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Banana Pseudostem as a Promising Agricultural Byproduct for Food Applications

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Abstract

Bananas produce a significant amount of agricultural waste, especially the pseudostem, which make up about 60–75% of post-harvest biomass. Abstract: Overview of the banana pseudostem valorisation as an affordable secondary crop with great potential for food production in the context of the circular bioeconomy. The pseudostem shows an extraordinary nutritional composition with 27–70% of dietary fiber (soluble and insoluble fractions), high amounts of the minerals potassium (up to 38 mg/100 g), calcium, and magnesium, as well as phenolic compounds with strong in vitro antioxidant potential. However, more advanced processing, such as drying, enzymatic extraction, ultrasonic extraction, and microencapsulation process are required to convert this food-by-product into functional food ingredients. Promising applications include bakery items, gluten-free products, meat products as a natural binder, as well as functional beverages and natural texturizers, showing better nutritional properties or sensory acceptance [6]. The pseudostem offers substantial health benefits such as improved intestinal health, increased cholesterol-lowering capabilities, blood glucose regulation, and anti-inflammation.Property of Naturopathic Approaches in the Treatment of Women — January 1, 2023 | By Dr. Our economic and environmental analyses show that there are significant benefits related to waste reduction, support for the circular economy, greenhouse gas emission reductions, revenue generation for smallholder farmers, and more. High moisture content (90–95%), storage difficulties, compositional heterogeneity across cultivars, imbedded technical extraction, and consumer acceptance obstacles still plague this otherwise attractive feedstock. This review incorporates recent cutting-edge research, showcasing banana pseudostem as a novel food ingredient which can convert from agricultural waste into a highly bioconverted food ingredient with high-scoring human nutritional value, thus significantly contributing to sustainable food systems, circular bioeconomy and United Nations Sustainable Development goals.

Keywords: Banana pseudostem, Agricultural waste valorization, Dietary fiber, Functional foods, Sustainable food systems, Circular bioeconomy

I. Introduction

Banana (Musa spp.) is one of the most economically important fruit crops in the world, with a production of around 125 million tons/year in 2021, grown in over 150 countries across tropical and subtropical areas (Pillai et al., 2024). Bananas are a major source of food security for over 400 million people around the globe, making them the 4th most important staple crop worldwide (Pillai et al., 2024; Padam et al, 2014). India is the leading producer with over 34.9 million tons of annual production accounts for 26.7% of world production, followed by China, Indonesia, Brazil, Ecuador, and the Philippines (Alzate et al. 2021; FAO 2020). Because of the growth behaviour, high productivity, and the presence of cultivation all year round is a distinctive feature of banana plant, making banana valuable to be a temporary crop for the farmers, either small-scale or large-scale commercial (Thongpak et al., 2024).

Nevertheless, massive volumes of agricultural biomass waste are produced as a result of banana cultivation as it poses serious economic and environmental problems. Bananas are monocarpic; each pseudostem produces only one bunch of fruit, and pseudostems are cut down after harvest (Romero-Cárdenas et al.,

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2025). Recent data show that now we harvest around 1 ton of banana fruit for every 4 tons of banana agricultural residue (Alzate et al., 2021; Yasin et al. 2025). The pseudostem accounts for approximately 60–75% of total biomass after harvesting, resulting in over 114 million metric tons of organic waste every year globally (Alzate et al., 2021; Pillai et al., 2024; Balda et al., 2021).

Banana pseudostem is immensely needs to the environment in the case of its disposal. Conventional disposal methods are largely limited to natural decomposition of pseudostems in plantation fields, or open burning, which is one of the major environment-related issues (Kumari et al., 2025) This causes pest infestations, plant diseases and considerable greenhouse gas emission due to the creation of methane and carbon dioxide during anaerobic decomposition during natural decomposition (Alzate et al. 2021; Wang et al. 2024). Transportation and disposal of fresh pseudostems gets complicated due to their extremely high moisture content (90–95%) (Alzate et al., 2021; Majumdar & Jagadale, 2023).

Agricultural waste valorization is a key concept of circular bioeconomy that is turning materials that were previously seen as waste into resources (Romerocárdenas et al., 2025; Alzate et al., 2021; Teigiserova et al., 2020). In terms of the United Nations Sustainable Development Goals (SDGs), this approach resonates strongly with SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) because it enables the mitigation of environmental pollution, generates usufructs to agricultural communities, and incites patterns of sustainable consumption (Alzate et al., 2021; Kumari et al., 2025; UNDP, 2024). Increasingly, circular economy approaches are recognized by a number of global initiatives focused on reducing food waste, including the U.S. National Strategy for Reducing Food Loss and Waste (U.S. EPA, 2024).

Banana pseudostem has been recently characterized for its nutritional and functional attributes (Pillai et al., 2024; Moretti et al., 2025; Li et al., 2022). Dietary fibre, followed by minerals (potassium, calcium, magnesium), phenolic compounds with proven antioxidant effects, and other active substances are major components of the pseudostem (Pillai et al., 2024; Saikia et al., 2025). Recent investigations provide evidence that pseudostem when properly processed can be used as a functional food ingredient in bakery items, meat doses, gluten-free products, functional beverages and as natural texturizers (Pillai et al.

The present review document integrates the entirety of scientific data related to the exploitation of banana pseudostem as a food material, covering its botanical architecture, chemical composition, processing methods, prospective applications, health benefits, economic feasibility, environmental sustainability, and implementation problems. This paper aims at promoting the sustainable use of banana agrowastes and circular economy initiatives in agriculture by reviewing the scientific knowledge generated from peer-reviewed literature from 2020 to 2025 (Zhang et al., 2024; Zhou et al., 2024), using recent publications as an example; where the argue the utilization of banana pseudostems, leaves, and fruits for value-added products.

II. Botanical Structure and Chemical Composition

Structural Overview

The closest structure in banana to a tree is the pseudostem, yet this is an entirely different type of organ that makes clear the difference between a banana and a real tree. The banana pseudostem is not a true stem with woody vascular tissue; rather, it is a false stem formed by a series of leaf sheaths creeping up from an underground corm (Pillai et al., 2024; Kumari et al., 2025). It can achieve one of the tallest of the structure, up to 6-8 meters with 15-30-centimeter diameter at basal (Pillai et al., 2024; Othman et al., 2020). Figure 1: Parts of thePsuedostem of a banana tree (Inner to outer).

