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Development and Characterization of Synbiotic Yogurt Enriched with Banana Extract: A Comparative Analysis of Physicochemical, Nutritional, and Sensory Attributes

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Abstract

This paper critically discussed the preparation of a new synbiotic yogurt fortified with banana extract (BEY). Its physicochemical, nutritional, and sensory profiles were the main objectives of the study, and the study compared the product to the traditional simple yogurt. This was added with 15% (w/w) of banana extract after a blanching treatment to inactivate polyphenol oxidase. The findings showed that enrichment significantly ($p < 0.05$) changed the following important parameters: pH was raised by 1.58 to 4.58, viscosity was increased by 48 to 1850 mPa s, and syneresis was decreased by 43 to 8.6. BEY was found to have increased amounts of dietary fiber (1.6 g/100g), potassium (312 mg/100g), vitamin B6 (0.285mg/100g), and total polyphenols (142.6 mg GAE/100g), which defines its functionality. The sensory analysis indicated higher acceptance of BEY (8.6 vs. 6.5 on a 9-point hedonic scale), with the large changes in the aspects of sweetness, texture, and the overall taste ratio. The results verify that banana extract is a multifunctional food additive as it is a natural sweetener, a natural texturizer, a natural stabilizer, and a fortifier. The study can offer a scientific basis for developing a clean-label, health dairy product that will support consumer preference toward functional foods through the natural synergy between yogurt probiotics and banana prebiotics.

1. Introduction

In ancient civilizations, Yogurt has continually been deemed as a principal constituent in healthy diets in different countries, with the primary benefits, despite other popular uses, as a high level of probiotics, digestion, and a large amount of essential nutrients such as calcium, phosphorus, and high-quality protein (Savaiano & Hutkins, 2021). A general rise in consumer consciousness of the diet health nexus has triggered a surge in innovation in the international food market, especially with respect to the so-called functional foods, which are those products that are purposely fortified with bioactive compounds to provide proven physiological effects beyond the conventional nutritional needs (Granato et al., 2020; Swanson et al., 2020). The latter paradigm shift of food being medicine has given the room to the emergence of new fermented dairy products that can focus on a particular health issue yet are sensory attractive and convenient. Amongst growing functional food environment, fruit-fertilized yogurts have become a popular and commercially feasible category that successfully fills the gap between health-conscious formulations and the desired taste convenience of the product category (Cais-Sokolinska and Walkowiak-Tomczak, 2021; Jakobsen et al., 2019).

Fruits fortification of yogurt does not only add to the palatability and visual appeal but also to the complementary phytochemicals, fibers and micronutrients and the resultant synergetic interactions with the dairy matrix to produce products with improved nutritional profiles. Among a wide range of fruits that can be enriched to serve such purposes, the banana (Musa spp.) offers some of the most attractive

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benefits both in terms of nutritional and technological benefits (Qu et al., 2023). The unique chemical composition of the banana, in which high amounts of potassium, dietary fiber (especially pectin), vitamin B6, and natural sugars (fructose, glucose, and sucrose) were identified, combined with a high profile of bioactive compounds such as dopamine, catechins, and carotenoids, makes it a perfect candidate in the formation of functional foods (Singh et al., 2016). Moreover, availability, low cost, and round year-round availability of banana are factors of global availability and performance that increases its viability as an enrichment ingredient. (Chenet al., 2023). The strategic inclusion of banana ingredients in yogurt fermentation systems does not only provide nutritional fortification, but it could allow the development of an actual synbiotic food product a combination of viable probiotic microorganisms in yogurt and prebiotic fibers derived by bananas that may potentially synergistic health conditions, especially gastrointestinal functionality and metabolic control (Menezes et al., 2019). This symbionic strategy is consistent with recent nutritional science which has shown the significance of nutritionally sustaining existing populations of probiotics with relevant prebiotic substances to increase their survival, colonization, and metabolic action in the gastrointestinal tract (Zheng et al., 2022). The resulting item is therefore a combination of numerous positive factors: the already established health benefits of yogurt fermentation, the nutritional benefits of components of bananas, and the possible enhanced impact of their intentional integration. Nevertheless, creating a quality banana-enhanced yogurt product is not an easy task and its technical issues go beyond mixture of ingredients (Tsai et al., 2019; Han et al., 2022).

