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Nutraceuticals and Circular Bioeconomy from Banana

Banana, one of the world's most consumed fruits, offers immense potential for a circular bioeconomy through innovative value addition. Starch-rich cultivars and export-reject bananas are being transformed into low-fat chips, high resistant starch flour, modified starches provides low glycaemic, ready-to-cook foods and functional instant powders that support food security, improve satiety and promote gut health. Ripe banana powder, puree, non-starch polysaccharides, clarified fortified juices, wine and vinegar add versatility in the banana based products basket. Banana biomass, including leaves, flower, rhizome, peel and pseudo-stem residues, has also been utilized for producing xylitol-based low GI sugar free confectioneries, diabetic-friendly syrups and nutraceutical products. Encapsulation technologies using banana starch have enabled controlled delivery of probiotics and bio-actives such as β-carotene, laminarin and fish oil, enhancing stability and bioavailability for functional foods. Central core stem juice fortified with minerals like iron and vitamins demonstrates the potential of underutilized biomass for nutritionally enriched beverages with entrepreneurship opportunities. Beyond food applications, banana biomass has been converted into hydrogels, bioplastics, intelligent packaging materials, thermoplastic cutlery, fibre composites and biodegradable alternatives. Peel derived pectin, anthocyanin from flower, cellulose from pseudostem, mid rib, dietary fibre from scutcher and rhizome-based products, further support a zero-waste framework, highlighting banana as a sustainable resource for food, nutraceutical, biomedical and eco-friendly industrial applications.

Keywords: Banana; Bio-processing innovations; Functional food; Nutraceuticals

BANANA is one of the most important fruit crops in the world, with an annual global production exceeding 155 million tonnes cultivated across more than 130 countries. It ranks among the top staple and commercial fruit crops due to its year-round availability, affordability and nutritional significance. India is the world's largest producer of banana, contributing nearly 20% of global production with an annual output of about 39 million tonnes from approximately 0.9 million hectares. Beyond internationally traded *Grand Naine*, India houses more than 20 traditional as well commercial banana varieties specific to different states. GI tag has also been obtained for varieties like *Kamalapur Red Banana*, *Matti*, *Virupakshi*, *Sirumalai*, *Nanjangud Rasabale*, *Myndoli banana* and *Chengalikodan Nendran*.

Beyond its economic importance, banana cultivation supports the livelihood of millions of farmers, traders, processors and workers involved in the supply chain. Banana is considered a highly nutritious fruit containing about 20–25% carbohydrates, 2–3% dietary fibre and significant levels of potassium (350–400 mg/100 g), vitamin B_6, vitamin C, magnesium and natural antioxidants. Green bananas contain 40–60% resistant starch on a dry weight basis, making them highly valuable for the development of low glycaemic index and gut-friendly functional foods. Resistant starch acts as a prebiotic, improves colonic health, enhances satiety and helps regulate blood glucose levels, thereby supporting the management of diabetes, obesity and cardiovascular disorders. Banana flowers, peels and pseudo-stems are also rich in fibre, phenolics and bioactive compounds with antioxidant and therapeutic properties.

Banana processing industries convert fresh fruits into chips, puree, flour, powder, beverages, bakery products, pasta, extruded snacks and baby foods. Green banana flour and banana starch have gained major attention as functional ingredients because of their high resistant starch and dietary fibre content. The global functional food market is expanding rapidly and is projected to exceed $500 billion in the coming years, creating significant opportunities for banana-based nutraceuticals and health-oriented products. Banana-derived resistant starch, pectin, dietary fibre and bioactive compounds are increasingly incorporated into diabetic-friendly foods,

synbiotic formulations and nutraceutical supplements. Encapsulation technologies utilizing banana starch have improved the stability and controlled release of probiotics, fish oil, β-carotene and other sensitive bioactives, thereby enhancing their bioavailability and shelf life.

Tertiary processing and circular bioeconomy approaches have further widened the utilization potential of banana biomass. Nearly 60–70% of the banana plant biomass, including pseudo-stems, peels, leaves, rhizomes and flowers, remains underutilized after harvest. These residues are now being converted into pectin, dietary fibre, natural sweeteners such as xylitol, biodegradable packaging materials, starch-based bioplastics, fibre composites and functional beverages. Banana pseudo-stem alone can generate nearly 60–80 tonnes of biomass per hectare, representing a substantial resource for value addition and rural entrepreneurship. The complete valorization of banana biomass demonstrates a sustainable circular bioeconomy model where food, nutrition, functional ingredients, nutraceuticals and eco-friendly biomaterials are produced simultaneously while minimizing waste generation. Such integrated approaches not only improve economic returns and nutritional security but also contribute toward environmental sustainability and sustainable agro-industrial development.

