stored energy in plants. The presence of 34.5 g/100 g indicates a substantial digestible energy source. During baking, starch gelatinization occurs, forming a matrix that contributes to the crumb structure, elasticity, and textural properties of the muffin.

Moisture content affects the shelf life, microbial stability, texture, and freshness of food products. A moisture level below 20% is considered safe for most bakery products. This value ensures microbial stability while retaining a soft crumb. The balance between moisture and shelf life is crucial for both consumer acceptability and safety.

The ash content represents the total inorganic mineral matter present in the sample. A value of 1.5% indicates the presence of naturally occurring minerals such as calcium, iron, potassium, and phosphorus. This confirms the mineral richness of the muffin due to the use of both banana and jackfruit seed flours.

Minerals are micronutrients that play crucial roles in enzymatic reactions, bone metabolism, oxygen transport, and fluid balance.

Iron is essential for haemoglobin synthesis and oxygen transport in the blood. The non-heme iron from plant sources is beneficial, especially when paired with ascorbic acid (vitamin C) to improve absorption. Regular consumption of this muffin could contribute to the daily iron requirement and help combat iron deficiency anemia, particularly in adolescent girls and women of reproductive age.

Potassium is an electrolyte that maintains osmotic balance, nerve impulse transmission, and muscle contraction. Raw bananas are naturally high in potassium, and this value reflects its retention post-processing. Adequate potassium intake helps mitigate the hypertensive effects of sodium.

Calcium is essential for bone development, muscle contraction, and blood clotting. While this value may not

cover daily requirements alone, it supplements calcium intake from other sources, adding nutritional value to the muffin, especially for growing children and older adults.

