

Physiochemical characterization of dried bamboo leaf powder and its utilisation in the development of value-added products

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Abstract. Bamboo is a very rich and versatile natural resource with great potential for value-added uses. Even though bamboo has a rich chemical composition and fiber content, it is underutilized in most industries. In this research, the physiochemical properties of dried bamboo leaf powder and its possible use in food products were investigated. Bamboo leaves were sourced, oven-dried, and milled into powder, which was added to a baked item, namely cookies, at different levels. Physiochemical characteristics of the powder from dried leaves and the finished product were determined, namely moisture content, protein, fat, ash constitution, and sensory characteristics, according to A.O.A.C. standard procedures. Bamboo leaves contain bioactive molecules in the form of phenolics and flavonoids, providing antioxidant and functionality to make them match increasing trends towards health-focused and sustainable food production. Few researches work, though, are carried out regarding the value addition in dried powder of bamboo leaves incorporated into food. With enhanced process technologies and considering quality traits, the current work aims at optimizing the market readiness of bamboo food products. Results corroborate the sustainability of bamboo leaves as a potential substitute for traditional ingredients and as a means towards environmental and economic sustainability. More research in the future must prioritize the expansion of uses of bamboo in food and bioproduct industries, optimization of processing and consumer acceptance challenges.

KEY WORDS: Elemental analysis, SEM, antioxidant, flavonoids, antioxidants

1. INTRODUCTION

Bamboo is a highly abundant and versatile natural resource that remains significantly underutilized despite its chemical composition and fiber content. The properties of bamboo, such as its high growth rate and ability to adapt to various environmental conditions, provide various ways for its application in various industries, including construction, food production, and biotechnology [1]. In particular, bamboo's utilization extends to the production of high-end commodities like laminated panels and biofuels, as well as being a critical resource for the nutraceutical industry, illustrating its potential to contribute significantly to both economic and ecological sustainability. Moreover, its unique characteristics allow bamboo to serve not only as a building material but also as a food source, providing sustenance for millions of people globally, thus highlighting its critical role in both local and global economies. In addition, bamboo can be processed to yield high-grade dissolving pulp and bioethanol, further emphasizing its economic viability and versatility as a biomass source, while addressing sustainability issues associated with conventional raw materials [2]. Bamboo, a member of the *Poaceae* family, encompasses over 1250

species globally and holds significant economic value, with a 2012 market worth approximately US\$34.2 billion. China and Thailand in Asia particularly, dominates the bamboo market on global scale. On the other hand, where the global forest areas have declined, bamboo forests have increased by 3% annually. Brazil holds one of the largest bamboo reserves, containing a significant portion of American bamboo species [3].

Furthermore, the multifaceted uses of bamboo underscore the importance of developing strategies that optimize its processing methods, particularly in overcoming challenges such as the presence of silica that can hinder industrial applications, thus paving the way for a more sustainable and efficient utilization of this valuable natural resource. The escalating demand for eco-friendly materials in various sectors has positioned bamboo as a viable and sustainable alternative, offering not only rapid growth rates but also a diverse range of applications that can meet contemporary environmental and economic needs [1]. This is particularly relevant in the construction and materials manufacturing industries, where bamboo's unique properties, such as its high strength-to-weight ratio and resistance to weathering, have made it an increasingly attractive substitute for conventional building materials.

Additionally, the ability of bamboo to flourish in diverse climates while requiring minimal agricultural inputs further enhances its appeal as a sustainable building material, fostering a shift towards more environmentally responsible practices in the industry [4]. Bamboo leaves exhibit a diverse range of morphological, chemical, and functional characteristics, which are crucial to consider for their effective utilization. The leaves are typically large, thin, and green in color, showcasing a hierarchical structure composed of specialized tissues such as fibers and vascular bundles. This complex leaf anatomy contributes to the unique physical and chemical properties of bamboo leaves, which can vary considerably depending on factors like bamboo species, harvesting season, and methods employed for drying [5].

By considering these physiochemical attributes, the optimization of the extraction process of bioactive compounds will enhance the quality and functionality of value-added products derived from bamboo leaf powder. Understanding of the physiochemical properties of dried bamboo leaf powder is essential to formulate products and ensure the successful application of this resource in various industries, including food and nutraceuticals, as specific attributes such as nutrient composition, functional characteristics [6], and safety profile like cytotoxicity and allergic reactions must be thoroughly evaluated. Furthermore, a detailed characterization of these characteristics will facilitate the design of effective processing techniques and optimize formulations, leading to the creation of high-value products that meet consumer demands and regulatory standards, thereby enhancing the marketability of bamboo leaf powder as a viable ingredient or raw material.