Green banana-based functional foods and nutraceuticals: The simplest and most direct form of banana value addition involves the preparation of low-fat chips, resistant starch-enriched flours, fortified pasta and extruded powders. Banana processing has expanded far beyond traditional products such as chips, dried slices, intermediate moisture foods, leather, pickles and other products. Bananas are increasingly utilized for the production of flour, starch, ready cook foods like pasta, noodles, bakery products, breakfast mixes, instant beverage powders and functional snack foods. Banana flour and starch are gaining importance as functional ingredients because they can improve the nutritional quality of conventional foods while also enhancing texture and stability during processing.

Unripe bananas are particularly valued because they contain high amounts of resistant starch, which behaves similarly to dietary fiber. Foods prepared using unripe banana flour are associated with slower digestion, improved satiety and better blood sugar management. As a result, banana flour is being incorporated into diabetic-friendly foods, gluten free products and weight-management formulations. The functional properties of banana flour are strongly influenced by the stage of maturity and processing methods used. Unripe banana flour generally exhibits higher water absorption, swelling capacity and lower digestibility, making it suitable for health-oriented products. Processing methods such as freeze drying, spray drying, blast freezing, ultrasonication, are being used to improve shelf life, texture and stability while retaining nutritional quality. These techniques also help preserve resistant starch content and improve the suitability of banana ingredients for industrial food applications. A major opportunity in banana value-addition lies in the utilization of rejected and surplus fruits. Large quantities of bananas are discarded during grading and export due to cosmetic defects, bruises or size variations, despite being nutritionally sound. These rejected fruits can be converted into starch, flour and processed food ingredients, thereby reducing postharvest losses and improving resource utilization.

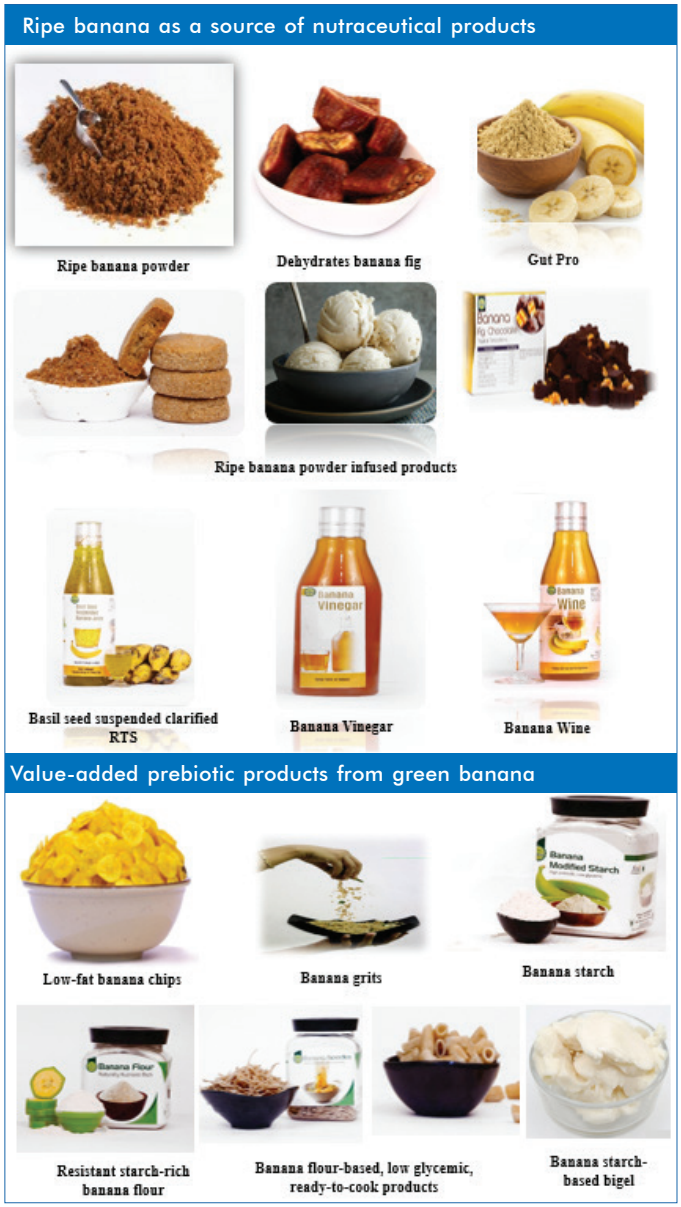
Green processing approaches such as enzymatic treatment, ultrasonication, heat-moisture treatment and retrogradation are gaining attention because they improve starch functionality without relying heavily on chemicals. These methods enhance solubility, cooking stability and resistant starch formation while supporting cleaner and more sustainable processing systems. Such innovations are creating new opportunities for the development of health-promoting foods and nutraceutical ingredients from banana resources. The nutritional significance of banana starch modifications lies in their impact on glycemic response, satiety and gut health. Resistant starch fractions, whether produced through chemical or enzymatic routes, consistently reduce the hydrolysis index and estimated glycemic index of banana starch. Phosphorylated starch demonstrated the highest prebiotic activity score, promoting the growth of probiotics like *Lactobacillus acidophilus* and related strains. Fermentation of these starches in the colon leads to the production of short-chain fatty acids, which contribute to improved colonic health, modulation of lipid metabolism and appetite regulation. These attributes highlight the dual functionality of modified banana starch as both a technological ingredient and a nutraceutical component.