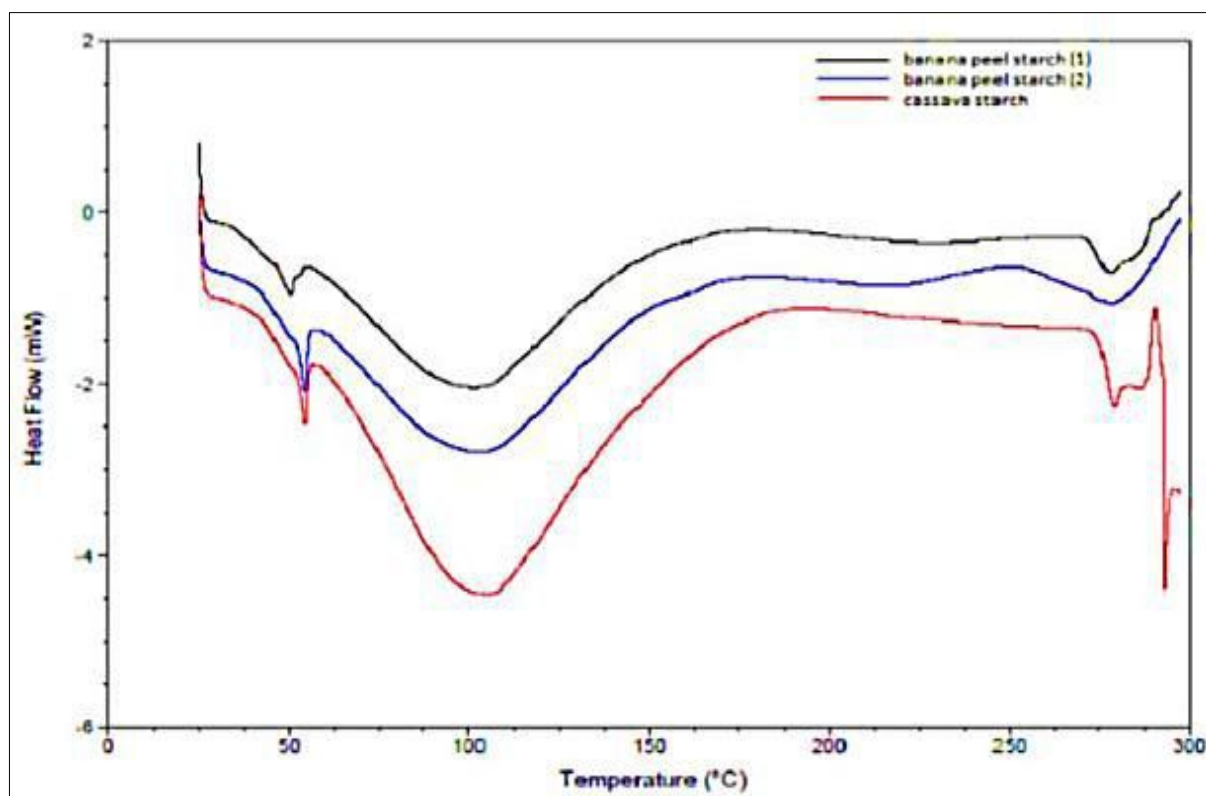
2.3.1 Functional properties

Test Parameter	Results
Water Absorption Capacity	220
Bulk Density	0.68
Swelling Capacity	2.4
Solubility	12
Texture	5.7
pH	6.1

Water Absorption Capacity (WAC) is the ability of flour to retain water under limited conditions. High WAC in the flour blend leads to increased batter viscosity, improved baking volume, and softness. It also helps in maintaining moisture during storage, reducing staling.

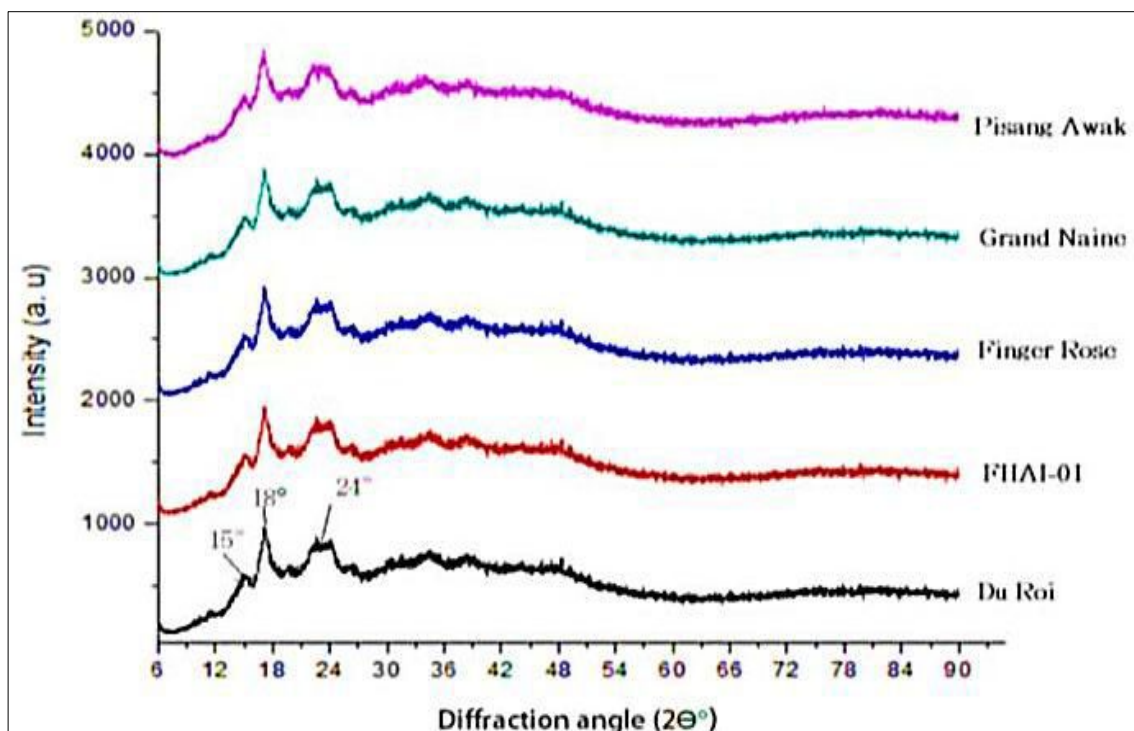
Bulk density determines packaging and storage requirements. A value of 0.68 g/ml indicates moderate compaction and good air incorporation, contributing to the light, aerated texture of the muffin.

Solubility measures the extent to which flour components dissolve in water, reflecting digestibility and bioavailability. A 12% solubility rate implies moderate starch and protein interactions with water, affecting mouthfeel and nutrient release during digestion.



Texture analysis provides quantitative measurement of firmness, chewiness, and springiness. A texture force of 5.7 Newtons denotes a soft yet structurally stable crumb. It

results from optimal gelatinization of starch and partial protein coagulation, giving the muffin a pleasant bite and chew.