The growing interest in utilizing various parts of the bamboo plant, particularly the leaves, stems from their potential contributions to both sustainability and economic diversification, as they can be processed into value-added products such as animal feed, herbal remedies, and bioplastics, which further supports the case for bamboo as a multifunctional resource that can play a crucial role in addressing ecological challenges while providing economic opportunities for communities dependent on this versatile plant [7].

Furthermore, the leaves, often considered agricultural waste, can be harvested sustainably and transformed into innovative products, promoting a circular economy approach that maximizes resource efficiency and minimizes environmental impact, thus reflecting the growing recognition of bamboo's versatility and potential in both local economies and global sustainable development initiatives [7]. Traditional uses of bamboo leaves include their incorporation into local culinary practices as

wrappers for food, as well as their employment in traditional medicine practices, where they are believed to possess various health benefits, including anti-inflammatory and antioxidant properties, demonstrating the cultural significance and diverse applications of this abundant natural resource [8]. Moreover, bamboo leaves have been utilized in various cultural rituals and artisanal crafts, highlighting their integral role in the heritage and livelihood of communities that depend on this valuable plant throughout generations, thus further enhancing the narrative of bamboo as a vital resource that transcends its utilitarian applications [9]. Recent trend in the exploration of transforming raw materials into higher-value products is one of the key research areas in food sciences [9].

For this purpose, food scientists often explore various underutilized sources of food value. Value addition plays a critical role in maximizing the economic potential of bamboo, as it involves converting raw bamboo leaves and other parts into higher-value products through innovative processing techniques and sustainable practices, thereby fostering economic growth and promoting more efficient resource utilization within the bamboo sector [6], conducted a research on the supplementation of bamboo powder in cookies. This transition towards value-added products aligns with contemporary global trends that emphasize sustainability, circularity, and the development of eco-friendly alternatives to conventional materials therefore, positioning bamboo as a versatile and invaluable resource that can contribute to these broader environmental and economic objectives [3].

This approach not only enhances the profitability of bamboo-related enterprises but also supports rural development and provides employment opportunities for local communities, thereby reinforcing the role of bamboo in promoting sustainable livelihoods and regional economic resilience. Despite the numerous potential applications of bamboo leaves, research specifically focused on the value addition of dried bamboo leaf powder remains limited. There is a significant gap in the literature that requires further exploration, particularly in terms of its nutritional benefits, processing methods, and market opportunities [10].

Addressing this knowledge gap could unlock new research options for the sustainable and economically viable utilization of this abundant biomass resource, fostering the development of innovative food, pharmaceutical, and biotechnological applications that leverage the unique properties of bamboo leaves [9].

2. MATERIALS AND METHODS

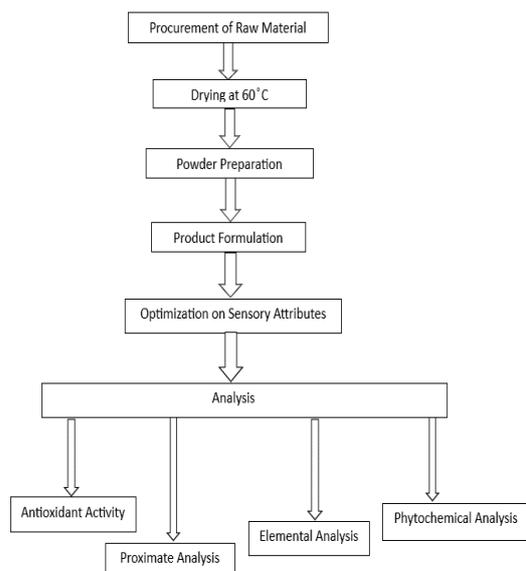


Figure 1: Flowchart of bamboo leaf powder cookie development and analytical procedures.

2.1 Procurement of Raw Material

Bamboo leaves were procured from the available sources and oven drying was performed due to the ease of the process and rapidity. Dried leaves were kept in a desiccator for excess moisture removal. The dried leaves then grinded and formed into powder. The dried material is stored in airtight packets for further use.

2.2 Development of value-added products:

For the development of value-added product baking product preferably cookies were formulated by incorporating different levels of bamboo leaf powder.



