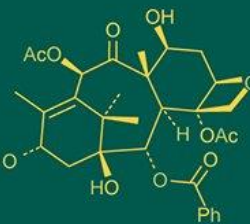
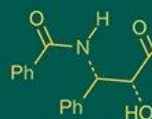
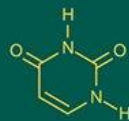


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Valorization of banana peel: Physicochemical properties and functional potential of peel powder

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Abstract

Banana peel, a major agro-waste constituting nearly 30-40% of the fruit, was investigated for physicochemical and functional properties to explore its potential as a sustainable food ingredient. Fresh peel exhibited high moisture content ($92.70 \pm 0.40\%$), near-neutral pH (6.28 ± 0.06), bulk density ($413.40 \pm 8.85 \text{ kg/m}^3$), particle density ($947.60 \pm 10.92 \text{ kg/m}^3$), tapped density ($1376.20 \pm 5.36 \text{ kg/m}^3$), and peel thickness ($4.35 \pm 0.39 \text{ mm}$). The total colour difference ($\Delta E = 53.79 \pm 0.70$) and biomass ratios (pulp-to-peel 1.55 ± 0.15 , pulp-to-fruit 0.59 ± 0.04 , fruit-to-peel 2.63 ± 0.14) highlighted its compositional characteristics. Banana peel powder demonstrated improved stability with reduced moisture ($5.50 \pm 0.10\%$) and low water activity (0.35 ± 0.01). The powder showed bulk density ($461.80 \pm 0.45 \text{ kg/m}^3$), tapped density ($1576.4 \pm 39.83 \text{ kg/m}^3$), Carr Index (0.71 ± 0.01), and Hausner Ratio (3.41 ± 0.09) indicating poor flowability typical of fibrous powders. Functional properties included high water holding capacity ($8.74 \pm 0.74 \text{ g/g}$) and oil holding capacity ($1.79 \pm 0.36 \text{ g/g}$), while nutritional analysis revealed crude fiber ($5.22 \pm 0.43\%$) and ash content ($12.00 \pm 0.01\%$). These findings confirm that banana peel powder is rich in dietary fiber and mineral with strong hydration and binding properties and making it a promising candidate for functional food applications. Its valorisation not only reduces environmental burden but also supports sustainable utilization of agro-waste. The results demonstrate that banana peel can be effectively converted into a stable, nutrient-rich powder with high dietary fiber and mineral content. This study highlights the potential of banana peel powder as a functional ingredient in food formulations, while also contributing to sustainable waste utilization.

Keywords: Banana peel, tray drying, physico-chemical composition, moisture content, crude fiber, ASH content

Introduction

Banana (*Musa spp.*) is one of the most important fruit crops worldwide, with India being the largest producer, followed by China, Indonesia, Brazil, Ecuador, and Nigeria (FAO, 2023). The peel, which constitutes nearly 30-40% of the fruit's weight, is often discarded as waste, yet it contains significant amounts of dietary fiber, phenolic compounds, flavonoids, and antioxidants (Agama-Acevedo *et al.*, 2020). Valorization of banana peel not only reduces environmental burden but also provides a sustainable source of functional food ingredients (Zakaria Salih *et al.*, 2021). It contains considerable amounts of dietary fiber, including cellulose, hemicellulose, lignin, and pectin, which contribute to its functional and nutritional properties (Emaga *et al.*, 2007; Happi Emaga *et al.*, 2008). In addition, banana peel contains carbohydrates, proteins, essential minerals such as potassium, calcium, sodium, and manganese, along with bioactive compounds including phenolics, flavonoids, carotenoids, and polyunsaturated fatty acids (Wachirasiri *et al.*, 2009; Wani & Dhanya, 2025). These constituents exhibit antioxidant, antimicrobial, and anti-inflammatory properties, making banana peel a promising raw material for food and nutraceutical applications (Nagarajaiah & Prakash, 2011).

Banana peel powder exhibits important physicochemical traits moisture, bulk density, pH, water-holding capacity (WHC), oil-holding capacity (OHC), and color values that determine its stability, texture, and functional performance in food systems (Mohd Dom *et al.*, 2021). Its high soluble fiber, strong hydration, and fat-binding capacity make it superior to many conventional fibers, supporting gut health and reducing risks of cardiovascular disease, diabetes, and colon cancer (Bhavani *et al.*, 2023) [12, 1, 35, 11, 14, 32, 33, 18, 17, 6].