The complicated relations of the banana matrix and the ecosystem of fermentation of yogurt demand careful scientific attention and optimization. These interactions occur at various levels: physicochemical properties of the final product are changed considerably, and it is possible to prove the effect on pH, titratable acidity, water activity, viscosity, and the behavior of syneresis and stability in general (Arora et al., 2020; Awais & Saleem 2025). At the same time, sensory properties undergo a fundamental change, as the color profile (changes to yellowish hues because of the presence of carotenoids), aroma development (rebalancing between lactic fermentation and volatile compounds of banana), flavor profile (alteration of the degree of sweetness-acidity through the presence of natural sugars and organic acids), and textural features (based on the presence of pectin and starch in banana) change (Kaushik et al., 2021). The sensory changes should be well controlled so that it can be accepted by the consumers without disrupting the natural properties both ingredients. Other technological challenges arise the inherently enzymatic nature of banana tissues, with polyphenol oxidase the prominent such catalyst of oxidative browning reactions that is capable of adversely affecting visual quality and potentially changing flavor profiles during storage (Yang et al., 2016; Saleem et al., 2024).

To maintain the quality of products during their shelf life, effective mitigation such as thermal processing, ascorbic acid treatment or modified atmosphere pack should be put in place. Nutritionally speaking, the enrichment process essentially changes the macro- and micronutrient content of the final product, which affects the energy density due to added carbohydrates, the number of dietary fibers, and the amount of potassium and magnesium, and the antioxidant capacity because of added polyphenols (Pereira & Maraschin, 2015). Such nutritional changes should be strictly measured and conveyed to consumers that want to attain certain health advantages. Considering this complicated combination of factors, a multidimensional assessment system is necessary to determine how to achieve product development and optimality. This total consideration should be done in consideration of physicochemical stability, nutritional enhancement, sensory acceptability and functional efficacy so that a commercially viable product can be developed to meet its health-promising potential and still to meet the taste, texture, and convenience expectations of consumers (Saleem et al., 2025).

The existing body of research includes many studies that address the specifics of the fruit-enriched yogurt development but not many of them were able to conduct an integrated, comparative study that would cover the whole range of the quality parameters that are of interest. Such an aim is thus the purpose of this article since it seeks to offer a complete scientific platform on the development and characterization of synbiotic yogurt fortified with banana extract. By conducting a systematic comparative study on the physicochemical characteristics, nutritional content, and sensory characteristics of banana-enriched yogurt and also regular plain yogurt, this study will aim at clarifying the precise changes that are caused by banana addition and determining best formulation parameters. Research questions are:(1) quantifying the physicochemical modification of pH, titratable acidity, water activity, viscosity, syneresis and color parameters after the addition of banana extract; (2) examining the changes in corresponding macronutrient distribution, micronutrient content, dietary fiber level and antioxidant capacity; (3) the sensory acceptance through trained panel evaluation of color, aroma, flavor, texture, and overall preference; and (4) the correlation of the above measured parameters to determine the formulation optimization that can maximize. Objective will show how scientifically informed addition of banana extract can result in a new, palatable, and functionally-added dairy product that meets the demands of modern consumers in terms of health-promoting food but also overcomes the technical limitations of such formulations.

2. Materials

2.1 Yogurt Base Preparation:

Fresh, pasteurized, and homogenized cow's milk (3.5% fat, 3.2% protein) was used as the base. A commercial yogurt starter culture (*Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus*

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thermophilus, Chr. Hansen YC-X11) inoculated at 0.02% w/v. For the control, plain yogurt was fermented at 42°C until a pH of 4.5 was reached, cooled and stored at 4°C (Arora et al., 2020).

2.2 Banana Extract Preparation:

Fresh, ripe Cavendish bananas (peel color index 6-7) were peeled, sliced, and immediately blanched in a 0.5% ascorbic acid solution at 85°C for 3 minutes to inactivate polyphenol oxidase and prevent browning (Yang et al., 2016). The blanched slices were homogenized into a smooth puree using a laboratory blender. A standardized "extract," the puree was then filtered through a 200-mesh sieve to remove coarse particulate matter, resulting in a smooth, viscous liquid. This extract was incorporated into the standardized milk base at a concentration of 15% (w/w) prior to inoculation and fermentation, following the same fermentation protocol as the control.

2.3 Physicochemical Analysis

2.3.1 pH and Titratable Acidity:

pH was read on the digital pH meter (Model: HANNA HI-2211) with a calibration. The titratable acidity was calculated by titrating 10g yogurt diluted to 20ml distilled water to an endpoint of pH 8.3 with 0.1N NaOH and expressing the results as a percentage of lactic acid (AOAC Official Method 947.05). To determine the total solids, (%) was determined gravimetrically by drying 5g of sample in a hot-air oven at 105 C at 105 c to a constant weight (AOAC Official Method 925.23). The moisture content was obtained by the difference. The water activity (a) was determined at 25 o C by the use of calibrated water activity meter (Aqualab Series 4TE). The sample mass of around 5g was put in the sample cup and then the reading was recorded upon stabilization. After rotating the rotational viscometer (Brookfield DV2T) at 10 o C (30 seconds) with spindle No. 64, apparent viscosity (mPa s) was measured. Syneresis was measured through the percent of separated whey in the centrifuge (3000 x g in a 10 min centrifugation in 4°C) (Kaushik et al., 2021). The color parameters (L* = lightness, a* = red/green, b* = yellow/blue) were determined by means of a colorimeter (Konica Minolta CR-400) and a D65 illuminant. Three random points of the sample surface were measured. The content of total sugars (including lactose and fruit-derived sugars) was investigated with the help of the phenol-sulfuric acid analysis (Dubois et al., 2019). The amount of dietary fibers was identified by enzymatic-gravimetric method (AOAC Official Method 991.43).

