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BANANA PEEL AND BIOMASS VALORIZATION: NUTRITIONAL, BIOACTIVE, FUNCTIONAL-FOOD AND NANOCELLULOSE PERSPECTIVES FOR CIRCULAR BIOECONOMY

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ABSTRACT

Banana (*Musa spp.*) is one of the world's most important globally produced and consumer fruits and its production and processing system generates immense amounts of side biomass in the forms of peel, pseudostem, leaves, rachis, inflorescence and rejected fruit. The peel itself makes up ~30-40% of the entire weight of the fruit, is usually wasted and contains adequate amounts of dietary fibre, pectin, resistant starch, minerals, phenolic compounds, carotenoids and lignocellulosic materials. This review combines and contrasts the latest evidence for utilization of banana peel and relevant banana by-products, from global, Indian and Tamil Nadu scale production and waste, through nutritional, physicochemic and phytochemical properties, up to its applications in biological systems, nutraceutical and functional foods, down to two relatively poorly synthesized and inter-connected themes: cellulose and nanocellulose recovery/utilization and systematic research overview of existing and emerging research themes versus continued challenges. Special attention is given to the emerging uses of cellulose nanocrystals, cellulose nanofibres and bacterial nanocellulose from *Musa spp.* biomass (especially peel, pseudostem, rachis) in Pickering emulsion stabilization and smart biodegradable active packaging. Critically, the literature is analyzed from both pre-clinical, clinical, evidence-based and conventional nutritional perspectives while also discussing challenges related to clean extraction, integrated biorefining, nanocellulose based systems and product stability, toxicity evaluation and regulations at an industrial scale and practical, circular bio-economy oriented solutions for major banana producing regions like India, especially Tamil Nadu

KEYWORDS: *Musa spp.*, agro-industrial by-products, nutraceuticals, nanocellulose, circular bioeconomy

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1. INTRODUCTION

Musa spp. (family Musaceae) are year-round tropical fruiting crops and constitute one of the largest food commodities globally in value as compared to fruits, cereals and other farm crops, ranking fifth in global trade value behind cereals, sugar, coffee and cocoa [1]. It provides the cheapest nutrient sources of carbohydrates for more than 400 million of world populations [2]. Large quantities of residue biomass are produced during both the production of bananas, including, pseudostem, leaf, rachis, inflorescence,

discarded rejected/immature fruits and peel during their subsequent processing and consumption stages. Since banana fruits are only fruited once annually, the entire plant (pseudostem, leaves) is then chopped and these are sometimes burnt, dumped in land and consequently create bad odors, environmental contamination and GHG emissions.[3,4] With respect to other side products, *Musa* spp. peel alone typically constitutes around 30-40% of the total fruit weight,[5,3] and it contains high proportions of resistant starches, minerals, phenolics, carotenoids, proteins and carbohydrates such as fiber and pectins. These compounds not only impart some therapeutic effects but are also regarded as significant valuable ingredients with vast utility for use in foods and related nutraceuticals and this has prompted further research into *Musa* spp. peel application.

More attention has been paid in the last decade to the extraction of novel bioactive and nutrient compounds, their identification and applications to reduce the waste stream and consequently to achieve an active circular economy of bioresources. The lignocellulose components of *Musa* biomass also show significant potential, particularly to serve as readily-available renewable sources of cellulose nanocrystals (CNs), nanocellulose (NCs) and cellulose nanofibers (CNFs) for numerous food applications and the packaging industry [6].

This review article presents the latest literature regarding the recovery and utilization potential of *Musa* peel and other bio-waste of *Musa* spp. This review covers the global, Indian and Tamil Nadu production and waste generation pattern, nutritional and physicochemical characteristics, bioactive components and their uses in various food products from local to global markets, followed by two important less-consolidated themes: utilization of nanocellulose extracted from *Musa* biomass for developing Pickering emulsions and active packaging applications and a comparative research overview of existing issues related to food and functional ingredient recovery versus persistent issues for effective implementation in the food, nutraceutical and food processing industries. It also gives emphasis to utilizing nanocellulose extracted from peel, pseudostem and rachis for Pickering emulsion and food packaging, compares the biological functions and nutraceutical potentials in detail and concludes with three practical steps for implementing effective valorization of *Musa* by-products.