Ripe and over ripe banana for nutri-beverages: In contrast, ripe banana powder contains more natural sugars, making it more suitable for sweet confectionary products such as cakes, cookies, muffins and desserts where flavor and sweetness are important. Foam mat drying transforms ripe banana pulp into stable banana powder using natural foaming agents, preserving important nutrients and probiotic properties. This powder can further be incorporated into biscuits and bakery products to improve dietary fibre content and functional quality. Dehydrated banana slices serve as lightweight, shelf-stable snacks; these serve as instant energy-rich snacks and can be conveniently used by military personnel, trekkers, athletes, travellers and school children due to their lightweight nature, portability and long storage stability. They can also be incorporated into breakfast cereals, bakery products, trail mixes and nutrition bars. Intermediate moisture foods like jam utilises ripe banana pulp to produce naturally sweet spreads with desirable flavour and texture characteristics and offers possibility of synbiotic food formulations. Banana ice cream developed from ripe banana pulp offers a naturally flavoured frozen dessert with enhanced creaminess and nutritional quality, while banana cake provides a soft-textured bakery product enriched with natural sweetness, minerals and dietary fibre. Conversion of ripe bananas into instant powder offers an effective strategy for utilizing surplus fruits and developing stable value-added products. Banana flour processed using twin-screw extrusion technology has improved solubility, dispersibility and rapid reconstitution properties as compared to conventional flour. The developed instant powder are suitable for applications in

beverage mixes, soups, porridges, bakery premixes, infant foods and nutraceutical products. Clarified banana juice prepared through enzymatic treatment helps to remove turbidity and viscosity caused by pectin and starch, resulting in a clear, appealing beverage with improved storage stability. This clarified juice also serves as an important base material for fermented products such as banana wine and vinegar. Functional beverages such as basil seed suspended banana juice combine the mineral-rich properties of banana, creating refreshing health-oriented drinks. Enzymatic clarification and controlled microbial fermentation improve flavour, aroma and storage stability while generating commercially valuable fermented products. Fermentation technologies further expand banana utilization through the production of banana wine and vinegar.

Secondary agriculture and bio-processing innovations

Xylitol: Low sugar alternatives from banana biomass: The global demand for natural sweeteners has accelerated due to rising concerns over obesity, diabetes and the adverse effects of artificial sweeteners such as aspartame and sucralose. Within this context, xylitol, a sugar alcohol with sweetness comparable to sucrose but only 2.4 kcal/g and a glycemic index between 7 and 13, has gained considerable commercial and therapeutic interest. Xylitol is particularly attractive because it provides sweetness similar to sugar while containing fewer calories and produces a much lower impact on blood sugar levels. It is also known for its dental health benefits, as it does not contribute to tooth decay. Banana pseudostem scutcher biomass, a residue generated during banana fiber extraction, is rich in hemicellulose-derived sugars and serves as a promising substrate for xylitol production using naturally occurring yeast strains like *Candida tropicalis* isolated from banana waste. Banana-derived xylitol can be used in sugar-free candies, chewing gums, gummies, syrups and diabetic-friendly food products due to its low glycemic response and pleasant sweetness profile.