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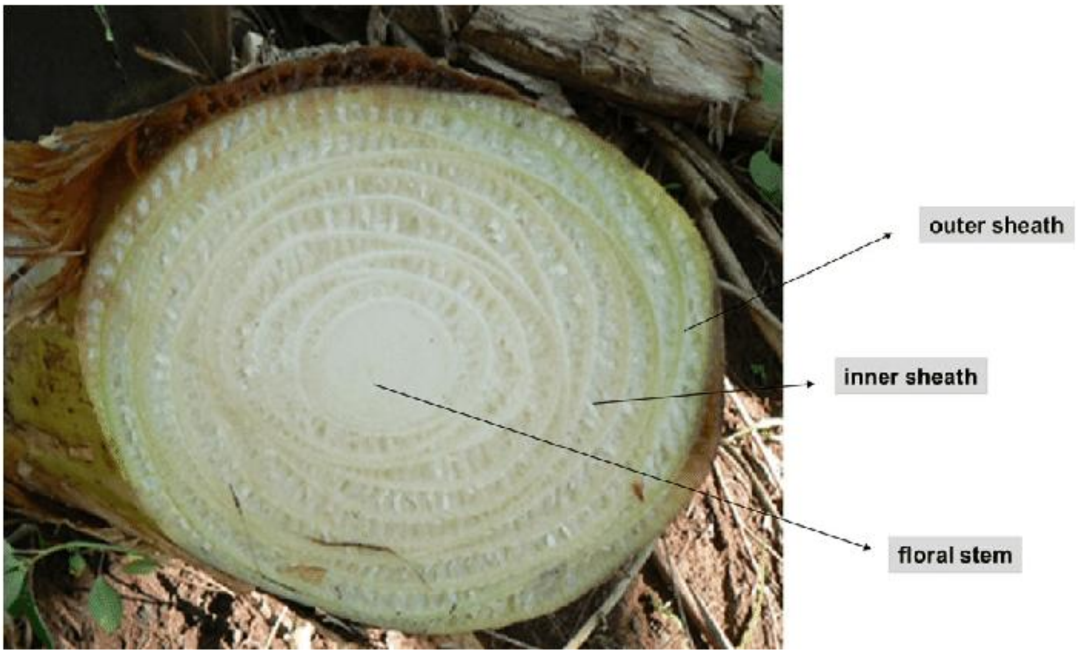

Figure 1: Banana tree pseudostem parts (from inner to outside) (Pinheiro et al., 2019)

It shows that at cross-sectional level three major anatomical zones are identified (Kumari et al., 2025). The most distal layers are typically more fibrous and mechanically robust, and contain much higher amounts of lignified structural fibers for fiber extraction applications (Romero-Cárdenas et al., 2025; Thongpak et al., 2024). The vascular tissue in the intermediate zone is specialized for the transport of water and nutrients across the plant architecture (Kumari et al, 2025). The innermost core is mostly made out of parenchyma tissue with phosphor levels that regularly exceed 95% of moisture in fresh pseudostems (Saikia et al., 2025; Pillai et al, 2023). This soft nature makes the inner core much more easily mechanically processed for food applications (Saikia et al., 2025; Muralikrishna et al., 2020). The chemical characterization of the banana pseudostem, the banana pseudostem, is presented in Table 1.

Table 1: the Chemical properties of banana pseudostem (Islam et al., 2023)

Chemical characters	**Banana pseudostem**	
	Non-enriched sap	**Enriched sap**
pH	5.29 ± 0.12	3.00 ± 0.09
EC (µS cm⁻¹)	6.47 ± 0.20	-
Total N (g L⁻¹)	4.25 ± 0.15	200 ± 9.21
Total P (g L⁻¹)	0.92 ± 0.02	66.31 ± 4.17
Total K (g L⁻¹)	1.92 ± 0.04	123 ± 5.40
Total Ca (mg L⁻¹)	6.0 ± 0.21	49.05 ± 2.47
Total Mg (mg L⁻¹)	83.39 ± 3.80	83.39 ± 4.78
Na (mg L⁻¹)	2.30 ± 0.08	2.30 ± 0.11
Cu (mg L⁻¹)	2.5 ± 0.10	2.5 ± 0.13
Zn (mg L⁻¹)	1.0 ± 0.03	1.0 ± 0.05
B (g L⁻¹)	0.25 ± 0.01	3.25 ± 0.13

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Fiber Content and Composition

The main nutritional component of the banana pseudostem is fibre. Total fiber content can differ a lot based on cultivar differentiation, maturity stage, and testing methods with reported values widely ranging from 27 to 70% dry weight basis (Pillai et al. 2024, Saikia et al. 2025). Banana pseudostem consists of high levels of soluble and insoluble dietary fiber, and insoluble dietary fiber (IDF) usually accounts for 70–85% of total dietary fiber (Li et al., 2022; Pillai et al., 2024).

Cellulose content varies between 27–52.4%, depending on cultivar variety, with significantly higher cellulose content being found in the Nanica cultivar (52.4%) than the Maçã cultivar(27.0%) (Moretti etal 2025). Hemicellulose content accounts for 25–34% of the pseudostem dry weight (Moretti et al., 2025). Lignin accounts for 5–10% of pseudostem, with higher concentrations found in outer sheaths (Alzate et al., 2021). The proportion of resistant starch in pseudostem carbohydrates depends on the cultivar and the processing conditions, causing its value to be between 2.7 and 16.7% (Moretti et al., 2025; Reynolds et al., 2020). Fig. 2 provides the layers of banana fibers from the pseudostem.