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In bakery applications, banana peel flour enhances moisture retention, swelling capacity, and texture stability, while its minerals and bioactive compounds (flavonoids, tannins, anthocyanins, terpenoids) impart antioxidant and therapeutic benefits. At higher incorporation levels, it modifies water absorption, cooking loss, and microstructure, improving porosity and functional properties such as emulsification and foaming capacity (Mohd Dom *et al.*, 2021). Thus, converting banana peel into powder represents a sustainable valorization strategy, reducing agro-industrial waste while enriching foods with nutritional and functional value (Bhavani *et al.*, 2023) [17, 6].

Dietary fiber plays a vital role in maintaining human health by improving gastrointestinal function, regulating blood glucose levels, lowering serum cholesterol, and lowering the chance of developing chronic illnesses like obesity, diabetes, cardiovascular disorders, and colon cancer (Anderson *et al.*, 2009; Mudgil & Barak, 2013). The demand for natural and fiber-enriched food products is rising as consumers become more conscious of the need of eating healthily. However, conventional sources of dietary fiber are often expensive and may not adequately meet industrial demand. In this regard, banana peels provide an affordable and sustainable substitute source of dietary fiber that can be successfully applied to the creation of functional food ingredients (Rawat & Ghosh, 2025) [2, 19, 26].

Fresh banana peel is characterized by elevated moisture content and the presence of endogenous enzymes, particularly polyphenol oxidase, which catalyze oxidative browning reactions and accelerate quality deterioration during handling and processing. To mitigate these effects, appropriate pretreatment strategies including blanching, citric acid immersion, and sulphite treatment are commonly employed prior to drying, with the primary objectives of inactivating enzymes, suppressing microbial proliferation, and preserving the color integrity and nutritional quality of the final dried product (Wachirasiri *et al.*, 2009; Aurore *et al.*, 2009; Queiroz *et al.*, 2008) [32, 25].

Drying represents a critical unit operation in the processing of banana peel powder, exerting a profound influence on its physicochemical properties, nutritional composition, and storage stability. Among the various drying techniques employed for moisture removal, tray drying is widely adopted owing to its operational simplicity and economic feasibility; however, prolonged exposure to elevated temperatures inherent to this method may result in thermal degradation of heat-sensitive bioactive compounds, including phenolics, carotenoids, and vitamins. Vacuum drying offers a superior alternative in terms of color retention and preservation of bioactive constituents, as the reduced oxygen partial pressure minimizes oxidative deterioration during processing. Solar drying, while cost-effective and energy-efficient, is often associated with inconsistent product quality attributable to uncontrollable environmental variables such as ambient temperature, humidity, and solar irradiance fluctuations. Consequently, systematic optimization of drying parameters is essential to yield banana peel powder with sufficiently low moisture content, enhanced shelf stability, and improved retention of dietary fiber and phytochemical constituents (Nascimento *et al.*, 2016; Sogi *et al.*, 2013) [20, 28].

Although physicochemical and functional properties of banana peel powder have been reported for several varieties including Cavendish, Saba, and related cultivars, with

parameters such as bulk density, tapped density, pH, water holding capacity, and oil holding capacity being characterized, studies on Cavendish banana peel flour have primarily focused on green and ripe stage comparisons without variety-specific differentiation at the cultivar level. To the best of the authors' knowledge, no prior investigation has been reported on the comprehensive physicochemical and functional characterization of peel powder derived specifically from the G9 banana hybrid cultivar, thereby establishing the novelty and scientific contribution of the present study.

2. Material and methods

Experiments were carried out at the Department of Food Engineering, College of Food Technology, Pulivendula, and Dr. NTR College of Agricultural Engineering, Acharya N.G. Ranga Agricultural University (ANGRAU), Andhra Pradesh, India.

2.1 Preparation of Banana Peel

Fresh banana peels obtained from mature green Grand Naine (G9) bananas of stage 2 maturity were procured from local farmers washed thoroughly under running tap water to remove dirt and other impurities. The cleaned peels were drained to remove excess moisture and cut into uniform pieces (2-3cm) using a stainless-steel knife to ensure uniform drying. Physico chemical properties of the banana peel was determined of the raw banana peel.