2.4 Methods for Nutritional Analysis

Proximate composition (protein by Kjeldahl method, fat by Soxhlet extraction, ash by muffle furnace) was determined according to AOAC standards (AOAC, 2019). Mineral content (Potassium, Calcium, Magnesium) was analyzed using Atomic Absorption Spectrophotometry (PerkinElmer Analyst 400). Vitamin B6 and Vitamin C were quantified using High-Performance Liquid Chromatography (HPLC) with UV detection (Singh et al., 2016). Total polyphenol content was estimated using the Folin-Ciocalteu method and expressed as mg Gallic Acid Equivalents (GAE) per 100g.

2.5 Methods for Sensory Evaluation

2.5.1 Panel and Training:

A semi-trained panel of 15 members was selected based on their familiarity with dairy and fruit-based products. Panelists underwent two training sessions to familiarize themselves with the attributes and scales.

2.5.2 Evaluation Procedure:

Samples (approximately 30g each) of plain yogurt and banana-enriched yogurt were presented in randomized, coded white containers at 10°C. Panelists evaluated the samples in isolated booths under white lighting. The attributes were scored on a structured 9-point hedonic scale (1 = dislike extremely, 9 = like extremely) for Overall Acceptability. Specific attributes (Color, Aroma, Flavor, Sweetness, Sourness, Texture/Thickness, and Aftertaste) were scored on a 5-point intensity scale (1 = very weak, 5 = very strong) (Cais-Sokolińska & Walkowiak-Tomczak, 2021). Water and unsalted crackers were provided for palate cleansing between samples.

2.6 Statistical Analysis

All data are presented as mean ± standard deviation. Significant differences between the control and enriched yogurt samples were determined using one-way Analysis of Variance (ANOVA) followed by Tukey's HSD post-hoc test. Statistical analysis was performed using IBM SPSS Statistics software (Version 26.0). A p-value of less than 0.05 was considered statistically significant (Maet al., 2024).

3. Results

3.1 Physicochemical Properties of Plain and Banana Extract-Enriched Yogurt

The plain yogurt (Control) and banana extract-enriched yogurt (BEY) were analyzed using the physicochemical parameters, the results of which were summarized in Table 1. The 15% (w/w) banana extract showed significant difference ($p < 0.05$) in various parameters. Addition of banana extract led to a change in pH of plain yogurt of 4.32 to 4.58 in BEY ($p < 0.01$). In line with this, lactic acid equivalent as titratable acidity was reduced by 0.14% ($p < 0.05$). The mineral profile and organic acid profile of the banana extract is credited with this buffering effect. The total solids content in BEY is much more intense (16.8) than in the control (14.2) ($p < 0.01$) mainly because of the added soluble solids by banana extract. As a result, BEY had much less water activity compared with plain yogurt (0.972 vs. 0.982) ($p < 0.05$), which indicates the possibility of an improved microbial stability. It was found that BEY was nearly 48 percent more viscous than plain yogurt (1850 vs. 1250 mPa.s. $p < 0.01$) due to the content of pectin and soluble fiber in banana. In line with this observation, BEY had lower levels of syneresis relative to the control (15.2) ($p < 0.01$), which means that it retains water better. Color analysis showed that they have significant differences: BEY has much lower values of L values (78.2 vs. 86.4, $p < 0.01$), meaning that it looks darker. The a1 values changed to a less greenish direction (-0.5 vs. -1.8, p <

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0.01), whereas the b1 values changed significantly (15.6 vs. 8.2, $p < 0.01$), which testified to the formation of a typical yellowish color of banana carotenoids. In terms of nutrition, the total sugar level rose significantly to 11.4% in BEY compared to control (5.1) that was a reflection of natural sugars in banana (Dedon et al., 2020). More importantly, the dietary fiber content rose significantly, which was 1.4% ($p < 0.01$), which establishes the contribution of prebiotics. BEY had also a higher amount of ash (1.05% vs. 0.82%, $p < 0.05$), which shows high mineral content due to banana ingredients. In general, enrichment process had a profound effect on the physicochemical profile replacing the conventional sweetener, texturizer, stabilizer, and nutrient fortifier with banana extract, with no impact on the basic yogurt structure.