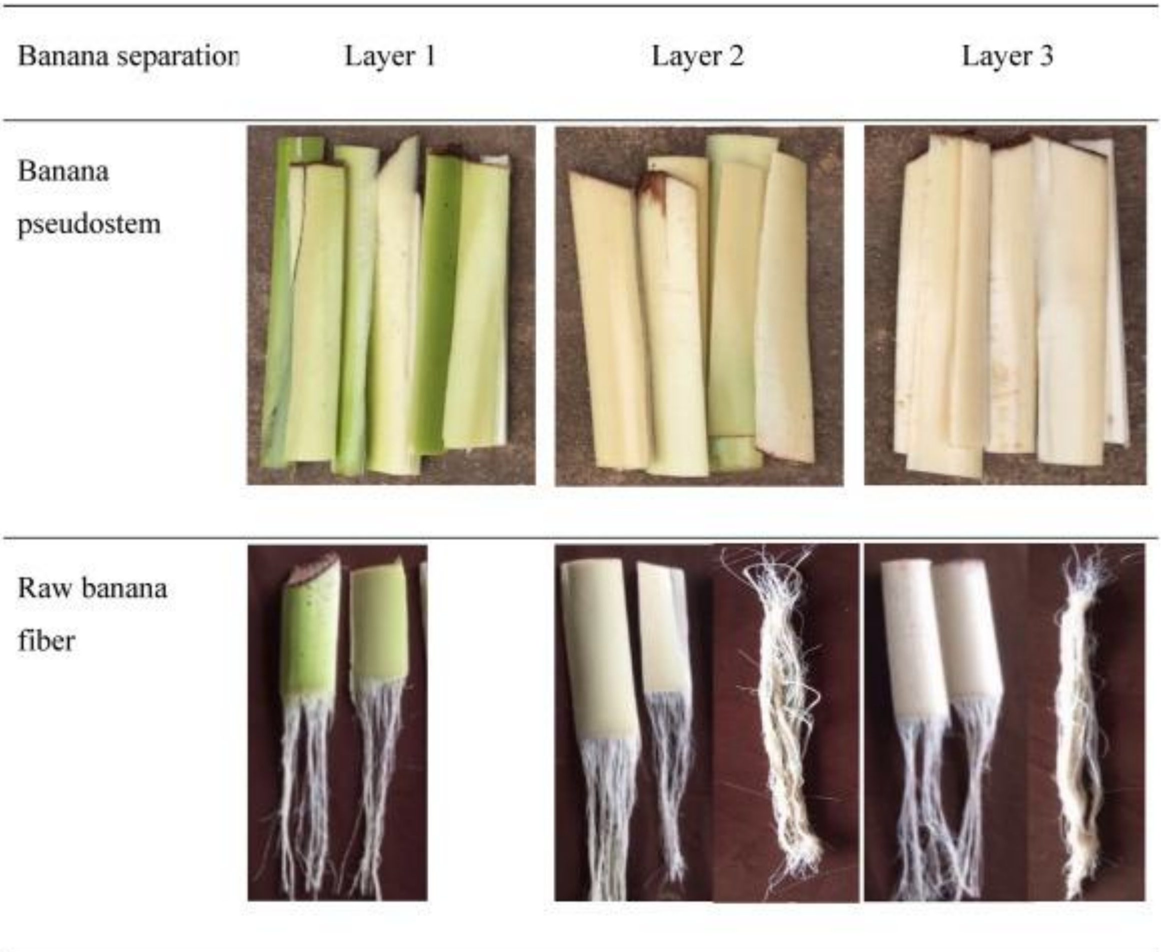

Figure 2: offers the pseudostem layers of banana fibers (Ruangnarong et al., 2024)

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Mineral Content and Micronutrients

Pseudostem of banana can be a rich source of vital minerals (Li et al., 2022). Contrarily, potassium, the most abundant mineral, specially in some varieties (30–38 mg/100g), which can offer some health benefits regarding blood pressure regulation and maintenance of body mollifies (Li et al., 2022; Sharma et al., 2021). The calcium content varies between 80–122 mg/100g based on all cultivars (Li et al., 2022). Different cultivars contain 15–39 mg/100g Mg (Li et al., 2022). Phosphorus content is about 10–25mg/100g, and trace minerals such as manganese, iron, zinc, and copper are also present in nutrition relevant quantities (Li et al., 2022, Pillai et al., 2024).

2.4 Phenolic Compounds and Antioxidant Capacity

The specific phenolic compounds present in banana pseudostem constitute its antioxidant properties (Pillai et al., 2024; Gayathry & John, 2023). The total phenolic content has been reported to vary greatly as per the cultivars of pomegranate used and different methods of extraction (Moretti et al., 2025; Gayathry & John, 2024) between 153.5 and291 mg gallic acid equivalents (GAE)/g of extract. They include gentisic acid, protocatechuic acid, gallic acid, caffeic acid, trans-cinnamic acid and trans-ferulic acid, and syringic acid (Gayathry & John, 2024; Naveed et al., 2018).

Different in vitro antioxidant assays show high capacity to scavenge free radicals, with DPPH radical scavenging capacity ranging from 70-92%, ABTS radical scavenging activity of 82-91%, and FRAP values of 2.0-3.5 mmol Trolox equivalents per gram extract (applying different conditions and cultivars) (Gayathry & John, 2023; Sharma et al., 2021). Methanol extracts show 65–85% metal chelating activity which indicates considerable binding capacity toward the pro-oxidant transition metals (Gayathry & John, 2024). Apart from antioxidant function, banana pseudostem bioactivities exhibit significant antimicrobial effects against diverse pathogenic bacteria, with reported MIC values between 250–1000 µg/mL (Pillai et al., 2024; Tai et al., 2012). Figure 3 Proposed mechanism of antioxidant action of phenolic compounds in banana byproducts.

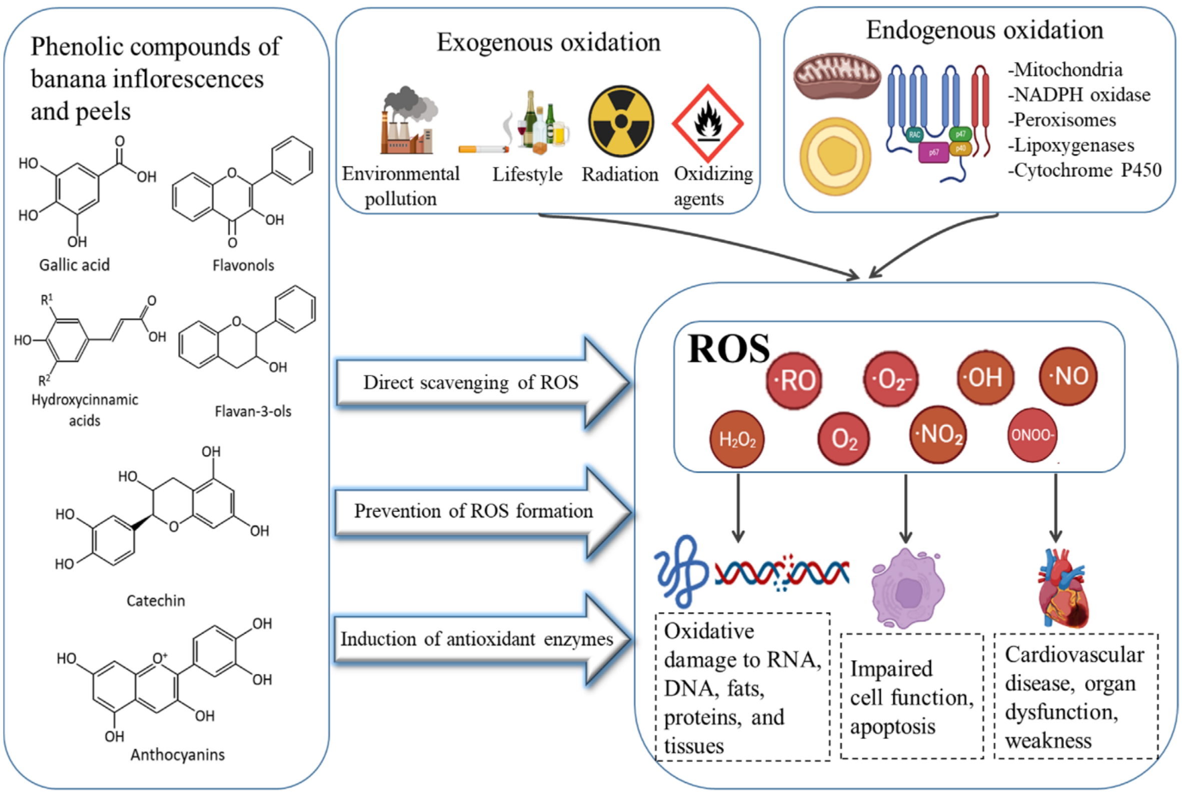

Figure 3: the mechanism of antioxidant action of phenolic compounds in banana by-products is proposed (Zou et al., 2022)

III. Processing and Preparation Methods

3.1 Drying Technologies

Drying is the most basic processing step in the transformation of fresh banana pseudostem into stable food raw materials (Suhaimi et al., 2022; Pillai et al., 2024). The non-conventional moisture content as high as 90-95% essentially requires immediate drying intervention to avoid rapid microbial spoilage within 24-48sthe post-harvest period (Saikia et al., 2025).