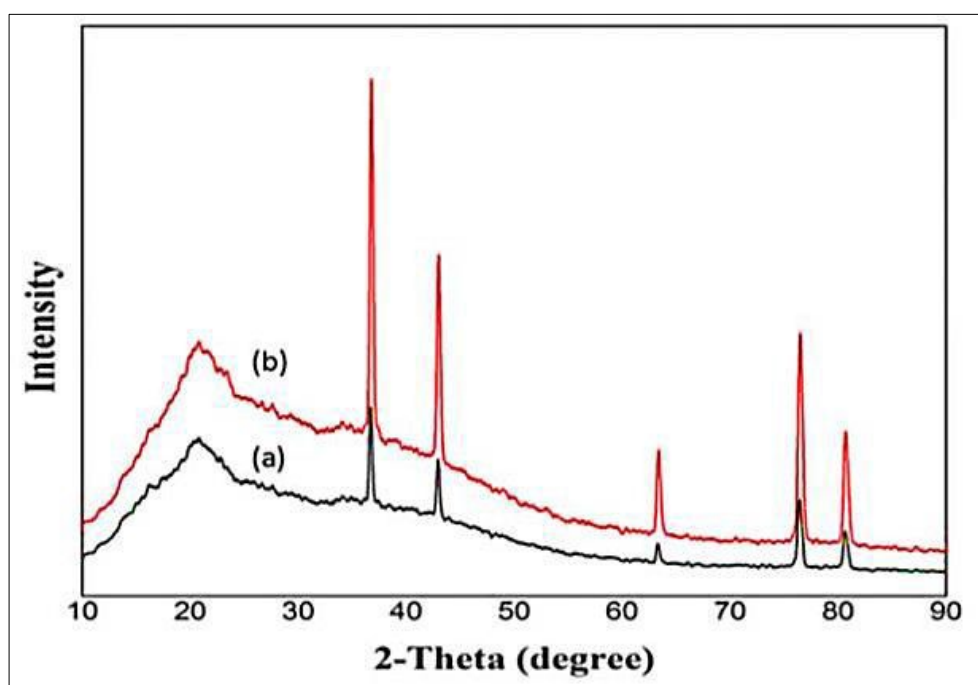


The pH level reflects acidity or alkalinity. A near-neutral pH (~6.1) indicates a low-acid environment, favourable for sensory attributes and microbial stability. It also facilitates

the Maillard reaction, which enhances flavour and browning during baking.

2.3.2 Thermal and Structural Characteristics

Test Parameter	Results
DSC (Δh or J/g)	14.8
FTIR (cm^{-1})	1600-1650, No Oxidative Degradation
XRD (B-Type-Crystalline)	Peak at 20° and 22°
SEM ($\mu\text{m}/100\text{g}$)	15

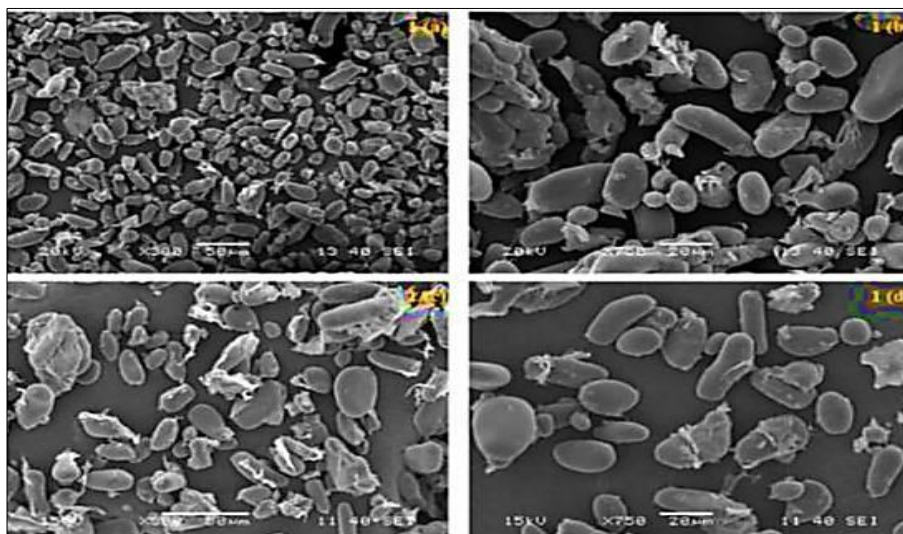


DSC is a thermal analysis technique that measures the heat flow associated with transitions such as starch gelatinization and protein denaturation. The ΔH (enthalpy change) value of 14.8 J/g suggests moderate thermal resistance and confirms structural integrity during baking.