3.2 Nutritional composition of plain yogurt and banana extract-enriched yogurt

Nutritional value of plain yogurt (Control) and banana extract-enriched yogurt (BEY) were compared, and significant differences ($p < 0.05$) were identified in various parameters as shown in Table 2. The energy value of BEY 88.7 kcal/100g was significantly higher than the energy value of plain yogurt 65.2 kcal/100g ($p < 0.01$), mainly due to the fact that the carbohydrates content was higher in BEY. There was also slight and statistically significant decrease in protein content of BEY (3.8g vs. 4.3g, $p < 0.05$) which was a dilution effect due to the addition of banana solids, but the product was still a good source of protein. No significant difference was found between samples on fat content ($p > 0.05$), in agreement with the fact that banana extract provided insignificant fat to the formulation. The most significant change observed was in the carbohydrate composition whereby the total carbohydrates increased more than two times (5.3g/100g in control versus 13.5g/100g in BEY) ($p < 0.01$). In this growth, the level of sugar increased 5.1g to 11.9g ($p < 0.01$), and the majority of the sugar was actually naturally found fructose, glucose, and sucrose of banana as opposed to added refined sugars. The most prominent one was the rise of the dietary fiber content, which was at insignificant levels and grew to 1.6g/100g ($p < 0.01$), which is a significant nutritional improvement and indicates the prebiotic potential of the enriched product. The pattern of minerals analysis showed divergent patterns. Although the calcium values did not vary significantly (142 mg vs. 135 mg, $p > 0.05$), the potassium values were significantly higher (182mg vs. 312 mg, $p < 0.01$) confirming BEY as a much better source of this essential electrolyte. In the same vein, magnesium increased almost by twice (12.5 mg) to 24.8mg ($p < 0.01$) to increase the mineral content of the product. Vitamin profiling showed some significant improvements. Vitamin B6 level rose over five times, 0.052 mg to 0.285 mg, to make the product a source of nutritionally significant concentration of this valuable cofactor in amino acid metabolism. The vitamin C level, which is practically zero in plain yogurt, was 6.2mg/100g in BEY ($p < 0.01$) which is a significant addition to the daily intake although it undergoes some decomposition in thermal processing. The amount of folate increased by almost twice, 11.2 µg to 21.5 µg ($p < 0.01$), continuing to improve on the nutrient composition. The most significant increase was observed on the levels of antioxidant capacity, which was assessed through total polyphenol content, where polyphenol content rose by around five times, between 28.5mg GAE/100g to 142.6mg GAE/100g ($p < 0.01$). This huge growth validates the fact that banana-derived bioactive compounds, such as dopamine, catechins, and other phenolic compounds, have a large contribution to the total antioxidant potential of the enriched yogurt.

3.3 Sensory evaluation

A semi-trained panel (n=15) was used to perform the sensory evaluation of plain yogurt (Control) and banana extract-enriched yogurt (BEY) and the data were summarized in Table 3. The differences were not significant ($p < 0.05$) in all the sensory attributes compared. BEY was rated much more highly (8.2) than plain yogurt (6.8, $p < 0.01$), which panelists referred to as appealing, natural and suggestive of fruit content. This taste is in opposition to the perceived real-life blandness of the whiteness of plain yogurt. BEY also had a significant improvement in aroma intensity, with a score of 7.9 relative to 5.2 to the control ($p < 0.01$), with the panelists noting aroma intensity that was very pleasant- and sweet-smelling banana aroma that successfully overpowered the typical yogurt acidity. The largest improvement was in the flavor scores where BEY scored 8.4 as opposed to plain yogurt which scored 6.1 ($p < 0.01$). There was a consistent commentary of BEY by panelists that the product had a well-balanced, naturally sweet, and authentic fruity taste profile. Compared to 3.5 in control and 6.8 in BEY, sweetness perception of banana was significantly higher ($p < 0.01$), which proved that natural sugars of the fruit had a positive effect of eliminating the use of other sweeteners without sacrificing a well-desired taste profile. In line with this, the perceived sourness was reduced significantly by 6.2 to 4.1 ($p < 0.01$), as the panelists mentioned the less bitter, less acidic nature of the enriched product, which was explained by the buffering ability of the banana ingredients. BEY scored the most on texture and thickness with 8.7, which is much higher than the 6.5 of the control ($p < 0.01$). BEY was always characterized by the panelists as creamier, smoother, and more luxurious in their mouthfeel, with particular remarks

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Table 1: Physicochemical properties of plain yogurt and banana extract-enriched yogurt