Figure 2: Control Sample (wheat flour cookies)



Figure 3: Cookies with different levels of bamboo leaf powder.

2.2.1 Physiochemical characterization of dried leaves and formulated product

To evaluate the quality characteristics of the developed product, parameters such as color, texture, sensory attributes, and nutritional profile were assessed for their acceptability and suitability for commercialization. Physiochemical characterization of the dried bamboo leaf powder, including the determination of its protein, fat, ash, and moisture content, was performed using standard methods [12].

2.3 Methods

2.3.1. Drying method

The standard method for moisture determination using a hot air oven can be summarized in three key steps. Weigh a predetermined quantity of the sample in a tray or dish. Place the dish in a hot air oven at 105 °C for a specified time (typically 3-6 hours) until a constant weight is achieved. Transfer the dried sample to a desiccator, cool to room temperature, and weigh immediately.

2.3.2 Proximate Analysis

It is a common procedure to analyse the major nutritional content of flour. It has six major constituents analyzed by different techniques. Analyzed by heating in a hot air oven (105°C ± 2°C) to constant weight. Crude Protein is determined by the Kjeldahl process [12], where nitrogen is calculated and converted into protein by using a factor (most often 6.25). Crude Fat is obtained by the Soxhlet extraction process with solvents such as petroleum ether. Crude Fiber is calculated by acid and alkali treatment of the sample to remove the digestible parts, so only indigestible fiber is left. Ash Content is determined by burning the sample in a muffle furnace at 550-600°C, with the remaining only inorganic minerals.

2.3.3. Antioxidant activity (DPPH ASSAY)

Prepare a DPPH stock solution in methanol or ethanol. Protect from light. Use a spectrophotometric-grade solvent. DPPH is light-sensitive. Dilute the stock to the desired concentration (often 0.1 mM). Check absorbance at 517nm. Prepare the working solution daily. Prepare samples and positive control (e.g., ascorbic acid) at

various dilutions in a suitable solvent. Combine samples and controls with an equal volume of DPPH working solution. Include a solvent-only blank. Incubate in the dark for a set time (e.g., 30 minutes). Measure the absorbance of each reaction at 517 nm using a spectrophotometer [10]. Zero the spectrophotometer with the blank. Calculate the % scavenging activity for each sample. Determine IC50 values. Correct for any significant background absorbance of the samples.

2.3.4. Elemental Analysis

Techniques are utilized to ascertain the elemental content of food, feed, and other material. Carbon, Hydrogen, Nitrogen, and Sulfur (CHNS) Analysis is conducted on a CHNS analyzer, in which the sample is burned, and the resultant gases (CO₂, H₂O, N₂, SO₂) are quantitated [13]. Atomic Absorption Spectroscopy (AAS) is applied to determine trace metals and minerals (e.g., iron, calcium, zinc) by measuring light absorption in a flame or graphite furnace. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is more sophisticated method that detects elements at ultra-trace concentration, frequently utilized for the determination of heavy metals (e.g., lead, arsenic, cadmium).

2.3.5. Phytochemical Analysis Methods (A.O.A.C 2019)

It helps in identifying and quantifying bioactive compounds in plant-based foods. The common methods. Alkaloids are detected using Mayer's test and Wagner's test (formation of precipitate). Flavonoids are identified by the Shinoda test (color change with magnesium and HCl). Phenols & Tannins are Ferric chloride test (blue-black or greenish colour). Saponins are Foam test (persistent froth formation).

3.RESULTS AND DISCUSSION

3.1 Proximate composition

The proximate composition of the control sample (wheat flour), bamboo leaf powder, and final product (cookies) shows rich nutritional enrichment on the addition of bamboo leaf powder. The water content of bamboo leaf powder is very low (4.51%) as compared to wheat flour (12.38%), giving rise to lower water content in the final product (5.70%). This reduction is beneficial as it results in enhanced shelf life and enhanced microbial safety of the cookies. A drastic increase in the total ash content, from 0.50% in wheat flour to 6.01% in cookies, demonstrates the existence of an amply endowed mineral profile in bamboo leaves such as calcium, magnesium, potassium, and other trace minerals. Not only does it increase nutritional content but also introduces potential health benefits.