2.2 Measurement of physicochemical properties of banana peel

2.2.1 Moisture content (%)

Moisture content of banana peel samples was evaluated gravimetrically by subjecting approximately 2 g of weighed sample, placed in tared aluminum dishes, to thermal drying at $105 \pm 2^\circ\text{C}$ until a stable mass was recorded between consecutive weighing intervals. The dried samples were subsequently equilibrated to room temperature inside a desiccator before final weighing, and the moisture content was thereafter computed on a wet basis (AOAC Method 925.10, 2023).

2.2.2 Peel Thickness

Banana peel thickness was measured, at five randomly selected points across each sample using a digital vernier caliper, and the average of these readings was recorded as the representative thickness value for that sample described by Patil and Shanmugasundaram, 2015 [24].

2.2.3 pH

The pH of the fresh banana peel was determined using two grams of banana peel sample was crushed with 20 mL of distilled water to obtain a uniform slurry. pH of the homogenized sample was calculated directly using a calibrated pH meter as described by Vasundhara *et al.*, (2021) [31].

2.2.4 Bulk Density and Particle Density

Bulk density of banana peel powder was determined by gently pouring a known mass of sample into a pre-weighed graduated cylinder and computing the ratio of sample mass to the occupied bulk volume, in accordance with the method described by Onwuka (2005). Particle density was subsequently established through the toluene displacement

method, wherein a known mass of sample was introduced into a calibrated measuring cylinder containing a fixed volume of toluene, and the volume of toluene displaced was utilized to compute the true density of the material, following the procedure outlined by Mohsenin (1986) [18].

2.2.5 Pulp to Peel Ratio, Pulp to Fruit Ratio, Fruit to Peel Ratio:

Fresh banana fruits were carefully separated into pulp and peel fractions, with each component individually weighed using an analytical balance to obtain accurate mass values for subsequent ratio calculations. The pulp to peel ratio, pulp to fruit ratio, and fruit to peel ratio were then derived by dividing the respective component masses against one another, following established protocols outlined by Patil and Shanmugasundaram (2015), Mohapatra *et al.*, (2016), and Abdullah *et al.*, (2017) [24, 16].

Colour: The color of the fresh banana peel was measured using a Hunter Lab Colorimeter (Make: *HunterLab ColorFlex EZ Colorimeter*, Model: CFLX/DIFF, CFLX-45).

Measurement of Physicochemical properties of banana peel powder:

The physicochemical properties of banana peel powder were determined using standard analytical methods. Key parameters including moisture content (AOAC, 2023), pH, bulk and tapped density, Carr Index, Hausner ratio, water activity, water and oil holding capacities, crude fiber, and ash content were measured, these evaluations provide essential insights into powder stability, flowability, and nutritional quality for food applications.

2.3.1 Moisture content (%)

The moisture content of the banana peel powder was determined by following the method described in (2.2.1) AOAC, (2023).

pH

Banana peel powder's pH was determined by dispersing two grams of powder in 15 mL of distilled water. The suspension was vortexed for 5 min and allowed to stand for 30 min at room temperature. The mixture was then centrifuged, and the pH of the supernatant was determined using a digital pH meter (Sartorius, Germany).

Bulk Density and Tapped Density

Bulk density of banana peel powder was determined by transferring a known quantity of sample into a pre-weighed 10 mL graduated cylinder, recording the occupied volume and powder mass, and computing the ratio of mass to bulk volume inclusive of interparticle voids, following the method of Rawat and Ghosh (2025) with slight modifications. Tapped density was subsequently measured by pouring approximately 100 g of powder into a 250 mL graduated cylinder via a funnel, recording the initial volume, and manually tapping the cylinder 250 times until no further volumetric reduction was observed, whereupon the final tapped volume was documented and the tapped density was calculated as the ratio of powder mass to the compacted volume method described by Boreddy and Subbiah, 2015 [26, 7].

Carr Index and Hausner Ratio

The Carr index was computed from the proportional difference between tapped and bulk density values,

expressing the degree of compressibility of the banana peel powder as established by Carr (1965) and Turchiulli *et al.* (2005). The Hausner ratio was subsequently derived by dividing the tapped density by the bulk density, providing a quantitative measure of powder flowability in accordance with the method described by Bhadra *et al.* (2014) [7, 8, 29].