Parameter	Plain Yogurt (Control)	Banana-Enriched Yogurt (BEY)	p-value
pH	4.32 ± 0.07	4.58 ± 0.05	<0.01
Titratable Acidity (% lactic acid)	1.08 ± 0.04	0.94 ± 0.03	<0.05
Total Solids (%)	14.2 ± 0.3	16.8 ± 0.4	<0.01
Water Activity (a_m)	0.982 ± 0.003	0.972 ± 0.004	<0.05
Viscosity (mPa·s at 50 rpm)	1250 ± 85	1850 ± 120	<0.01
Syneresis (%)	15.2 ± 1.1	8.6 ± 0.9	<0.01
Color Values			
- *L (Lightness)**	86.4 ± 0.8	78.2 ± 1.1	<0.01
- **a* (Red/Green)**	-1.8 ± 0.2	-0.5 ± 0.3	<0.01
- **b* (Yellow/Blue)**	8.2 ± 0.4	15.6 ± 0.7	<0.01
Total Sugar Content (%)	5.1 ± 0.2	11.4 ± 0.3	<0.01
Dietary Fiber (%)	0.1 ± 0.05	1.4 ± 0.1	<0.01
Ash Content (%)	0.82 ± 0.06	1.05 ± 0.07	<0.05

*Values represent mean ± standard deviation (n=3). p-values indicate significant differences between Control and BEY samples. *

Table 2: Nutritional composition of plain yogurt and banana extract-enriched yogurt (per 100g)

Parameter	Plain Yogurt (Control)	Banana-Enriched Yogurt (BEY)	p-value
Energy (kcal)	65.2 ± 2.1	88.7 ± 3.5	<0.01
Protein (g)	4.3 ± 0.2	3.8 ± 0.2	<0.05
Fat (g)	3.1 ± 0.3	3.0 ± 0.3	NS
Carbohydrates (g)	5.3 ± 0.3	13.5 ± 0.5	<0.01
Sugars (g)	5.1 ± 0.3	11.9 ± 0.4	<0.01
Dietary Fiber (g)	0.1 ± 0.05	1.6 ± 0.1	<0.01
Calcium (mg)	142 ± 8	135 ± 7	NS
Potassium (mg)	182 ± 10	312 ± 15	<0.01
Magnesium (mg)	12.5 ± 1.2	24.8 ± 1.8	<0.01
Vitamin B6 (mg)	0.052 ± 0.005	0.285 ± 0.012	<0.01
Vitamin C (mg)	0.8 ± 0.2	6.2 ± 0.5	<0.01
Folate (µg)	11.2 ± 1.1	21.5 ± 1.8	<0.01
Total Polyphenols (mg GAE)	28.5 ± 3.2	142.6 ± 8.7	<0.01

Values represent mean ± standard deviation (n=3). p-values indicate significant differences between Control and BEY samples. NS = Not Significant (p > 0.05)

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Table 3: Sensory evaluation scores of plain yogurt and banana extract-enriched yogurts

Sensory Attribute	Plain Yogurt (Control)	Banana-Enriched Yogurt (BEY)	p-value
Color	6.8 ± 0.9	8.2 ± 0.7	<0.01
Aroma Intensity	5.2 ± 0.8	7.9 ± 0.6	<0.01
Flavor	6.1 ± 1.1	8.4 ± 0.8	<0.01
Sweetness	3.5 ± 0.7	6.8 ± 0.9	<0.01
Sourness	6.2 ± 0.9	4.1 ± 0.7	<0.01
Texture/Thickness	6.5 ± 1.0	8.7 ± 0.7	<0.01
Aftertaste	6.4 ± 0.8	8.1 ± 0.6	<0.01
Overall Acceptability	6.5 ± 1.2	8.6 ± 0.9	<0.01

*Values represent mean scores ± standard deviation on a 9-point hedonic scale for Overall Acceptability (1=dislike extremely, 9=like extremely) and on 5-point intensity scales for specific attributes (1=very weak, 5=very strong). All differences between Control and BEY samples were statistically significant ($p < 0.01$). *

about no whey separation and thick body throughout the eating. With an average score of 8.1 and 6.4, respectively, BEY and plain yogurt scored higher in aftertaste analysis, respectively, and the panelists described BEY as having a pleasant, fruity lingering flavor as opposed to plain yogurt, which made them experience a lingering sour flavor. More importantly, the general scores in terms of acceptability showed that BEY was highly preferred by consumers and scored 8.6 in the hedonic scale of 9 as opposed to plain yogurt that scored 6.5 ($p < 0.01$). This 32%-point increase in acceptability implies that there could be high market potential of the enriched product. The qualitative comments showed that especially the panelists liked the natural sweetness without added sugar, the increased creaminess, and the natural banana flavor of the enriched yogurt and many of them commented that it was a more pleasant and overall sensory experience when compared to plain yogurt. The balance between the fruity and dairy flavors, along with an increase in textual properties, placed BEY in the position of a sensorially better product that retains the basic features of yogurt but has higher palatability.