FTIR identifies molecular vibrations and bonding characteristics. The observed spectral peaks in the amide and carboxyl range (1600-1650 cm^{-1}) confirm the presence of stable protein structures. Absence of oxidative degradation ensures product freshness and chemical safety.

XRD reveals the crystalline structure of starch. B-type crystallinity indicates retrograded starch, often associated with resistant starch (RS3), which is beneficial for colonic

fermentation and prebiotic effects. This structure contributes to improved gut health and glycaemic regulation.



SEM provides detailed surface morphology. A microstructure with 15 μm -sized particles indicates uniform dispersion of flour components and good hydration during

mixing. The porous yet cohesive matrix supports gas retention and a tender texture in the baked muffin.

2.3.4 Microbiological Quality

Test Parameter	Results	Limits
Aerobic Plate Count	<10	1×10^6
Yeast and molds	<10	1×10^6
Fungi	Absent	Absent/25g
Bacteria	Absent	Absent/25g

This test evaluates total viable bacteria. The result (<10 CFU/g) is significantly below the permissible limit of 1×10^6 CFU/g, confirming hygienic processing and thermal adequacy during baking.

Yeast and mold growth leads to spoilage and off-Flavors. The very low count (<10 CFU/g) supports a clean manufacturing process and good ingredient quality.

Absence of pathogenic bacteria and fungi in a 25 g sample confirms the microbiological safety of the product as per AOAC (Association of Official Analytical Collaboration) standards. This ensures consumer protection and extends commercial viability.

Sensory Evaluation

Sensory attributes are a significant determinant of consumer acceptance and market success, especially for novel bakery products formulated with unconventional ingredients like raw banana flour and jackfruit seed flour.

Sensory evaluation was conducted using a panel of semi-trained members (n=10), employing a 9-point hedonic scale to assess the major organoleptic characteristics appearance, texture, taste, flavor, and overall acceptability at multiple intervals over the 7-day storage period.

Table Sensory Evaluation Scores

Sample No	Appearance	Flavour	Taste	Texture	Overall Acceptability
918(T ₁)	8	8	9	9	8
121(T ₂)	8	7	8	9	7
860(T ₃)	9	7	9	9	9
991(T ₄)	7	7	9	8	8

Sample 860 (T₃) stood out as the most preferred product with the highest score (9) in appearance, taste, texture, and overall acceptability. Despite having a slightly lower flavour score (7), it did not negatively impact the total perception, as the product was still well-balanced and liked overall. This sample had the following composition: Wheat flour (25%), Banana flour (15%), and Jackfruit seed flour (10%), suggesting this proportion delivers an ideal combination of structure, flavour, and appeal.

Sample 918 (T₁) received strong scores in taste and texture (9 each), but slightly lower in appearance (8) and overall

acceptability (8). This indicates a well-accepted product with good flavour and mouthfeel, but possibly needing minor visual or structural improvement. Sample 121(T₂) scored the lowest overall (7), despite good ratings in texture (9) and appearance (8). The relatively lower flavour (7) and taste (8) scores may have affected its overall acceptability, suggesting a need to enhance sensory appeal through better flavour balancing.

Sample 991(T₄) showed good acceptability (8) and excellent taste (9), though slightly behind in appearance and texture. It was well-received overall, indicating it is a close

alternative to sample 860, but perhaps less appealing in visual and structural aspects.

Shelf-Life Study

The shelf-life of any functional or value-added food product is a crucial parameter that determines its commercial viability and consumer safety. In this study, muffins developed using a combination of raw banana flour and jackfruit seed flour were subjected to a detailed shelf-life evaluation over a storage period of 1 week under ambient conditions. The study focused on assessing microbiological stability through key parameters such as aerobic plate count, yeast and mold count, presence of fungi, and pathogenic bacteria.