Table 1: Carr Index classification ranges

Carr Index	Flow Character
0.01 - 0.10	Excellent
0.11 - 0.15	Good
0.16 - 0.20	Fair
0.21 - 0.25	Passable
0.26 - 0.31	Poor
0.32 - 0.37	Very Poor
> 0.38	Extremely Poor

Table 2: Hausner Ratio classification ranges

Hausner Ratio	Flow Character
< 1.11	Excellent
1.11 - 1.18	Good
1.19 - 1.25	Fair
1.26 - 1.34	Passable
1.35 - 1.45	Poor
1.46 - 1.59	Very Poor
> 1.60	Extremely Poor

Water Activity

The water activity (aw) was measured using a Water Activity Meter. The sample cup was filled to approximately half its capacity with banana-peel powder and placed in the measurement chamber. After the reading was stabilized, the water activity value was recorded.

Water Holding Capacity and Oil Holding Capacity

Water holding capacity (WHC) was determined according with minor modifications. 0.25 g of sample (W_1) was mixed with 10 mL of distilled water and allowed to stand for 24 h at ambient temperature. The mixture was centrifuged at 6700 rpm for 15 min at 25°C. After centrifugation, the sediment was weighed (W_2), and WHC was calculated using Eq. (1) (Rawat and Ghosh, 2025) [26].

$$\text{WHC (g g}^{-1}\text{)} = \frac{w_2 - w_1}{w_1} \quad (1)$$

Oil holding capacity (OHC) was calculated according with slight modifications. 0.5 g of sample (W_1) was mixed with 5 mL of refined palm oil and stored at 5°C for 1 h. The mixture was centrifuged at 6700 rpm for 15 min at 25°C. After removal of the unbound oil, the sediment was weighed (W_2). OHC was calculated using Eq. (2) (Rawat and Ghosh, 2025).

$$\text{OHC (g g}^{-1}\text{)} = \frac{w_2 - w_1}{w_1} \quad (2)$$

Crude Fibre Content

The crude fiber content was calculated using AOAC Method 978.10. 2 g of dried sample (W_s) was subjected to acid digestion with 200 mL of 1.25% (w/v) sulfuric acid (H_2SO_4) for 30 min under boiling conditions. The mixture was filtered and washed thoroughly with hot distilled water. The residue was then digested with 200 mL of 1.25% (w/v) sodium

hydroxide (NaOH) solution for 30 min, followed by filtration and washing until neutral pH was attained. The residue was shifted to a pre-weighed crucible and dried at 130°C for 2 h. The crucible containing dried residue was weighed (W_2) and subsequently incinerated in a muffle furnace at 550°C for 2 h. The crucible was weighed again (W_3) after cooling in a desiccator. Crude fibre content was determined using Eq. (3).

$$\text{Crude fiber (\%)} = \frac{w_1 - w_2}{ws} \times 100 \quad (3)$$

Ash Content: Total ash content was calculated using the AOAC (1980) [5] method. Approximately 2 g of banana peel powder was weighed into a pre-weighed crucible and initially charred on a heating mantle (Model: BT 1-19, Biotechnics India) until smoke evolution ceased. The crucible was then transferred to a muffle furnace (Model: KMF.1, Kemi, India)

and incinerated at 550°C for 6 h. After complete ashing, the crucibles were cooled in a desiccator and weighed. Ash content was calculated using Eq. (4).

$$\text{Ash content (\%)} = \frac{W_3 - W_1}{W_2 - W_1} \quad (4)$$

3. Results and Discussion

3.1 Physicochemical Properties of Fresh Banana Peel

Fresh banana peels utilized in the present study were obtained from stage 2 *Musa* sp. fruits and subjected to characterization prior to processing. The peels were subsequently dried using a hot air oven maintained at 50°C until a constant weight was achieved, after which the dried material was ground using a laboratory blender and sieved through a 250-mesh screen to obtain a uniform banana peel powder for further analysis. The physicochemical properties of fresh banana peel are presented in Table 3.