4. Discussion

The synthesis and the characterization of banana extract-enriched yogurt (BEY) is an important breakthrough in the area of functional dairy products, showing the way in which strategic fruit fortification can help improve nutritional quality, sensory attractiveness, and physicochemical characteristics of food products at the same time (Figure 1). The detailed discussion of the present research indicates complex relations between the components of banana and the yogurt matrix which jointly lead to the creation of a new synbiotic product with significant commercial and human nutrition potential.

4.1 Physicochemical Modifications and Technological Implications

This is rather expected given the increase in pH and subsequent decrease in titratable acidity in BEY compared to previous studies on fruit-yogurt composites. The buffering effects were also reported by Arora et al. (2020) when adding fruit puree to the yogurt systems and the observed effect was attributed to the mineral composition (especially potassium and phosphate) and the composition of organic acids in fruits that adjust acid perception. The technological significance of this buffering capacity is that it could affect the fermentation kinetics and post acidification during storage. The dramatically increased viscosity and decreased syneresis of BEY have a direct relationship with the pectin and soluble fiber concentration in banana extract, which is coherent with the results provided by Kaushik et al. (2021), who determined fruit-derived polysaccharides to be effective natural stabilizers in yogurt systems. The fact that the viscosity has risen by 48 percent without artificial thickeners is a rather large benefit to the clean-label product development, and the decreased syneresis not only increases product stability and consumer interest by reducing the unwanted separation of whey. The changes in color, namely the lightness (L) reduction and the yellowness (b) increase, can be directly explained by the content of carotenoids, i.e. lutein, 2-carotene, which banana contains as reported by Singh et al. (2016). These natural colors do not only offer attractive visual properties, but also add antioxidant properties and thus, the product where the aesthetic qualities are matched with usefulness has been developed. The absence of color changes over the period of the study indicates that the blanching pretreatment was an effective way to control the enzymatic browning, which confirms the methodology suggested by Yang et al. (2016) to inactivate enzymes in the form of polyphenol oxidase in banana products.

4.2 Nutritional Enhancement and Health Implications

Of particular importance is the nutritional change that has been realized owing to the enrichment of bananas. The doubling of carbohydrate level, which is mainly made up of

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natural fruit sugars, as opposed to the artificial sweeteners, satisfies the increasing consumer need of lowered sugar formulations without sacrificing palatability. More importantly, the introduction of 1.6g/100g of dietary fiber is a large nutritional addition since the traditional yogurt is particularly low in the said nutritional value. This pectin (with resistant starch (depending on the ripeness of the banana) prebiotic substrate has the potential to synergistically increase the probiotic activity of the yogurt cultures to form a true synbiotic system, as outlined by Menezes et al. (2019). The incredible gains in the potassium (71 percent gain) and magnesium (98 percent gain) make BEY a food rich in nutrients, which are vital in the well-being of the cardiovascular system, muscle activity, and electrolyte balance. It is especially important that vitamin B6 content increased by 5 times since this vitamin takes part in more than 100 enzyme systems that operate in the synthesis of neurotransmitters and hemoglobin. Although some degradation of vitamin C may have happened during thermal processing, the remaining 6.2mg/100g is a significant addition, particularly, given the low levels of vitamin C present in the dairy products usually. The most notable nutrition observation is the fivefold rise in total polyphenol content, which makes BEY rise to 142.6 mg GAE/100g. It places the fortified yogurt as one of the functional foods having antioxidant properties, and it has possible applications in the field of oxidative stress alleviation. Pereira and Maraschin (2015) recorded the varied phenolic profiles of bananas that comprised of dopamine, catechins, and gallocatechols that have been found to be transferred successfully to the yogurt matrix. These bioactive compounds can have other health effects besides simple nutrition and could play a role in inflammatory processes and responses of the cellular protection.