Green and ripe bananas as sources of nutraceutical, synbiotic and functional food products

Encapsulation and smart release systems: Another emerging area in banana secondary processing is the development of encapsulation systems for protecting and delivering sensitive nutrients and bioactive compounds. Banana starch is particularly suitable for this purpose because of its film-forming ability and high amylose content. It can act as a natural carrier material that protects functional ingredients from degradation during processing, storage and digestion. Banana starch, when combined with plant proteins such as faba bean protein, can effectively encapsulate compounds like fish oil, antioxidants, probiotics and dietary fibers. Advanced techniques such as ultrasound-assisted encapsulation have improved the stability and retention of these compounds, achieving high encapsulation efficiencies and better protection against oxidation. Such systems help preserve sensitive ingredients and allow their gradual release in the digestive system, improving their nutritional effectiveness. Banana starch based encapsulation systems are also being explored for probiotic and syn-biotic food products. In these formulations, probiotics are delivered together with banana resistant starch, which acts as a prebiotic and supports beneficial gut bacteria. These technologies have been tested in fortified beverages and smoothies, where they improved protein content, antioxidant stability and overall nutritional quality.

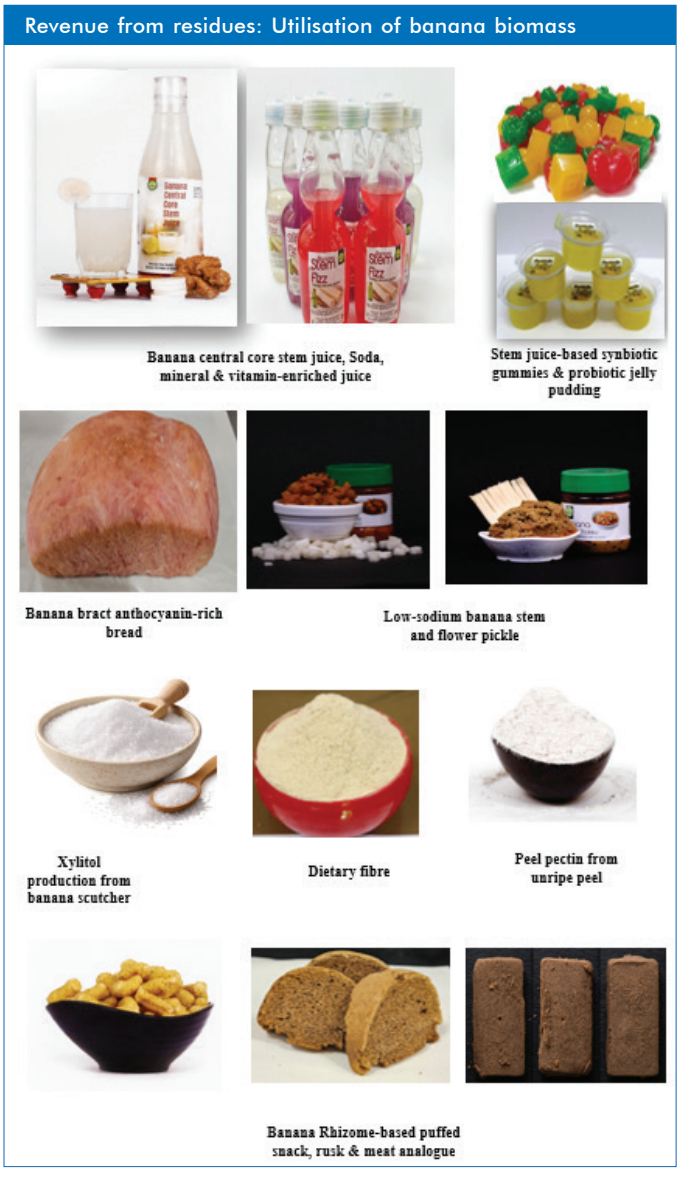
Central core stem: Beyond therapeutic for precise delivery systems: Banana central core stem juice is rapidly emerging as a promising functional beverage in the expanding nutraceutical market, which is projected to reach nearly $18 billion by 2028. Although nearly 5–6 tons of banana pseudostem biomass are discarded after harvest, this underutilized material is exceptionally rich in dietary fibre, minerals, antioxidants and bioactive compounds. Traditionally recognized for its refreshing taste, detoxifying nature and kidney health benefits, banana stem juice also possesses antioxidant and anti-inflammatory properties. Remarkably, nearly 20,000 litres of juice can be extracted from one hectare of banana stem, creating entrepreneurship opportunities worth approximately ₹20 lakhs, while even partial utilization of available biomass could support a nutraceutical economy.