2. PRODUCTION OF BANANAS AND THE GENERATION OF THE PRIMARY BY-PRODUCTS

2.1 Global Scene

Globally, the output is about 120 million tons, with plantations more than the 150 countries, producing the largest quantity of bananas across the continents of Asia, America, Africa etc.[7] Exports accounted for nearly 14% of total production, approximately 20 million tons annually. Ecuador remained the highest volume banana exporter, even though largest producer of raw product is in Asia (namely India).[8] An examination by the Food and Agriculture Organization has revealed that latest trends show increased logistics pressures as well as impact from disease in the form of Fusarium wilt Tropical Race 4, which affects the volume of global exports.[8]

Out of the total production, hardly 40% of the crop yield is utilized effectively. Including losses from peeling and processing, this means around 114 million tons per year of banana residue is generated as waste.[2] Peel comprises about 35-40% of total fruit weight, which may add up to roughly 42 million tons of peel generated every year globally [7]. Along with peeling losses, pseudostems and rachis are also produced, in the proportion of 3 tons per ton of fruit harvested for pseudostem and 150 kg/ton for rachis. Yield of all parts varies with fruit variety, cultivation system used and product produced [6].

2.2 National Situation: India

India continues to be the leading global producer of bananas, with earlier national figures placing annual output near 29.2 million tonnes.[1,9] Trade estimates put the present value at nearly 37-38 million tonnes, grown on nearly one million hectares.[10] However, India accounts for less than 2% of the export market share due to higher domestic consumption.[10] Two-thirds of the total banana-producing area of India is spread across the following major banana-producing states: Andhra Pradesh, Maharashtra, Karnataka, Tamil Nadu and Uttar Pradesh.[10]

2.3 Local Situation: Tamil Nadu

Tamil Nadu accounts for about 0.13 million hectares of banana growing area in India, but distinguishes itself from other regions of India based on the diversity of banana species grown, comprising 15+ common commercial varieties. These include Poovan, Rasthali, Karpuravalli, Ney Poovan etc.[11] Five regions dominate banana production in the state and form its backbone: Tiruchirappalli, Thanjavur, Erode, Coimbatore and Pudukkottai. In the state, an enormous area of banana cultivation, along with a widely spread network of fruit vendors, juice centers and small-scale fruit processing units, produces a comparably enormous range of fruit peel and biomass, underscoring the direct relevance of further study of these valuable waste materials.[11]

2.4 Environmental and Economic Consequences of Residue Generation

Given its high moisture and organic compound content, banana peel degrades rapidly after collection, producing bad odors and emitting greenhouse gases upon disposal [12]. The emission of methane gas as a result of anaerobic decomposition, smoke from open burning and impact on land and soil quality by leached contaminated residue are among the other factors that add to the overall detrimental consequences of disposing of this biomass.

The transportation cost of residue alone adds significantly to the operational costs of farmers and processors.[4] The rate of degradation of fresh peels is relatively fast because of the higher moisture content, with consequently related challenges for storage, transit and handling. The direct effect is that the producer bears collection and disposal costs as if it were waste material, or otherwise turns it into an additional income source. This is based on utilization of the fruit peel by fractionating out its fiber, phenol, cellulose and pectin content, along with the prerequisite of an appropriate collection method, hygiene and drying mechanism.[2]

3. BANANA BY-PRODUCTS BESIDES THE PEEL

Though peels are widely researched, other banana residue streams have potential for valuable recovery, with chemical and structural properties that complement banana peel.

3.1 Pseudostem and Rachis

The pseudostem, a large and fleshy residue remaining after fruit harvesting, is rich in cellulose, hemicellulose and lignin, containing fiber that has long been utilized in ropes, textiles, papers, boards and packaging materials and can be used for extraction of nanocellulose via various mechanical and chemical pre-treatment methods.[13,6] The rachis, the stem that holds the bunch of bananas, is likewise rich in cellulose, hemicellulose and lignin and can be used in pulp and paper or as a reinforcement material [6].

3.2 Leaves and Inflorescence

Banana leaves are a good source of fiber, minerals, protein, ash, pigments and phenolic compounds and are commonly used as food-serving material in various areas, apart from modern applications including edible disposables, fiber-reinforced plastic and extraction of antioxidant and antimicrobial compounds. Major limitations arise from seasonal availability, high moisture content and field-chemical contaminants. The banana inflorescence, or the so-called 'flower', contains fiber, protein, minerals and secondary metabolites such as phenolic compounds, alkaloids, saponins, flavonoids, tannins and glycosides.[4] It is used in culinary traditions and can find applications in the food ingredient sector as a fiber and protein enrichment, including in meat alternatives.