Table 3: Physicochemical Properties of Fresh Banana Peel (n = 3)

S. No	Physicochemical Property	Mean ±SD
1	Moisture Content - Wet Basis (%)	92.70±0.40
2	Moisture Content - Dry Basis (%)	12.79±0.63
3	Peel Thickness (mm)	4.35±0.38
4	Particle Density (kg/m ³)	948.00±10.92
5	Bulk Density (kg/m ³)	413.00±8.85
6	Tapped Density (kg/m ³)	1376.00±5.36
7	Porosity (%)	56.37±0.95
8	pH	6.30±0.06
9	Colour - L* (Lightness)	62.97±0.24
10	Colour - a* (Redness/Greenness)	-28.41±0.95
11	Colour - b* (Yellowness/Blueness)	22.78±1.49
12	Colour - ΔE (Total Colour Difference)	53.79±0.70
13	Pulp: Peel Ratio	1.55±0.15
14	Pulp: Fruit Ratio	0.59±0.04
15	Fruit: Peel Ratio	2.63±0.14

The moisture content of fresh banana peel was recorded at 92.70±0.4% (wet basis), reflecting the highly perishable nature of the material and its susceptibility to rapid microbial deterioration. This elevated moisture level is characteristic of tropical fruit by-products and is consistent with the findings of Happi Emaga *et al.* (2007), who reported moisture values exceeding 88% in fresh banana peel, attributable to the high water-binding capacity of the cell wall polysaccharides and pectin constituents present in the peel tissue. The near-neutral pH of 6.30±0.06 observed in the fresh peel indicates a mildly acidic environment, which is favorable for its incorporation into food systems without substantially altering product processing conditions [13].

The bulk density and particle density of fresh banana peel were determined as 413.00±8.85 kg/m³ and 948±10.92 kg/m³, respectively, with a corresponding porosity of 56.37±0.95%, indicative of a loosely packed internal pore structure characteristic of fresh biological tissue with intact cellular architecture (Mohsenin, 1986) [18]. The peel thickness was recorded at 4.35±0.38 mm, a parameter that directly governs drying rate and heat penetration efficiency during thermal processing, as thicker peels present greater resistance to moisture diffusion and consequently necessitate extended drying durations to attain the desired final moisture content (Karam *et al.*, 2016; Doymaz, 2010) [10]. The tapped density (1376±5.36 kg/m³) was markedly higher than the bulk density, reflecting considerable compressibility of the material attributable to the flexible and fibrous nature of the

fresh peel structure (Mohsenin, 1986) [18]. Colorimetric analysis yielded L* = 62.97±0.24, a* = -28.41±0.95, and b* = 22.78±1.49, indicative of a moderately bright green appearance characteristic of raw banana peel, wherein the negative a* value confirms the predominance of green pigmentation arising from the high chlorophyll content present in unripe fruit tissue (Pathare *et al.*, 2013) [23]. The total color difference (ΔE = 53.79±0.70) between peel and pulp was substantial, reflecting the markedly distinct pigmentation profiles of the two fractions attributable to differences in chlorophyll and carotenoid concentrations (Aurore *et al.*, 2009). The pulp-to-peel ratio (1.55±0.15), pulp-to-fruit ratio (0.59±0.04), and fruit-to-peel ratio (2.63±0.14) provide quantitative insights into biomass distribution within the fruit and are in reasonable agreement with values reported for similar banana cultivars (Happi Emaga *et al.*, 2007; Patil and Shanmugasundaram, 2015) [24, 13], collectively indicating that peel constitutes approximately 38% of total fruit mass a substantial fraction warranting systematic valorization as a functional food ingredient.

3.2 Physicochemical Properties of Banana Peel Powder

Following hot air drying and grinding, the banana peel powder exhibited substantially altered physicochemical characteristics compared to fresh peel, as summarized in Table 4. Moisture content declined sharply to 5.50±0.10% (wet basis), well below the critical threshold of 14% recommended for safe storage of plant-based powders,

thereby minimizing the risk of enzymatic browning, lipid oxidation, and microbial proliferation during extended storage periods. This reduction is consistent with results

reported by Pathak *et al.* (2017) [23], who observed comparable moisture levels in dried tropical fruit peel powders processed under similar conditions.

Table 4: Physicochemical Properties of Banana Peel Powder (n =3)

S.No	Physicochemical Property	Mean $\pm$ SD
1	Moisture Content - Wet Basis (%)	5.50 $\pm$ 0.10
2	Moisture Content - Dry Basis (%)	5.80 $\pm$ 0.10
3	Bulk Density (kg/m ³)	461.80 $\pm$ 0.45
4	Tapped Density (kg/m ³)	1576.40 $\pm$ 39.83
5	Carr Index	0.71 $\pm$ 0.01
6	Hausner Ratio	3.41 $\pm$ 0.09
7	pH	6.28 $\pm$ 0.06
8	Water Activity (aw)	0.35 $\pm$ 0.003
9	Water Holding Capacity (g/g)	8.74 $\pm$ 0.74
10	Oil Holding Capacity (g/g)	1.79 $\pm$ 0.36
11	Crude Fiber (%)	5.22 $\pm$ 0.43
12	Ash Content (%)	12.00 $\pm$ 0.01