To enhance consumer appeal and health benefits, banana stem juice has been developed into several innovative functional products. Zero-calorie sweeteners such as stevia and sucralose have been incorporated to create low-calorie beverages suitable for health-conscious consumers. Flavoured variants enriched with ginger, mint, jamun, guava and grapes further improve taste, colour, antioxidant activity and vitamin content. Advanced encapsulation and smart delivery systems using modified banana starch have enabled the fortification of stem juice with iron and folic acid. The optimized pectin-modified starch encapsulation system achieved excellent encapsulation efficiency and nutrient retention, supporting the development of stable fortified functional beverages. Beyond beverages, banana stem juice has also been utilized in probiotic gummies, jellies and pudding systems containing encapsulated *Lactiplantibacillus plantarum*. Modified banana starches such as hydroxyphosphorylated and oxidized starch improve probiotic survival, texture and storage stability.

Peel-derived biomaterials and functional foods: Banana peel, which accounts for nearly one-third of the total fruit weight, is a valuable byproduct with multiple avenues for valorization. Among these, pectin extraction has received considerable attention due to the peel's relatively high yield. Banana peel powder, rich in dietary fibre has been successfully used as a fortifying ingredient in bakery products such as muffins, where partial substitution of wheat flour enhances dietary fiber, phenolic compounds and antioxidant activity. This dual valorization pathway reinforces the role of banana peel as a versatile biomass stream contributing both to sustainable biomaterial development and to the growing market for healthier, value-added foods.

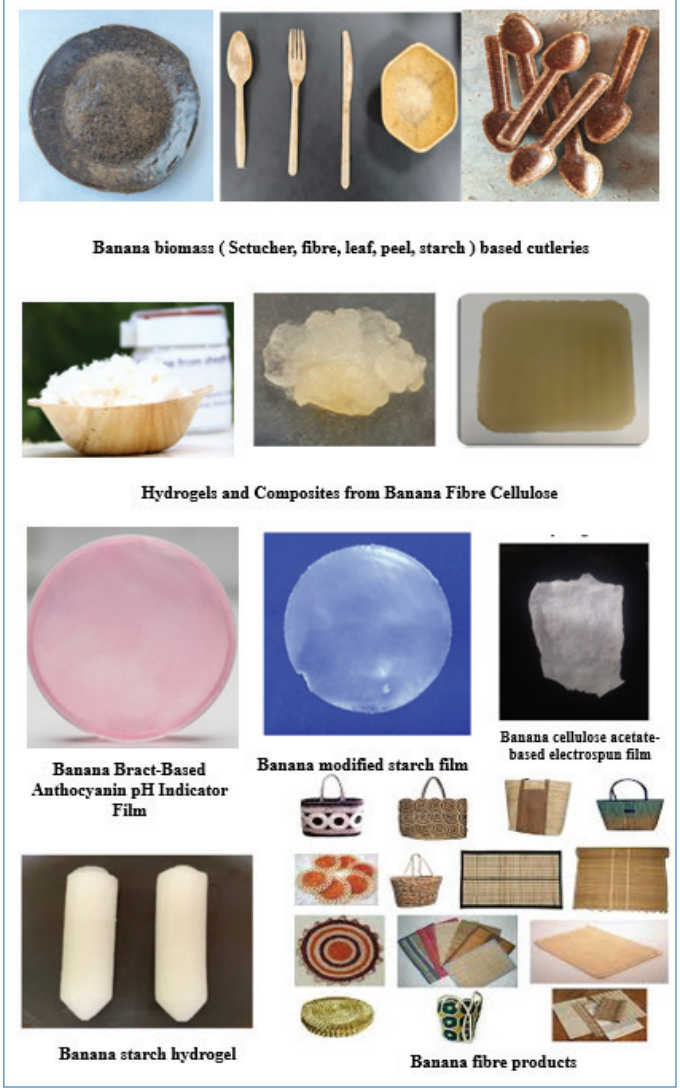
Other high value products using banana biomass: Banana flowers and rhizomes, which are often discarded after harvest, contain significant levels of phenolics, flavonoids and minerals. These biomasses have been processed into traditional pickles and snacks, which are now entering nutraceutical markets as antioxidant-rich functional foods. These biomasses have the potential of reducing oxidative stress, supporting cardiovascular health and improving lactation. Banana biomasses such as peel, pseudostem, leaves, rachis, rhizome and fruit waste are emerging as promising and economical feedstocks for the production of valuable platform chemicals. Rich in cellulose, hemicellulose, starch, sugars and lignin, these agro-residues can be efficiently converted into high-value bio-based compounds including sorbitol, acetic acid, levulinic acid, furfural, hydroxymethylfurfural (HMF), xylitol, lactic acid, bioethanol, succinic acid and other furfural derivatives through biochemical and thermochemical processes. Since banana cultivation generates enormous quantities of low-cost biomass residues annually, their utilization provides one of the cheapest and most sustainable raw material sources for producing industrially important chemicals and advanced bioproducts.