Contextual drying in a cabinet without blanching at 50°C yields the shortest drying time (8-12 hours) with maximal color retention and nutrient preservation (Suhaimi et al., 2022) More sensitive heat labile bioactive compounds are better preserved at lower drying temperatures (40°C), and pseudostem dried at 40°C with blanching showed high resistant starch contents (18-22%) (Suhaimi et al., 2022). The effect of blanching pretreatment upstream of preservation is mixed as it would effectively inactivate some of the enzymes that cause browning [12], but also leaching the water-soluble nutrients leading to a 10–15 and 15–20% decrease in total phenolic content and mineral contents respectively (Suhaimi et al., 2022).

Spray dry technology has the benefits to develop microencapsulated bioactive compounds from pseudostem extracts (Gayathry & John, 2024). The encapsulated powders achieved 75 wt% encapsulation yields and retention efficiencies of greater than 70 wt% and are characterized by inlet air temperature of 140-160 °C, feed flow rate of 10-15 mL/min and 15-20% wall material concentration of maltodextrin, according to optimization studies (Gayathry & John, 2024). Storing plant phenolic compounds after microencapsulation protects them against oxidative degradation during storage; in fact, antioxidant activity decreases to more than 85% of the initial activity after 6 months (Gayathry & John, 2024).

3.2 Advanced Extraction Technologies

Ultrasound-assisted extraction (UAE) is regarded as a novel green extraction technology which consumes less solvent and needs shorter time in extracting bioactive composites (Gayathry & John, 2024). Optimization Studies show highest yields of phenolic compounds (750–850mg GAE/100g pseudostem) at ultrasound frequency of 40 kHz, power intensity of 200–300 W, extraction time of 20–30min and 60–75% EtOH solvent (Gayathry & John, 2024).

Cellulases, pectinases and hemicellulase are the main enzymes that can facilitate extraction leading to 25–40% increase in soluble dietary fiber extraction, xylo-oligosaccharides with proven prebiotic effects, and phenolic compound recovery as compared with conventional non-enzymatic extraction (Moretti et al., 2025). The improved fermented properties as a fermentation substrate for lactic acid bacteria of the saponified pseudostem were shown through an increase in the cell counts of bacteria Log 9.18-9.75 CFU/mL than concentrations of Log 7.5-8.2 CFU/mL in untreated controls (Moretti et al., 2025).

3.3 Fiber Extraction Methods

Mechanical extraction methods using crushing, scraping, and decorticating machinery can achieve comparatively clean fibers at a yield of 20–30 kg per day (Romero-Cárdenas et al., 2025; Rahman et al., 2022). Chemical retting of 5–10% sodium hydroxide (NaOH) solutions for a period of 24 to 48 h has been shown to remove gummy materials, lignin and hemicellulose, yielding fibers with lower tex values (6.4) that are more suitable for textile processing (Romero-Cárdenas et al., 2025). The most sustainable approach seems to be biological retting based on microbial fermentation of the plant cell walls and an eco-friendly alternative, using indigenous microorganisms by controlling the environmental conditions over 5–10 days (Romero-Cárdenas et al., 2025). Banana pseudostem fiber extraction methods are presented in Figure 4.

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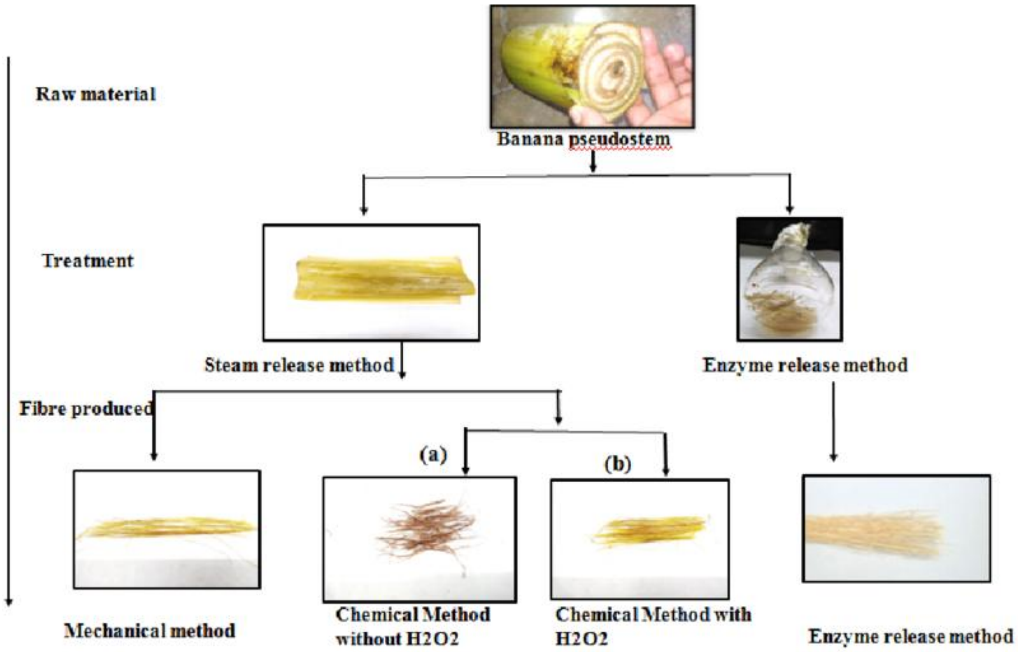

Figure 4: Banana pseudostem fiber extraction methods (Sharma et al., 2023)

3.4 Treatments for Reducing Astringency

Pillar et al., 2024, noted that raw banana pseudostem occasionally shows mild astringent or bitter taste attributes causing ascribed to the presence of tannins and some phenolic compounds. According to (Suhaimi et al., 2022), thermal degradation of tannins is possible to be achieved through blanching method by immersing the flour or powder into boiling water for 3–5 min, which sometimes can also reduce the tannin estimating from 30%–45%. The astringency in dried pseudostem flour can be reduced by 40–55% (with little effect on insoluble fiber content), by soaking in water or dilute salt solutions (1–2% NaCl) for 2–4 h (Pillai et al., 2024). Overcoming astringent properties with lactic acid bacterial fermentation reduced astringency by 50-65% and increased sensory acceptability scores by 35-45% (Moretti et al., 2025).

IV. .Food Applications and Product Development

4.1 Bakery Products and Gluten-Free Formulations

Bakery goods are the most widely researched area of application of banana pseudostem flour (Karaman et al., 2025; Al-Dairi et al., 2025). The inclusion of banana pseudostem flour at 5-15% substitution levels in wheat-based bread assures a 25-65%-increase in dietary fibre content without compromising sensorial acceptance (Pillai et al., 2024; Balda et al., 2021). Bread with 10% pseudostem flour have been shown by studies to increase total dietary fiber from 3.2% to 6.8%, and resistant starch from 2.1% to 4.6%, and reduce postprandial glucose area under the curve (Al-Dairi et al., 2025) by 15-20%.

Higher levels of incorporation (15–25%) of pseudostem flour are compatible with cookies and biscuits than bread (Karaman et al., 2025). For cookies, formulations with 15-20% of banana flour maintain high texture quality properties, and sensory acceptability scores higher than 7.0 on 9-point hedonic scales, and dietary fibre content from 8 to 12%, as opposed to 2 to 3% in traditional cookies (Karaman et al., 2025).