Carbohydrate content decreases from 73.30% in wheat flour to 55.43% in cookies due to the much lower carbohydrate content of bamboo leaf powder (34.20%). Decrease can be advantageous for low

glycaemic index food-needing patients or carbohydrate restrictive diet patients. The most important quality is in terms of fibre content, which more than doubles from 2.73% for the control sample to 29.01% for the finished product. Leaves of bamboo contain dietary fibres naturally, which can maintain the well-being of intestines, promote blood sugar level regulation, and bring about a sense of satiety. Protein levels also get enhanced from 13.49% in the wheat flour case to 16.34% in the cookies due to enhanced protein levels in bamboo leaf powder (18.22%). Further, the fat level of the final product is significantly reduced (1.88%) compared to wheat flour (4.84%), as bamboo leaf powder contains little fat (1.43%), thereby enhancing the applicability of cookies for low-fat diets.

Generally, the incorporation of bamboo leaf powder makes the cookies a more functional and more nutritious product with increased dietary fiber, protein, and mineral contents but reduced undesirable components like fat, unnecessary carbohydrate, and water. This gives bamboo leaf powder as a value-added ingredient that can be harnessed to produce healthier and value-added bakery foods for meeting new consumer demands for healthy and functional foods.

Table 1: Proximate analysis of bamboo leaf powder and cookies.

Proximate analysis	Control Sample	Bamboo Leaf Powder	Cookies
Moisture	12.38%	4.51%	5.70%
Total Ash	4.51%	5.25%	6.01%
Carbohydrates	73.30%	34.20%	55.43%
Fibre	2.73%	27.20%	29.01%
Protein	13.49%	18.22%	16.34%
Fat	4.84%	1.43%	1.88%

3.2 Elemental analysis

The composition of elements of the control sample (wheat flour) and bamboo leaf powder gives insightful data regarding mineral composition and nutrient contribution by using bamboo leaves as a food item additive in a cookie. The calcium content in wheat flour is 500 mg/kg, while in bamboo leaf powder it is 5.20 µg/g (which is the same as 5200 µg/kg or 5.2 mg/g), with the latter showing significantly higher quantities in the bamboo leaves. Calcium plays a crucial role in bone development and muscle contraction, and the higher concentration in bamboo leaves adds to the mineral content of the end product. Potassium is also found in wheat flour at 2800 mg/kg (2.8 mg/g), while it is present in bamboo leaf powder at 3.97 mg/g, which is higher once again. Potassium is also crucial in keeping electrolyte balance and functioning of the

cardiovascular system. Iron content required for oxygen transport and anaemia prevention in wheat flour is 84 mg/kg, while bamboo leaf powder has 4.03 µg/g (4.03 mg/kg) with a lower concentration. Nevertheless, when used in combination with other iron sources, bamboo leaf powder can still be a contributing factor in iron supply. Magnesium, crucial in muscle contraction as well as in energy metabolism, is found in wheat flour at 600 mg/kg, but bamboo leaf powder has only 5.02 µg/g (5.02 mg/kg), much lower. Zinc, crucial in immune function as well as enzyme functioning, is found to be richer in wheat flour (30 mg/kg) than in 1.56 µg/g (1.56 mg/kg) in bamboo leaf powder. Copper, a trace element to which cardiovascular and nervous system wellness is essential, is 20 mg/kg in wheat flour but only 0.012 µg/g (0.012 mg/kg) in bamboo leaf powder. In addition to the leaf, bamboo shoot has previously been studied for its good mineral content.

Placing these mineral results in perspective by comparing them to the preceding proximate analysis provides a picture of general nutrition. The sudden rise in the total ash content of the end cookies (6.01%) compared to wheat flour (0.50%) is due to the mineral content of bamboo leaf powder, specifically its high calcium and potassium content. Therefore, while certain minerals such as iron, magnesium, zinc, and copper are lower in bamboo leaf powder, the overall contribution is beneficial to the nutritional value of the cookies. This agrees with the employment of bamboo leaf powder as a functional food component, which agrees with the enhancement reported in protein, fibre, and mineral composition in the proximate analysis.

Table 2: Elemental Analysis.

Elemental analysis	Control Sample (wheat flour)	Powder results
Calcium	500 mg /kg	5.20 ug/g
Potassium	2800 mg/kg	3.97 mg/g
Iron	84 mg/kg	4.03 ug/g
Magnesium	600 mg/kg	5.02 ug/g
Zinc	30 mg/kg	1.56 ug/g
Copper	20 mg/kg	.012 ug/g

3.3. Antioxidant activity and Phytochemical analysis

Antioxidant activity and phytochemical composition in wheat flour and bamboo leaf powder vary considerably in favour of suggesting the possibility of using bamboo leaf powder as a functional food component to enhance nutritional and health-giving value in food.