Other innovative applications: Banana starch and processing residues are increasingly recognized as sustainable biomaterials with applications extending beyond conventional food uses. Modified banana starch, produced through physical, chemical or enzymatic treatments, exhibits improved stability, texture and digestibility, making it suitable for nutraceuticals, functional foods, edible coatings, biodegradable films and eco-friendly packaging systems. Owing to its high amylose content and excellent film-forming properties, banana starch can be blended with polymers such as polyvinyl alcohol or carboxymethyl cellulose to develop bioplastics with enhanced mechanical strength and barrier characteristics. Incorporation of anthocyanins extracted from banana flower bracts further enables the production of intelligent packaging materials capable of detecting food spoilage through *p*H-responsive color changes along with antimicrobial protection against common foodborne pathogens. Simultaneously, cellulose isolated from banana pseudostem has emerged as a valuable resource for biodegradable composites and hydrogel fabrication because of its hydrophilicity, porosity, biocompatibility and favorable tensile properties. These cellulose-based hydrogels support controlled release of bioactive compounds and show potential in wound dressings, oral delivery systems and tissue regeneration scaffolds. Banana



Banana biomass for valorisation and the circular economy

Potential applications of other banana biomass



Material applications from banana biomass

pseudostem fibers and processed banana leaves are also increasingly utilized in biodegradable household products, disposable tableware, packaging materials and lightweight composite structures as environmentally sustainable alternatives to synthetic and petroleum-based materials.

Entrepreneurship and market perspectives: The successful translation of these secondary processing innovations into viable enterprises hinges on techno-economic feasibility, consumer acceptance and regulatory compliance. Banana biomass valorization presents unique entrepreneurial opportunities for farmer-producer organizations, start-ups and SMEs. The establishment of decentralized biorefineries capable of producing xylitol, encapsulated nutraceuticals and fortified juices would not only diversify income streams but also reduce waste disposal burdens. Market demand for natural sweeteners, functional beverages and nutraceutical delivery systems is expanding rapidly, with consumer preference shifting toward clean-label, plant-based and sustainable solutions. Banana-derived products, by virtue of their low glycemic index, bioactive enrichment and eco-friendly origin, are well-positioned to capture this demand. Furthermore, partnerships with the food, pharmaceutical and nutraceutical sectors can facilitate scaling, while intellectual property protection and technology licensing can create additional commercialization pathways. Farmer-producer organizations and small enterprises can establish decentralized biorefineries that handle fruit rejects, peel drying, pseudostem fibre extraction and leaf-based product processing. Such clusters have the potential to diversify rural income streams, create employment for women and youth and foster rural industrialization in a sustainable manner.

SUMMARY

Banana exemplifies the transformation of a staple tropical crop into a model system for advancing nutraceuticals and circular bioeconomy. From resistant starch enriched flours and functional bakery products to peel-derived pectin, pseudostem-based hydrogels, intelligent packaging films and xylitol bioprocessing, every component of the plant demonstrates potential for high-value applications. This zero-waste approach underscores how banana biomass streams can be strategically integrated to enhance nutrition, reduce environmental burdens and generate sustainable livelihood opportunities. The convergence of science and technology has been central to this progress. Advances in starch modification, encapsulation platforms and digital traceability tools illustrate how fundamental research can be translated into tangible innovations. At the same time, entrepreneurship and decentralized biorefineries offer practical pathways for scaling these innovations, ensuring that smallholders, rural enterprises and start-ups become key beneficiaries of the banana-based bioeconomy. Looking ahead, banana provides a replicable blueprint for sustainable agri-food systems: A crop that addresses nutrition security, drives material innovation and supports environmental stewardship. By continuing to integrate multidisciplinary research with entrepreneurship and policy support, banana biomass valorization can evolve into a globally relevant pathway towards healthier diets, greener industries and resilient farming communities.

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