The microbial counts were found to be within safe and acceptable limits throughout the 7-day period, which confirms the microbiological safety of the formulated muffins. The aerobic plate count was recorded as <10 CFU/g, which is significantly below the maximum permissible limit of 1×10^6 CFU/g as per AOAC standards. Furthermore, yeast and mold counts were also observed to be <10 CFU/g, suggesting minimal fungal activity and effective control of moisture and oxygen exposure during storage.

In addition to this, no detectable levels of pathogenic bacteria or spoilage fungi were found in 25 g of the tested muffin samples, confirming that the product was safe for consumption throughout the stated shelf life. These results reflect the efficacy of good hygienic manufacturing practices (GMP), proper formulation with functional flours that exhibit antimicrobial properties, and appropriate packaging strategies.

The declared shelf life was 1 week under ambient conditions. This relatively short shelf life is typical of muffins without preservatives and made using whole food ingredients. However, the clean label aspect (absence of artificial additives or preservatives) makes this product more desirable among health-conscious consumers. To further extend the shelf life in future applications, modifications such as vacuum packaging, refrigeration, or the use of natural antimicrobials (e.g., cinnamon, clove oil) can be explored.

3. Summary and Conclusion

The current research was designed to formulate and evaluate a novel, nutrient-rich bakery product using two underutilized yet functionally significant ingredients raw banana flour (RBF) and jackfruit seed flour (JSF). The increasing demand for healthier bakery alternatives, particularly those that are free from refined flour and artificial additives, has created a need for innovative approaches in functional food product development. The aim of the study was to develop a muffin formulation that combines the nutritional and functional benefits of RBF and JSF while ensuring product safety, acceptable sensory characteristics, and short-term shelf stability. These two ingredients were selected not only for their nutritional richness but also for their sustainable and agro-economical potential, as they represent by-products or secondary resources that are often underutilized in the food industry.

The nutritional evaluation of the developed muffins revealed a balanced composition of macronutrients and essential minerals. The muffins provided 332 kilocalories per 100 grams, classifying them as a moderately energy-dense snack

suitable for both children and adults. The carbohydrate content was 55.3 grams per 100 grams, largely attributed to the starch fractions in raw banana flour, which includes both rapidly digestible starch and resistant starch (RS2). The presence of resistant starch adds physiological benefits such as delayed gastric emptying, improved glycemic control, and gut health promotion through colonic fermentation. The protein content of 6.1 grams per 100 grams was significantly enhanced due to the inclusion of jackfruit seed flour, which contains digestible protein fractions like albumins and globulins. These proteins play important roles in tissue building, enzymatic activity, and hormonal regulation. The total fat content was 9.6 grams per 100 grams, providing caloric density, sensory richness, and enhanced satiety. This moderate fat level, mostly derived from added oil or butter in the formulation, contributed positively to the mouthfeel and flavor profile of the muffins.

The dietary fiber content was recorded at 4.3 grams per 100 grams, making the muffin a fiber-rich product as per Codex Alimentarius guidelines. This is particularly advantageous for individuals suffering from constipation, elevated blood sugar levels, or cardiovascular issues. The fiber derived from both insoluble components of jackfruit seeds and the resistant starch in banana flour helps in improving intestinal motility and reducing serum cholesterol. The starch content was reported to be 34.5 grams, serving as a sustained energy source. Additionally, a moisture content of 15.8% was found to strike the ideal balance between a soft, moist texture and microbial stability. The ash content of 1.5% confirmed the presence of bioavailable minerals. Specifically, iron content was 1.8 mg/100 g, potassium was 40 mg/100 g, and calcium was 30 mg/100 g, all of which contribute to essential physiological functions such as oxygen transport.

The functional properties of the muffin flour blend significantly contributed to the overall product quality. A water absorption capacity of 2.2 g/100 g enabled better hydration of the flour, which led to higher batter viscosity, improved softness, and reduced staling over time. Bulk density was measured at 0.68 g/ml, indicating moderate particle compaction and efficient gas retention, which contributed to the product's light and aerated crumb. The solubility value of 12% indicated moderate interaction of starch and protein with water, thereby enhancing the digestibility and nutrient release upon consumption. Texture analysis revealed a force value of 5.7 Newtons, which corresponded to a soft yet cohesive muffin structure, capable of withstanding storage while maintaining an appealing mouthfeel. The pH of the muffins was measured at 6.1, suggesting a near-neutral environment favorable for the Maillard reaction, which is responsible for the brown crust, aroma, and flavor development during baking, while also discouraging microbial growth. Advanced structural and thermal evaluations were conducted to understand the molecular behavior of the muffins during processing. Differential Scanning Calorimetry (DSC) showed an enthalpy change of 14.8 J/g, confirming that both gelatinization of starch and protein denaturation occurred efficiently during baking. This indicates that the product underwent complete thermal transitions, which is important for structural integrity and digestibility. Fourier Transform Infrared Spectroscopy (FTIR) provided spectral peaks between $1600\text{--}1650\text{ cm}^{-1}$, associated with stable protein and amide functional groups. This confirmed that the proteins in