3.3.1. Antioxidant Activity (DPPH Assay)

Bamboo leaf powder contains 207.01 µmol of DPPH radical scavenging activity, exhibiting intense antioxidant activity. Wheat flour has very poor antioxidant activity; scavenging activities of approximately 9.25% to 13.8% have been reported by researchers. This massive discrepancy indicates greater antioxidant capacity in the bamboo leaf powder [9].

3.3.2. Total Phenolic Content (TPC)

Bamboo leaf powder is 84.02 mg GAE/g, which is significantly more than that of wheat flour's. TPC of wheat flour has values ranging in accordance with literature published from 0.885 mg GAE/g. Increased phenolic content of bamboo leaf powder accounts for greater antioxidant activity. Use of bamboo leaf extract improves antioxidant capacity in broilers.

3.3.3. Flavonoids

Contents of flavonoid in bamboo leaf powder are 82.40 mg CE/g, whereas in wheat flour lesser amount comparatively. Different researchers have estimated flavonoids content in wheat flour from 0.112 mg CE/g to 0.007 mg CE/g. Flavonoids are classified according to antioxidant and anti-inflammatory activity, therefore, bamboo leaf powder will be able to transfer great improvement in these characteristics in foods.

3.3.4. Alkaloids

Bamboo leaf powder contains 3.07% alkaloid differs from the roughly 0.62% in wheat flour. Alkaloids exert different physiological effects, which indicate a humongous difference between the two ingredients. Previously. Bamboo shoot has been extensively studied for its nutritional composition.

Table 3: Antioxidant Activity and Phytochemical Analysis.

Assay/ Compound	Control Sample (Wheat Flour)	Bamboo Leaf Powder
DPPH Assay	11.8%	207.01 µmol
Total Phenols	0.825 mg GAE/g	84.02 mg GAE/g
Flavonoids	0.009 mg CE/g	82.40 mg CE/g
Alkaloids	0.62%	3.07%
Tannins	0.46%	0.72%
Saponins	0.02%	0.42%

3.3.5. Tannins and Saponins

Bamboo leaf powder has 0.72% tannin and 0.42% saponins. Wheat flour has the lower tannin levels of 0.46% and saponins of 0.02 %. Tannins are reported to possess antioxidant activity, and saponins have a possible health activity such as cholesterol lowering. Addition of bamboo leaf powder to food items such as cookies is likely to enhance their antioxidant

activity and phytochemical value significantly and can lead to additional health effects in addition to nutrition.

3.4 Microstructure analysis (SEM)

The SEM microstructural analysis of powder of dried bamboo leaves [14] gives very significant information about its functional nature, which is supported by the nutritional and phytochemical facts. Surface morphology of the powder is fibrous and irregular due to mechanical grinding process of mature bamboo leaves. This is also clear from the high crude fiber content (27.20%), which in general indicates the occurrence of structurally intact cellulose and lignin-containing materials that are resistant to degradation. Such fibrous particles typically occur under SEM as rough, elongated, and jagged fragments with low sphericity, which confirms their origin from vascular tissues and sclerenchymatous structures of the leaf. This morphology is among the causative factors for the functional benefit of the powder on incorporation into food matrices, specifically in improved textural functionality and water holding capacity in biscuits. Porosity and lamellated character which are typical in dried leaf powders reflect effective drying or water loss that is confirmed by low moisture content (4.51%) of the sample.

These porous structures, appearing on SEM as surface fissures or open-cell networks, allow reabsorption of moisture upon mixing or baking and consolidate the powder as hydrophilically compatible. Additionally, cell wall breakage and fragmentation, observed as fractured cellular matrices on SEM, are caused by drying and pulverization processes.