The bulk density increased from 413.00 kg/m³ in fresh peel to 461.80 $\pm$ 0.45 kg/m³ in the powder, while tapped density rose from 1376 to 1576.4 $\pm$ 39.83 kg/m³, reflecting the structural densification that occurs upon removal of free and bound moisture during drying, followed by particle size reduction through milling. However, the Carr Index (0.71 $\pm$ 0.01) and Hausner Ratio (3.41 $\pm$ 0.09) obtained for banana peel powder indicate very poor flowability, as values of Carr Index exceeding 0.40 and Hausner Ratio above 1.6 are generally associated with cohesive, poorly flowing powders Table 3 & 4 (Carr, 1965; Bhadra *et al.*, 2014) [8]. This behavior is attributable to the fibrous and hygroscopic nature of banana peel, which promotes interparticle cohesion and resistance to flow. For industrial applications requiring free-flowing powder characteristics, blending with carriers such as maltodextrin or modification through spray drying may be warranted.

The water activity of the powder was recorded at 0.35 $\pm$ 0.003, a value below the critical threshold of 0.6 at which most microbial growth is inhibited, confirming the microbiological safety and storage stability of the product. The pH remained stable at 6.23 $\pm$ 0.06, comparable to that of the fresh peel, indicating that the drying process did not induce significant acidic or alkaline changes in the material.

The water holding capacity (WHC) of banana peel powder was notably high at 8.74 $\pm$ 0.74 g/g, indicating an exceptional capacity to absorb and retain water relative to its dry mass. This property is primarily governed by the abundance of hydrophilic dietary fiber components, particularly pectin and hemicellulose, which possess a large number of hydroxyl groups capable of forming hydrogen bonds with water molecules. Such a high WHC is advantageous for applications in bakery, meat, and restructured food products, where moisture retention contributes to improved texture, reduced syneresis, and enhanced product yield, as reported by Chantaro *et al.* (2008) [9] for carrot by-product powders with similar fiber composition. The oil holding capacity (OHC) of 1.79 $\pm$ 0.36 g/g, while comparatively lower than WHC, indicates a moderate capacity to bind lipids through physical entrapment within the porous fiber matrix, rendering the powder potentially useful as a fat replacer or emulsion stabilizer in processed food systems.

The crude fiber content of banana peel powder was determined as 5.22 $\pm$ 0.43%, confirming its classification as a dietary fiber-rich ingredient. Dietary fiber intake has been widely associated with beneficial physiological effects

including improved gastrointestinal function, reduced postprandial glycemic response, and lowered serum cholesterol levels (FAO/WHO, 2009). The ash content of 12.00 $\pm$ 0.01% reflects a substantial mineral fraction within the banana peel powder. This elevated ash content has been reported in several studies and is associated with the presence of potassium, magnesium, phosphorus, and calcium in banana peel (Emaga *et al.*, 2007; Anhwange *et al.*, 2009) [11, 3], lending further nutritional significance to this agro-industrial by-product as a potential mineral supplement or functional food ingredient.

4. Conclusion: The present study demonstrates that banana peel, conventionally discarded as agro-waste, possesses a range of physicochemical, functional, and nutritional attributes that render it suitable for valorization as a value-added ingredient. Fresh banana peel was characterized by high moisture content and a near-neutral pH, with structural properties reflective of intact cellular tissue. Upon conversion to powder through hot air drying and milling, significant reduction in moisture content, water activity, and improvement in storage stability were observed, supporting its potential for extended shelf life under ambient conditions. The powder exhibited outstanding water holding capacity and a moderate oil holding capacity, alongside significant levels of crude fiber and ash, collectively establishing its functional merit for incorporation into food formulations. However, the poor flowability indicated by the Carr Index and Hausner Ratio presents a processing challenge that warrants further investigation into particle engineering strategies. Overall, banana peel powder shows considerable promise as a sustainable, low-cost functional ingredient for the development of fiber-enriched and mineral-fortified food products, thereby contributing to the circular utilization of fruit processing by-products.

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