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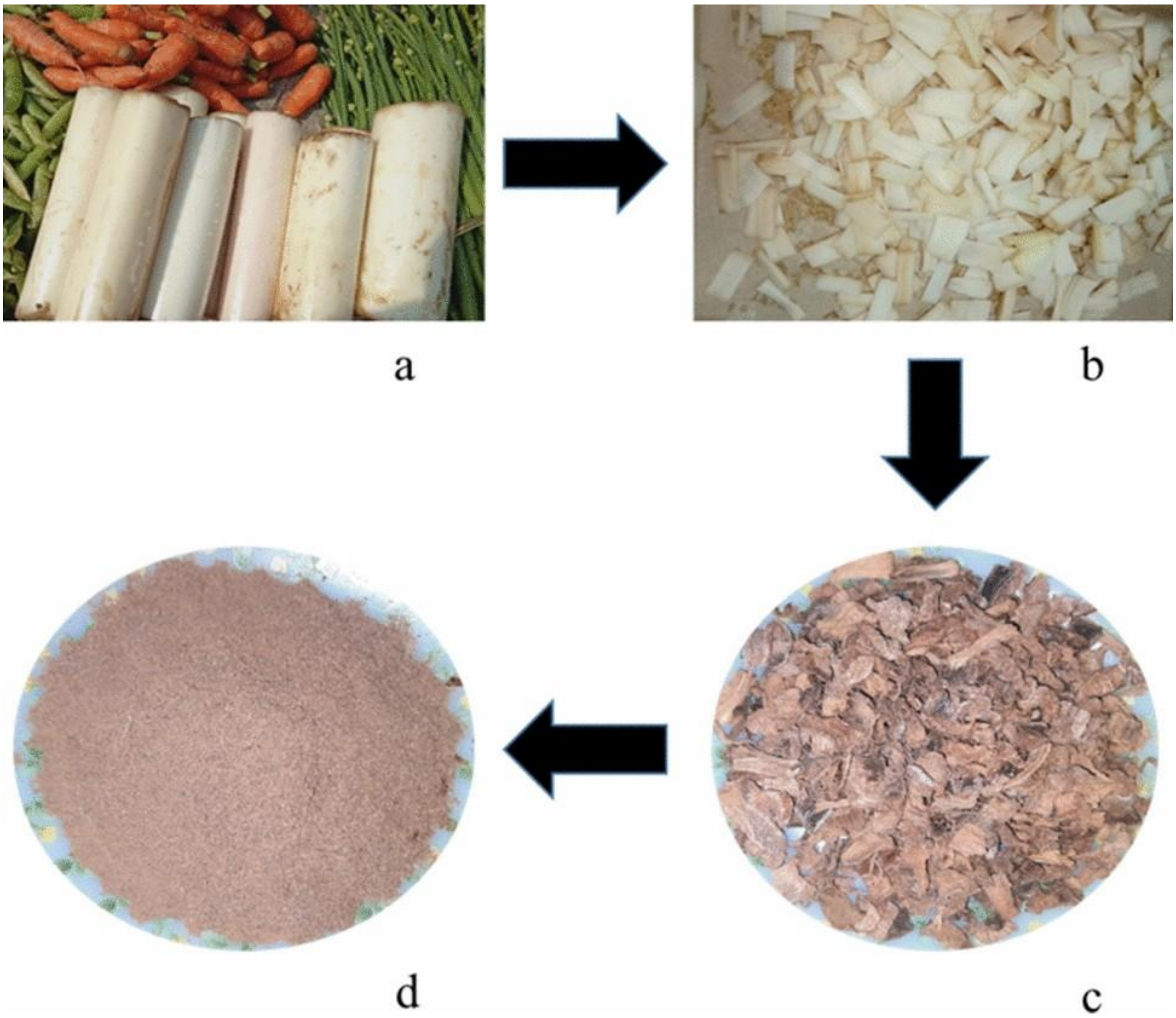
The incorporation of banana pseudostem or banana flour especially aids gluten-free bakery goods as the fiber matrix responds to gluten absence (Karaman et al., 2025; Al-Dairi et al., 2025). November 2–4 2025 @ TBC, VIT (VMRF) | Telehealth and BiopharmaResearch excellence in low gluten, gluten free cookies based on combinations of rice flour, banana flour and corn starch show better textural properties and 3-4 fold higher dietary fiber (Karaman et al, 2025). Based on the optimization results, 98.5% Erdemli banana flour 1.5% Grand Nain banana flour obtained maximum TPC antiradical activity and the best overall acceptability scores on gluten free cookies (Karaman et al., 2025) The banana stem pseudostem in wheat flour biscuits is illustrated in Figure 5.

Figure 5, Replacing the pseudostem banana stem in wheat flour biscuits (Chakraborty et al., 2021)



4.2 Meat Products and Functional Beverages

Banana pseudostem fiber serves as a natural binding agent and fat replacer in meat products (Pillai et al., 2024; Tsutsumi et al., 2025). Based on studies, substantial reductions in cooking loss by 15–30% and enhanced water-holding capacity during refrigerated storage by 20–35% at 2–5% levels have been demonstrated together with acceptable texture parameters (Pillai et al., 2024). For example, the addition of 3% pseudostem flour in chicken nuggets achieves a 15–20% reduction in fat, via partial fat replacement, with overall sensory acceptability scores above 7.5 on 9-point scales (Pillai et al., 2024).

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Banana pseudostem juice or powdered extracts are new applications of such functional beverages (Saikia et al., 2025; Pillai et al., 2024). As much as 60% of pseudostem juice suspended together with 40% of complementary fruit juices results in a ready to serve beverage with acceptable sensory characteristics, decent activity on crude fiber (3.2â€"3.8%), while also showing a substantial antioxidant capacity (Saikia et al., 2025) Characteristics like microbial count are confirmed well within permissible limits and acceptability score for sensory properties remain above 7.0, thus confirm the stability of the product for 2 months of storage (Saikia et al., 2025).

4.3 Novel Food Products

Banana pseudostem chips can serve as an innovative healthy snack due to the high content of dietary fiber (27%) and are obtained from fresh pseudostem which is cut into thin chips (2–3 mm thickness), flavored with different spices, and dried or fried (Saikia et al., 2025; Muralikrishna et al., 2020). Soon after harvest, postharvest processing of this species to remove bitter compounds is possible and when properly seasoned it produces acceptable consumer response (greater than 6.5 on 9-point hedonic scales) in sensory evaluation studies (Saikia et al., 2025). Another area of development is the fortification of dairy products with 2-5% banana pseudostem powder in ferments for formulating dairy products with improved dietary fiber content as well as favorable textural properties (Pillai et al., 2024; Kumari et al., 2025).