This disturbance enhances the bioavailability of intracellular nutrients such as proteins (18.22%) and carbohydrates (34.20%), meaning that SEM would exhibit partially collapsed or distorted cells, typically accompanied by cytoplasmic residue scattered on the surface. The other characteristic appearance in SEM imaging of mineral-enriched plant powders is microcrystalline structures or deposits. Bamboo leaf powder, with respect to its elemental analysis (e.g., calcium 5.20 $\mu\text{g/g}$, iron 4.03 $\mu\text{g/g}$, magnesium 5.02 $\mu\text{g/g}$), may have such properties as discrete, shiny spots, typical of crystallized or adsorbed mineral elements on the particle surface. Such surface deposits not only confirm the mineral density but also influence the electrostatic and colloidal behavior of the powder during food processing. The antioxidant capacity measured by DPPH assay (207.01 $\mu\text{mol Trolox/g DW}$) and the total phenol content (84.02 mg GAE/g) also suggest that phenolic compounds may form surface layers or be present as granular residues on the particle surface as observed by SEM, typically found with the ruptured cellular compartments. In general, microstructure of dry bamboo leaf powder, as can be anticipated under SEM, fits well with its

rich fiber content, effective drying characteristic, enrichment in minerals, and high antioxidant capacity. The shoot of bamboo has different characteristics relative to dried leaf. The microstructural characters are consistent with its functional role in the preparation of functional food for texture change, fiber enhancement, and contribution to health, formulation [15].

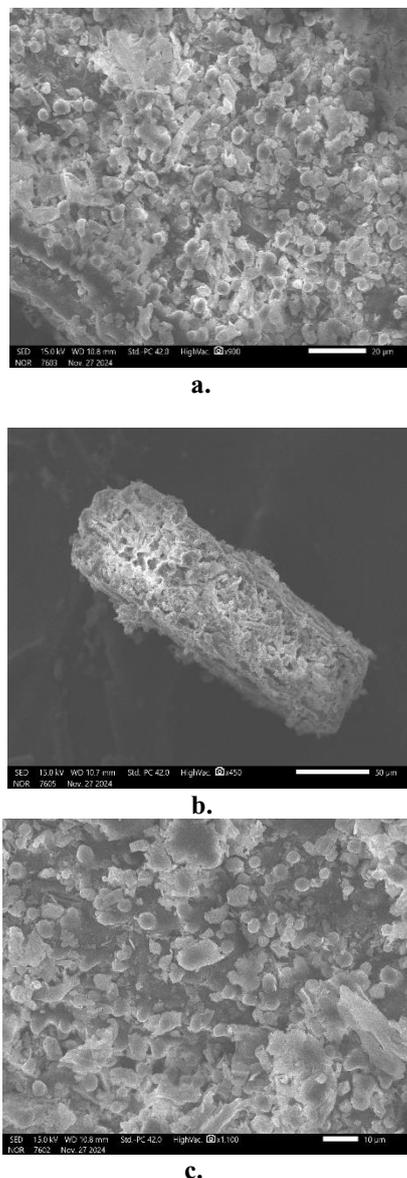


Figure 4: (a-c) Microstructure of dried bamboo leaf powder

4. CONCLUSION

Bamboo, a versatile and fast-growing Poaceae family member, is underutilized despite the richness of its chemical composition and promise in multiple industries. Bamboo leaves, one of its parts commonly treated as agricultural waste, have promising functional, nutritional, and antioxidant characteristics for value-added product applications.

It centres on the physiochemical, nutritional, and functional characterization of dried bamboo leaf powder and its use in cookie applications as a functional food ingredient. Dehydrated bamboo leaves were treated to powder and were examined for proximate analysis, elemental composition, antioxidant content, and phytochemicals following standard A.O.A.C. and FSSAI procedures. Bamboo leaf powder showed better nutritional properties than wheat flour in the form of higher fibre (27.20%), protein (18.22%), and mineral contents, specifically calcium (5.20 µg/g) and potassium (3.97 mg/g). The addition of the powder to cookies greatly improved their functional profile—increasing fiber to 29.01%, protein to 16.34%, ash to 6.01%, and decreasing fat and carbohydrate content. The antioxidant activity, as assessed by the DPPH assay, was 207.01 µmol in the powder and 349.07 µmol in the cookies, indicating the bioactive potential of the leaves. Phytochemical analysis indicated highly increased contents of total phenolics (84.02 mg GAE/g), flavonoids (82.40 mg CE/g), and alkaloids (3.07%) as compared to wheat flour. SEM microstructural analysis validated fibrous morphology, porous architecture, and mineral crystallization—characteristics improving water-holding capacity and nutrient bioavailability. These results highlight the value of bamboo leaf powder as a sustainable, high-nutrient ingredient that can be used in functional food innovation. Its use in bakery foods is consonant with prevailing global trends promoting circular economy, sustainability, and health-oriented dietary innovation. Additional studies and commercialization efforts may convert this biomass into high-value in food, nutraceutical, and biotechnology applications.

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