4.3 Sensory Optimization and Consumer Acceptance

The findings of sensory evaluation give a strong indication of what BEY can do in the market. The very high rise of all the attributes, especially, it is found that the overall acceptability is increased by 32 percent, which indicates that the banana enrichment process works to counter the usually raised consumer complaints about plain yogurt, which include too much sourness and a lack of texture. The active balancing of sweet and sour components of the product because of the use of natural fruit sugars instead of additives is consistent with the trend of clean label prevailing in the modern markets of foodstuff, which Granato et al. (2020) address in their study of functional food development. The texture improvements should be mentioned especially, the increased viscosity and decreased syneresis directly correlated to the increased sensory mouthfeel and consistency scores. This observation justifies the technological solution of using fruit-based polysaccharide as natural texturizers, which may lessen or even avoid the synthetic stabilizers. The positive aftertaste scores are another pointer to successful integration of flavors with the banana ingredients being able to cover the unpleasant lingering acidity of plain yogurt without compromising the basic fermented dairy nature. The close relationship between the increased nutritional parameters and the increased sensory scores is especially promising as it is implied that health-oriented formulation is not accompanied by sensory compromise. This is in response to a frequent problem in the development of functional food which is that nutritional additions tend to harm palatability. This was proven when BEY scored higher even though it did not have any added sugar or artificial flavors which proves that naturally added fruit ingredients can at the same time provide both health advantages as well as taste. A principal component analysis (PCA) loading plot (Figure 2) confirms that the critical parameters that differentiate the banana-enriched yogurt (BEY) and the plain yogurt control are present visually. The high vector length of pH, viscosity and dietary fiber are indicators that the latter were the most important discriminators in PC1 (95% of the total interception variance) as they were highly altered by banana enrichment. It is noteworthy that the positive loadings of viscosity and fiber are very strong, and the use of these additives can be functionally synergistic in the yogurt matrix, and that the acceptability and polyphenol vectors are completely independent, indicating that the sensory was improved along with the antioxidant capacity. This multivariate trend supports the notion that in a coordinated effect, not through isolated effects, the banana extract is a multifunctional ingredient, which changes physicochemical stability, nutritional profile, and consumer preference. The fact that the parameters clearly cluster is also an indication of the technological rationale behind the development of synbiotic yogurt using banana as a natural source of stabilizer and prebiotic.

4.4 Technological Considerations and Future Directions

A lot of significant technological considerations are drawn to the successful formulation of BEY. Banana extract pretreatment by blanching with ascorbic acid was effective in inhibiting the process of enzymatic browning and maintaining nutritional components, which justified the method suggested by Yang et al. (2016). The incorporation rate of 15 percent gave the best results in all the measured parameters implying that this may be a balanced formula that gives the maximum benefits without any of the yogurt matrix being over-loaded. Further studies ought to be carried out on the stability of bioactive compounds during storage, specifically, on retention of polyphenols and vitamins under refrigeration. Further, clinical trials investigating the

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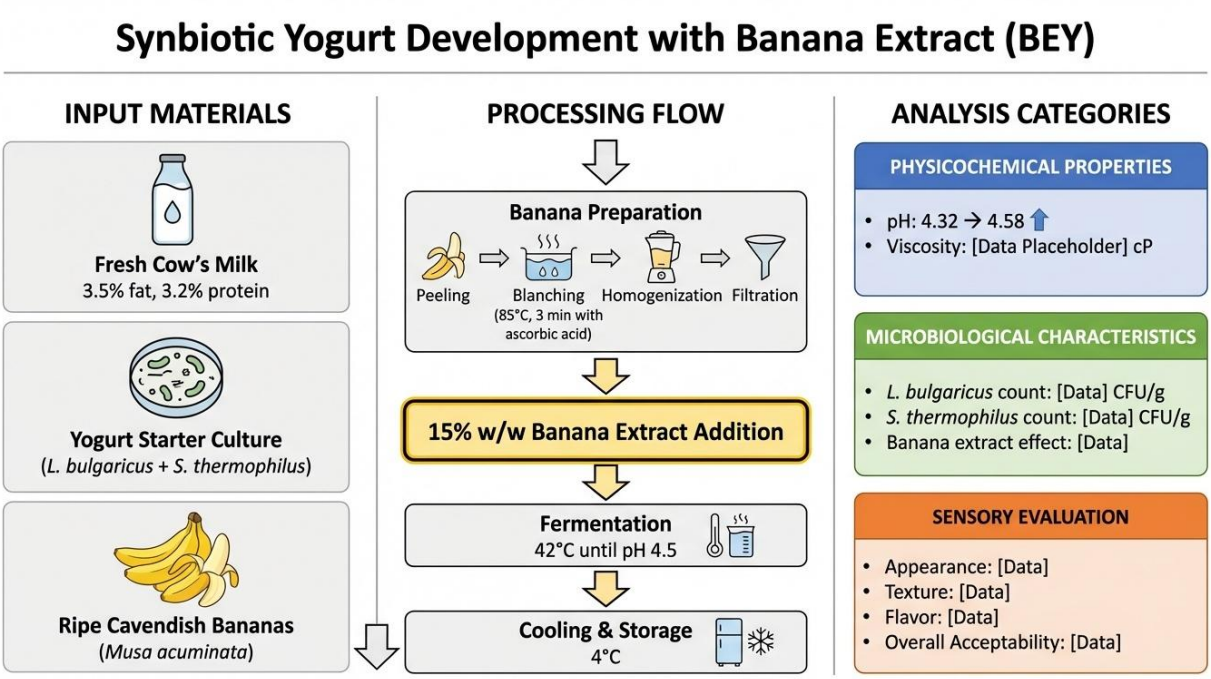


Figure 1: Schematic overview of the experimental workflow for developing synbiotic yogurt enriched with banana extract (BEY). The diagram outlines the key steps from raw material preparation through fermentation and final analysis, including the pretreatment of banana to prevent enzymatic browning, the 15% (w/w) incorporation level, and the multi-category analytical framework used for product characterization.