V. Health Benefits and Bioactive Properties

5.1 Digestive Health and Gut Function

This remarkable dietary fiber are offering significant digestive health advantages via various complementing mechanisms (Moretti et al., 2025; Li et al., 2022). Insoluble fiber (70–85% of total fiber) bulks up feces, swells 3–5 times its volume to mechanically provoke peristaltic contractions, shortens intestinal transit time of the total colon content by 25–40%, and triggers daily bowel movements (Li et al., 2022; Liu et al., 2024). Studies with fiber supplements show 50–70% improvement in bowel frequency and 40–60% reduction in straining at a bowel movement with the intake of incremental 20–30 g of fiber each day (Li et al., 2022; Daley & Shreenath, 2024).

Soluble fiber (15%–30% of total fiber) is fermented in the colon by bacteria into short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate that have several beneficial health effects (Moretti et al., 2025; Sonnenburg & Bäckhed, 2016). Butyrate is the main energy source for colonocytes, and it is known to help colonocytes maintain metabolic activity, stabilize the intestinal barrier, and may also protect against the development of colorectal cancer (Moretti et al., 2025; Chen et al., 2024).

Enzymatically processed banana pseudostem containing xylo-oligosaccharides selectively promotes the growth of probiotic Bifidobacterium and Lactobacillus species with prebiotic properties (Moretti et al., 2025). In vitro, lactic acid bacteria have been found to achieve much higher growth (Log 9.18-9.75 CFU/mL) from media containing banana pseudostem flour than from control media (Log 7.5-8.2 CFU/mL) (Moretti et al., 2025).

5.2 Cardiovascular Health and Cholesterol Management

It has been suggested that soluble dietary fiber is beneficial for cardiovascular health, and its mechanisms mainly include the binding of bile acids and the effect of reducing cholesterol content (Li et al., 2022; Gayathry & John, 2023; Liu et al., 2024). The main mechanism is the bile acid binding and sequestration in the intestinal lumen promoting de novo bile acid synthesis from hepatic cholesterol which results in low cholesterol stores in the liver and consequently in upregulation of LDL receptors [Li et al., 2022; Yu et al., 2019]. According to the meta-analyses of fiber intervention studies, the soluble fibers intake (5-10 g/day) can be associated with a reduction of total cholesterol of 5-15 mg/dL and LDL cholesterol of 5-10 mg/dL (Li et al., 2022; Chen et al., 2024).

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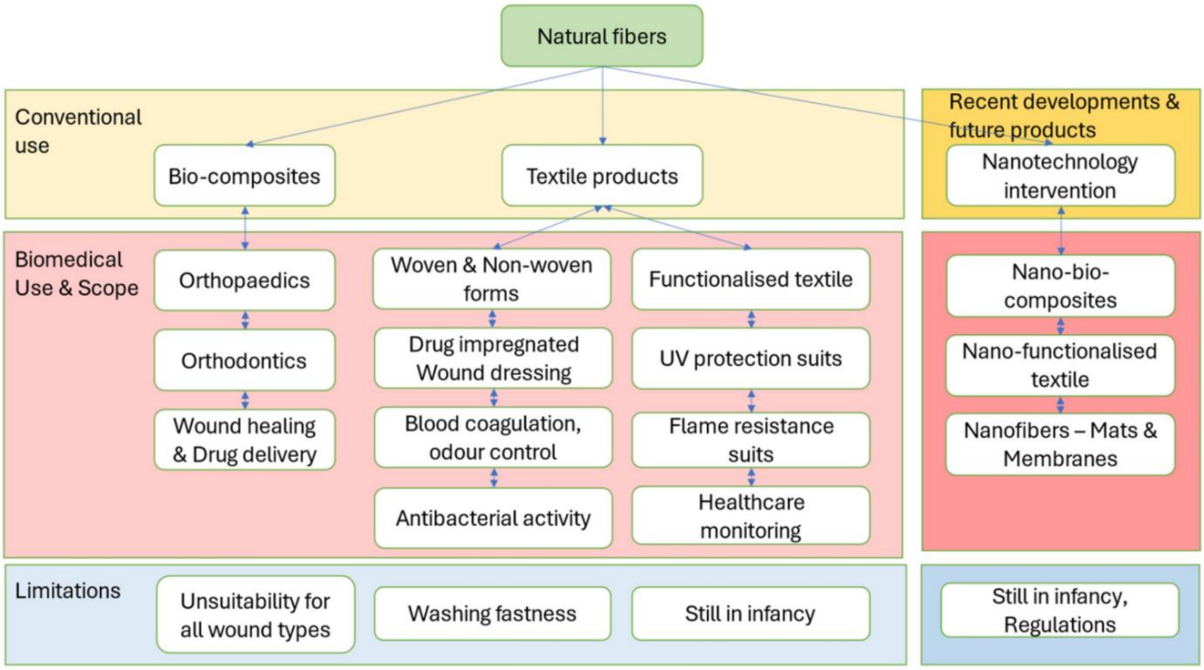
The significant potassium content (30-38 mg/100g) further with its blood pressure regulating effects offer some additional protective cardiovascular effects as several observations indicate that an increase of potassium intake corresponds with a decrease of approximately 2-5 mmHg in systolic blood pressure and 1-3 mmHg in diastolic blood pressure (Li et al., 2022; Xu et al., 2020). Abstract: Antioxidant phenolic compounds protect LDL cholesterol particles from oxidative modification, a critical early step in atherosclerotic plaque development (Gayathry & John, 2023; Pillai et al., 2024). Studies in vitro that show extracts from pseudostems reduce the oxidation of LDL by between 35-55% (Gayathry & John, 2023). Figure 6 Schematic summary of applications of natural fibers in the biomedical fields.

Figure 6: Overview of natural fiber applications in biomedical field (Umapathi et al., 2025)



5.3 Glycemic Control and Diabetes Management

Banana pseudostem has many characteristics that could modulate blood glucose profiles such as high in dietary fiber that modulates the kinetics of glucose absorption, substantial resistant starch, and bioactive components to inhibit carbohydrate-digestive enzymes (Gayathry & John, 2023; Moretti et al., 2025; Reynolds et al., 2020). Soluble fiber slows gastric emptying through forming viscous gels in the small intestine and through providing a physical barrier to glucose diffusion (the two mechanisms additively reduce postprandial glucose excursions by 15–30% in clinical studies) (Li et al., 2022; Yan et al., 2024).

Its resistant starch content reaches as high as 2.7-16.7% depending on the variety and processing conditions (Moretti et al., 2025; Reynolds et al., 2020), making it a starch that is resistant to enzymatic digestion in the small intestine and instead undergoes colonic fermentation with subsequent production of SCFAs that are known to improve insulin sensitivity (Moretti et al., 2025; Reynolds et al., 2020). In people with insulin resistance, long-term intake of resistant starch (20–30 g carbohydrate/day) increases insulin sensitivity by 10–25% and decreases fasting glucose by 5–10% (Moretti et al., 2025; Zou et al., 2025).

Banana pseudostem extracts inhibit α-amylase by 40 to 65% and α-glucosidases by 35 to 55% in in vitro enzyme inhibition studies at normal concentrations (Gayathry & John, 2023). They are known to inhibit α-amylase and α-glucosidase in a dose-dependent manner, with IC50 values from 250–450 µg/mL and 180–350 µg/mL, respectively according to extract preparation and cultivar (Gayathry & John, 2023). A number

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of clinical validation studies show that dietary fiber is independently associated with decreased risk of all-cause mortality (González-Marrero et al., 2025; Zou et al., 2025) and cardiovascular mortality (Zou et al., 2025) in type 2 diabetes and prediabetes.