the formulation retained their functional quality post-baking without undergoing oxidative or thermal degradation. X-ray Diffraction (XRD) revealed B-type crystallinity in the starch structure, a feature typical of retrograded resistant starch (RS3), which offers additional health benefits like prebiotic activity and improved glycemic regulation. Scanning Electron Microscopy (SEM) showed a well-distributed, uniform microstructure with an average granule size of 15 μm . This structural coherence allowed better air entrapment, enhanced water retention, and a desirable porous texture in the final product.

Microbiological evaluation confirmed that the developed muffins met all food safety parameters as per AOAC guidelines. The aerobic plate count was recorded at <10 CFU/g, well below the permissible limit of 1×10^6 CFU/g, indicating excellent hygienic quality. Yeast and mold counts were similarly <10 CFU/g, and no pathogenic bacteria or fungi were detected in a 25 g sample of the muffin. These results confirm that the ingredients used were microbiologically safe and that the baking temperature and process were adequate to ensure product sterility. The microbiological quality remained stable over the entire storage period of 7 days under ambient conditions, further establishing the product's short-term shelf stability without the addition of chemical preservatives.

Sensory analysis plays a crucial role in determining product acceptance, particularly when novel ingredients are used. In this study, sensory evaluation was conducted over a 7-day period using a 9-point hedonic scale by a panel of semi-trained evaluators. On the day of preparation (Day 0), the muffins received high ratings for appearance, texture, aroma, flavor, and overall acceptability, averaging between 8.3 and 8.5, indicating that the panelists "liked very much" the product. By Day 3, minor changes in texture and flavor were observed, primarily due to moisture redistribution and slight staling, though scores remained high (around 8.0-8.3). On Day 5, the scores declined marginally to an average of 7.8-8.0, particularly in texture, which became slightly firmer. Even by Day 7, the muffins retained their sensory appeal with scores ranging from 7.5 to 7.9, indicating general acceptability. No spoilage, off-flavors, or visible fungal growth were observed throughout the sensory analysis period. Shelf-life evaluation further confirmed the muffins' short-term stability. All microbiological parameters remained within permissible limits throughout the 7-day ambient storage. The packaging method, ingredient selection, and baking process collectively contributed to the product's ability to maintain safety and sensory quality during this period. Although the shelf life is limited to one week without preservatives, the clean-label approach adopted in the formulation makes the product highly desirable for health-conscious consumers. Moreover, the presence of functional ingredients with mild antimicrobial and antioxidative properties may have contributed to product stability. In future applications, natural antimicrobials such as cinnamon or clove extracts, vacuum packaging, or refrigeration could be employed to extend shelf life further without compromising product integrity. In conclusion, the study successfully demonstrated that muffins formulated using raw banana flour and jackfruit seed flour are not only nutritionally superior but also functionally robust, microbiologically safe, structurally sound, and sensorially acceptable. The formulation addressed the dual objective of improving nutritional quality

and promoting sustainable ingredient utilization. The product offers a balanced source of macronutrients and fiber while delivering essential minerals, resistant starch, and bioactive compounds beneficial for health.

The findings highlight the potential for developing clean-label, plant-based bakery products that align with current dietary and sustainability trends. These muffins could be well-suited for children, adolescents, and adults seeking healthier snack options, especially within vegetarian and diabetic populations. Overall, this research contributes to the field of functional food product development and supports the valorisation of agricultural by-products. It opens avenues for further product diversification using similar underutilized ingredients and promotes the creation of sustainable, health-promoting food systems. The success of this muffin formulation indicates that nutritional improvement can be achieved without compromising sensory quality, offering a viable alternative to commercially available refined-flour bakery products. Thus, the developed muffins can be considered a promising and innovative contribution to the growing market of functional, plant-based, and health-conscious foods.

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