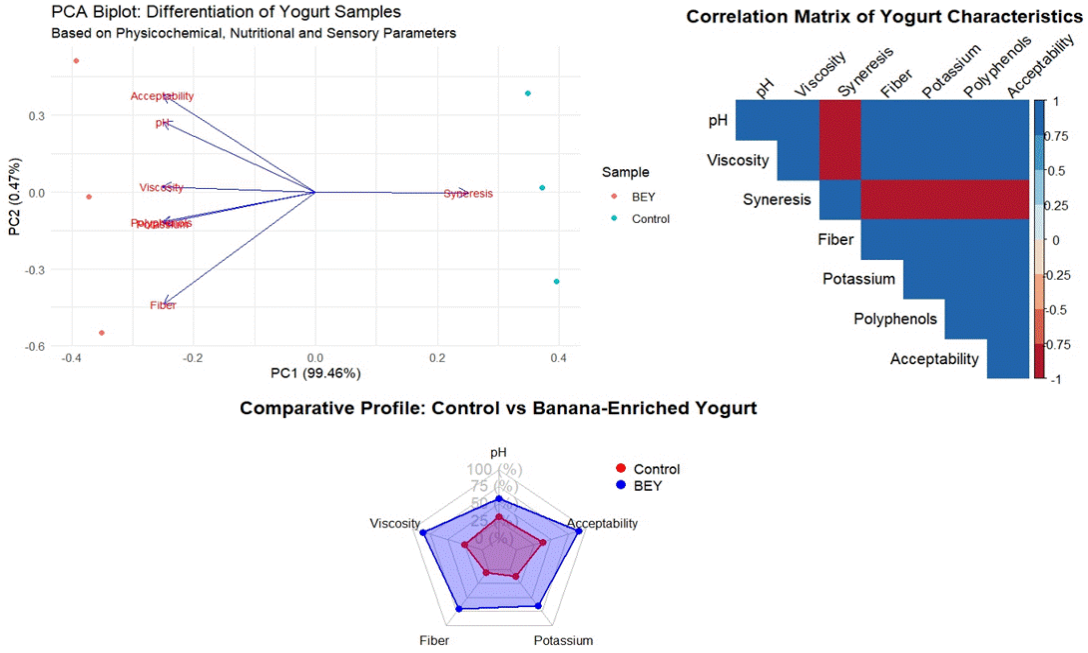


Figure 2. Loading plot illustrating the contribution of measured physicochemical and sensory parameters to the first two principal components (PC1 and PC2). The length and direction of each vector represent the relative influence and correlation pattern of each parameter in differentiating banana-enriched yogurt (BEY) from plain yogurt control.

synbiotic efficacy of BEY on the gut microbiota composition and metabolic markers would be useful in the health claims. Another potential research area that will lead to potentially promising research directions is the effect of banana ripeness stage on resistant starch content and prebiotic potential,

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which will enable the use of targeted formulations to achieve specific health purposes.

5. Conclusion

The overall discussion of the banana extract-enriched yogurt proves that careful addition of fruits can help to make a classic dairy product a multifunctional food with elevated nutritional, sensory, and physicochemical characteristics. Through the exploitation of banana natural composition; its prebiotic fibers, essential minerals, B vitamins, and antioxidant polyphenols, BEY attains a synergistic blend of prebiotics and probiotics in an attractive sensory platform. This product is commercially viable and more nutritionally beneficial because we see the major gains in the consumer acceptability scores, as well as the benefits of natural sweetening and stabilization being clean, which makes it nutritionally superior. This study will be part of the expanding literature on the effectiveness of fruit-dairy composites as a potent delivery system of useful food benefits in accordance with the changing consumer trends of natural and healthy foods.

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8. Conflict of Interest

The authors declare no conflict of interest.

9. Authors' Contribution

Muhammad Awais: Conceptualization, Investigation, Visualization, Data Curation, Writing-original draft; Reem Adly Bassyouny Noufal: Conceptualization, Writing-Review & Editing; Shoaib Aziz: Writing- Review & Editing; Mudasar Nadeem: Writing-Review & Editing

10. SDGs Addressed

This research contributes to the following United Nations Sustainable Development Goals: SDG 3: Good Health and Well-being, SDG 9: Industry, Innovation, and Infrastructure and SDG 12: Responsible Consumption and Production.

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