5.4 Anti-Inflammatory Properties

Through diverse molecular mechanisms such as inhibition of pro-inflammatory enzyme systems and modulation of inflammatory signaling pathways, it is evident that the phenolic compounds exert substantial anti-inflammatory activities (Pillai et al., 2024; Gayathry & John, 2023; Naveed et al., 2018). Particular phenolic acids such as caffeic acid, ferulic acid and protocatechuic acid are also reported to reduce inflammatory mediator production in cell culture studies by 30–50% due to the inhibition of cyclooxygenase (COX) and lipoxygenase (LOX) enzymes (Pillai et al., 2024; Saleem et al., 2011). NF-κB signaling is modulated by catechin and epicatechin, inhibiting the transcription of pro-inflammatory cytokines, including TNF-α, IL-1β, and IL-6 in activated immune cells by 25-45% (Pillai et al., 2024).

VI. Economic and Environmental Sustainability

6.1 Environmental Impact Reduction

Valorizing banana pseudostem for food applications provides substantial environmental benefits (Alzate et al., 2021; Romero-Cárdenas et al., 2025; Wang et al., 2024). Primary benefits include waste volume reduction transforming 60-75% of banana plant biomass from liability to asset, preventing open burning those releases greenhouse gases, and avoiding uncontrolled decomposition producing methane emissions (Alzate et al., 2021; Rai et al., 2025). Life cycle assessment studies show that the conversion of pseudostem into food packaging and fertilizer products reduces up to 45–65% of the global warming potential, 30–50% of acidification potential, and 40–55% of eutrophication potential compared to conventional disposal methods (Alzate et al., 2023; Wang et al., 2024). Per hectare of banana plantation, around 220 tons pseudostem biomass is produced yearly, and the decomposition/ combustion of this biomass releases 15-25 T of CO2 equivalent emissions (Alzate et al., 2021). Pakistan alone generates approximately 7.7 million tons of pseudostem biomass annually, representing massive valorization potential (Environmental Blog, 2025). Figure 7, shows cellulose-based biopolymers from banana pseudostem waste.

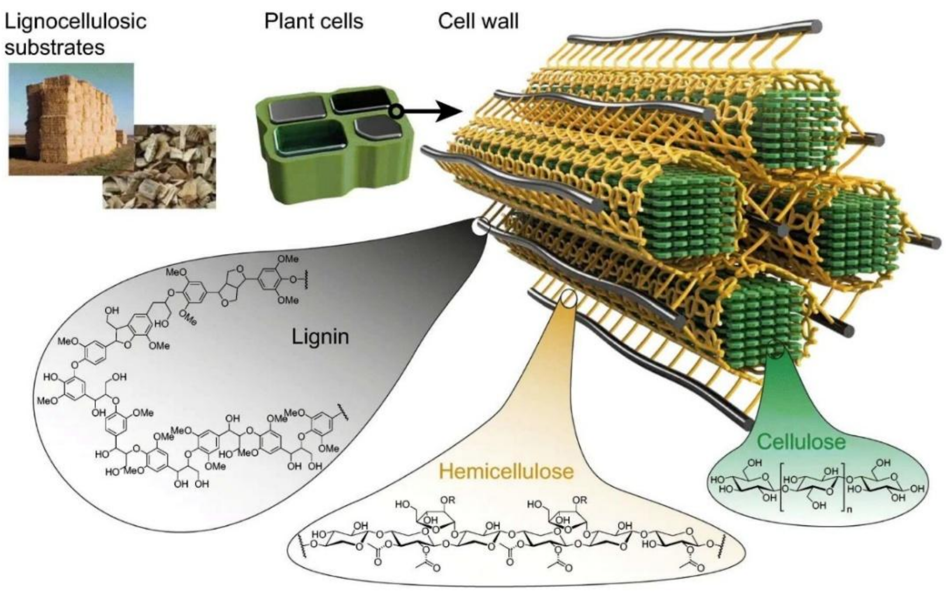

Figure 7: cellulose-based biopolymers from banana pseudostem waste (Waithaka et al., 2025)

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6.2 Circular Economy Integration

The valorization of banana pseudostem stands as an exemplar of circular economy principles whereby material loops are closed and that waste generation has been minimized while new economic value is created out of materials that are traditionally considered waste (Alzate et al., 2021; Romero-Cárdenas et al., 2025; Teigiserova et al., 2020). Integrated biorefinery concepts that utilize the pseudostem through cascading utilization strategies have been studied to maximize the value extracted with multiple products produced from the same feedstock (Alzate et al., 2025; Zhang et al., 2024). An example of an optimized biorefinery would be to: recover bioactive compounds and soluble fiber for use in an optional pharmaceutical or functional food process; process the remaining fiber into cellulose for production of bioplastic or textile applications; convert residue-rich in lignin for biochar; and anaerobically digest the final residues for production of biogas for energy (Alzate et al., 2025; Pandey et al., 2022).

As the pseudostem has a high moisture content which renders long-distance transport economically and environmentally unfeasible (Alzate et al., 2025), localized processing models are especially crucial. Decentralized processing facilities near banana growing areas can conduct preliminary processing to create stable intermediate products ready for shipment to central refineries (Alzate et al., 2025; Zhou et al., 2024). This distributed processing approach also creates jobs at rural farming communities, helping local development and social sustainability (UNDP, 2024).

6.3 Economic Viability and Market Opportunities

The feasibility analyses provide evidence of the capacity for recurrent income along the pseudostem value chain (Alzate et al., 2021, Environmental Blog, 2025; Wang et al., 2024). At farm level pseudostem is a zero-cost feedstock, presently discarded as a waste material. Market prices of processed pseudostem fiber are from $0.50-1.50/kilogram while pseudostem flour for food applications may have market prices from $1.00-2.50/kilogram (Environmental Blog, 2025), with conservative estimates of both (more details in section 5).

So for famers with one hectare giving 220 tons fresh pseudostem (cca 22 ton dry weight), even a 20% capture of available biomass, transformed into flour selling at a $1.50/kg would mean $6,600 additional income per hectare/year or representing a 15-30% income increase on typical smallholder banana farmers (Environmental Blog, 2025) Farmers are paid for pseudostems that were waste and can help produce cleaner, safer plantations the in more market and processing infrastructure developed regions of places such as the Sindh province of Pakistan (Environmental Blog, 2025).

Prospective markets for pseudostem-derived products include consumer products such as bran, flakes, or its flour that can be used in cookies, bread, and other baked goods (Karaman et al., 2025; Herrero et al., 2020); easily scalable consumer markets for these products are supported by increasing awareness of dietary fiber health benefits, growing gluten-free product markets, and demand for sustainable, and plant-based ingredients; global gluten-free product markets are estimated at $8–10 billion; a compound growth rate of 7 ~ 9% is expected (Karaman et al., 2025; Herrero et al., 2020). The food manufacturers look for-natural source of fiber to fortify their product, the textile companies aim for a sustainable natural fibre to replace synthetic one, and the packaging industries search for biodegradable material to reduce plastic wastes (Kumari et al., 2025; Romero-Cárdenas et al., 2025; Polyak et al., 2023).

VII. .Challenges and Implementation Barriers

7.1 Technical and Processing Challenges

Although banana pseudostem represents an unexploited reservoir of benefits, good valorization requires overcoming different technical obstacles (Alzate et al., 2025; Pillai et al., 2024). This high product moisture content (90–95%) is primarily responsible for the greatest challenges in producing cellulosic sugars from lignocellulosic biomass, as it necessitates rapid processing (within 24–48 hours of harvest) to avoid microbial contamination and spoilage, requires high energy input drying operations, and drastically increases transportation costs due to an economic collection radius of only 15–30km from processing facilities (Alzate et al., 2025; Majumdar & Jagadale, 2023).

This, together with compositional variability across cultivars, maturity stages and growing conditions, makes it difficult to standardize processing parameters and final product specifications (Moretti et al., 2025; Gayathry & John, 2024). However, its cellulose content ranges in proportion from 27% to 52% (dry basis), fiber from 27% to 70% (dry basis), resistant starch from 2.7% to 16.7% (dry basis), and phenolic compounds from 153 to 291 mg GAE/g extract (Moretti et al., 2025; Thongpak et al., 2024). Despite drying, storage stability continues to be a challenge, as any residual moisture, residual enzyme activity and pest susceptibility can deteriorate product quality over long (3–6-month) storage periods (Pillai et al., 2024).

7.2 Supply Chain and Market Development

The development of an adequate pseudostem supply chain has been identified as a major challenge for enabling large-scale valorization (Alzate et al., 2025; Zhou et al., 2024). The fresh pseudostem is bulky and high in moisture content, resulting in high transport costs which restricts a viable collection radius to 15–30 km from the processing facility (Alzate et al., 2025) which, consequently makes centralized processing financially unattainable. This problem could be partially alleviated by decentralized mobile [or smaller fixed-scale] preprocessing units, although the implementation of distributed types of equipment and trained instances in many instances will be needed (Alzate et al., 2025).

Consumer acceptance is a major challenge, especially for direct-to-food applications where pseudostem represents a novel food (Pillai et al., 2024; Saikia et al., 2025). Consumer perception surveys show that awareness of banana pseudostem as food ingredient is limited (15-25% awareness in most regions), and other consumer perceptions, such as skepticism regarding the consumption of "waste" materials, safety, taste, and nutritional adequacy, require substantial consumer education and marketing efforts (Saikia et al., 2025). Clarifying misconceptions relating to the product benefits (i.e., environmental advantages, nutritional properties, and functional characteristics) through effective product positioning strategies reduces consumer skepticism and instills positive associations (Saikia et al., 2025; Polyak et al., 2023).

7.3 Regulatory and Safety Considerations

Approval of new food or food ingredients from naturally occurring organisms, such as members of the Family Musaceae (bananas) where pseudostems may be used as food ingredient for an unproven purpose, requires extensive safety assessment data [toxicological studies (Domsanska et al., 2023; Pillai et al., 2024) allergenicity and compositional analysis to show the absence of significant levels of constituent contaminants (Pillai et al., 2024)]. Although banana pseudostem have a long traditional history of use in some cultures which supports that it is generally safe, such regulatory approval is very costly and needs extensive safety documentation and testing (more than $50,000–200,000 for one application; Alzate et al., 2021, e.g., under European Union Novel Foods Regulation or US FDA Generally Recognized as Safe (GRAS) designation).

The monitoring of contaminants is needed, since the heavy metals from soil, pesticide residues at the time of agricultural practices, and mycotoxins from fungal contamination during, not properly storage can accumulate on plant level (Pillai et al., 2024; Rahman et al., 2022). The maximum residue limits (MRL), good agricultural practices (GAPs), good manufacturing practices (GMPs) and testing (Pillai et al., 2024) protects the product and regulators.

VIII. Conclusions and Future Works

8.1 Conclusions

Banana pseudostem is a highly underutilised agricultural biomass resource with significant prospects for valorisation into functional food ingredients, enabling operationalisation of circular bioeconomy principles by providing a solution to environmental challenges, enhancing nutritional security, and generating socio-

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economic benefits. This updated review composes the scientific evidences that banana pseudostem represents a food-like with nutritional composition with highly functional dietary fiber (27-70%), excess of minerals, particularly potassium and calcium bioactive phenolic compounds with antioxidant and antimicrobial potency.

Optimized drying protocols, enzymatic extraction technologies, ultrasound-assisted extraction, and micro-encapsulation strategies are advanced processing technologies converting this high-moisture agricultural waste into shelf-stable functional food ingredients. Practical applications have been shown for bakery products, gluten-free formulations, meat products, and functional beverages, indicating technical feasibility and potential consumer acceptability with sensory acceptability scores above 7.0, and 2–4-fold increased dietary fiber.

It is claimed to be beneficial for digestive health, to protect the cardiovascular system by lowering cholesterol levels, to help regulate blood sugar levels to help people with diabetes, and to have anti-inflammatory effects. Analysis of environmental sustainability shows reductions in greenhouse gas emissions of 45-65% and increases in farmer income of 15-30% High moisture content and compositional variability, supply chain constraints, and regulatory requirements present challenges that will require cohesive and coordinated multi-stakeholder efforts.

In sum, banana pseudostem valorization is a meaningful contribution towards the United Nations Sustainable Development Goals that not only generates economic value, but also contributes to sustainable agricultural practices. Continued investment in research, technology development, and policy for upcycling banana pseudostem from agricultural waste into a functional food ingredient would make it possible to usefully add its contribution to the transformation of the Global Food Systems.

8.2 Future Works

The next steps for research should focus on the passage of banana pseudostem valorization from laboratory demonstrations to industrial scale. However, robust clinical trials assessing health benefits in human populations are still required to translate mechanistic findings into substantiated health claims. These include the development of advanced processing technologies, maximizing processing energy efficiency, exploring novel drying techniques, integrated processing systems, and upscaling methods, which are all urgent priorities.

Innovative product development, unique applications like ready-to-eat snacks, and new products for specialized nutrition, will help extend market access. On the other hand, the need to facilitate practical implementation barriers through supply chain optimization, designing effective collection systems and decentralized processing models aimed at smallholder production systems. Policy will be guided by thorough life cycle assessments that will quantify environmental impacts, and efforts to select new cultivars and breeding programs should aim to produce varieties with higher fiber content and higher and wider bioactive profiles.

A coordinated international approach is needed to harmonize safety assessment protocols, as regulatory pathway development must be in concert to enable a biosimilar to be approved in multiple jurisdictions. Analysis of consumer behavior, drivers of acceptance will help make an impact in shaping the markets. This requires interdisciplinary collaboration involving food science, nutrition, agriculture, engineering, and economic expertise. Public-private partnerships can catalyze technology transfer and commercialization and international collaboration will help to optimize the global impact by ensuring that the benefits reach the innovative smallholder farmers in developing countries where the needs are highest.

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