3.3 Rejected/Overripe Fruits

Fruits rejected for the fresh market due to physical damage, aesthetic issues or peculiar shape often still have high carbohydrate, protein, starch, sugar, fiber and mineral content. They can be processed into banana puree, flour, fermented beverages (such as wine and vinegar) and ethanol; some parts can also be used for pectin and starch extraction.

4. NUTRITIONAL AND PHYSICOCHEMICAL COMPOSITION OF BANANA PEEL

The composition of banana peel varies greatly depending on the cultivar, ripeness of the fruit, growing conditions, drying technique and method of chemical analysis. For that reason, data values from the literature must be considered as estimates rather than fixed figures.

4.1 Proximate Composition

Banana peel is a nutrient-rich substance that contains a high proportion of carbohydrates, starches, crude protein, fibre, beneficial fatty acids and various other micronutrients [12]. Dry-basis compositional data has shown approximate percentages of 59.5-76.6% carbohydrate, 47-53% dietary fibre, 5.5-7.9% crude protein, 2.2-11.6% lipid and 9-11% ash for the peel [6], while dietary fibre content alone has separately been reported to fall within 40-50% on a dry-weight basis [1]. Nitrogenous matter can account for about 4-10% of peel dry matter and protein content has been estimated to range from 8% to 11% of both banana and plantain peel dry weight [14].

Peel also serves as a valuable mineral source, with earlier studies documenting substantial levels of potassium, calcium, sodium, iron and magnesium.[1] Approximately 40% of the total fatty acids found within the peel consist of linoleic acid and linolenic acid [3] and for each 100 g of dried peel material, the energy value is estimated at approximately 18.89 MJ/kg, indicating good energy potential beyond its simple use as waste [5]. In comparison with the edible portion of the banana, peel has relatively high amounts of ash, crude fibre and fat, which give it distinct functional properties [3].

4.2 Dietary Fibre, Pectin and Resistant Starch

The fibre fraction of banana peel consists of between 30% and 45% insoluble fibres, such as cellulose and lignin, whereas total soluble fibres (mainly pectin) fall between 5% and 10% and these soluble fractions have been linked to helping lower elevated blood glucose and cholesterol levels [1]. The pectin from banana peel contains both galacturonic acid and various neutral sugars such as glucose, galactose, arabinose, rhamnose and xylose, with its technological behaviour depending on molecule size, degree of esterification, acetylation and pH [15].

Depending on ripeness, some varieties of banana peel may contain a range of resistant-starch compounds, which are not broken down in the digestive system until fermented in the large intestine by microbes with the extent of this effect governed by starch structure, processing history and the accompanying nutrient matrix.[1,3]

4.3 Cellulose, Hemicellulose and Lignin: The Lignocellulosic Fraction

Banana peel is a complex lignocellulosic material. In a summarised composition reported by earlier authors,[6] banana peel levels were estimated at 12.2% cellulose, 2.5% hemicellulose and 18.4% lignin, though considerable variation exists in the concentrations of both cellulose (18-59% range) and hemicellulose (17-20% range) between varieties and analytical methods. This structural material of the peel can be used for the extraction of microcrystalline cellulose, or on an even smaller scale in the form of cellulose nano- and nano-fibres and can be supplemented with simultaneously extracted pectin and phenolic fractions.

4.4 Physicochemical Functional Properties

Water-holding capacity, oil-holding capacity, swelling capacity, bulk density, particle-size distribution, colour, pH, solubility, emulsion activity and stability, thermal properties and surface charge all combine to determine how best to use a peel ingredient, such as a flour, hydrocolloid, stabilizer or encapsulating agent. These properties are dictated by factors such as the specific banana cultivar, ripeness and drying method and are expected to change as the banana ingredient is incorporated into food products or other materials [12].

5. BIOACTIVE AND PHYTOCHEMICAL PROFILE

Banana peel contains abundant secondary phytochemical plant constituents such as phenolic acids, flavonoids, carotenoids, tannins, alkaloids, terpenoids and phytosterols [5]. One study[16] identified up to 40 different compounds from the phenolic class, with the highest overall phenolic concentration (about 47 mg gallic acid/g dry weight, as GAeq), where flavan-3-ols, including procyanidins, were the

predominant group. Gallocatechin, a flavan-3-ol, was found at roughly five-fold higher concentration in the peel compared with the pulp [1].

A LC-ESI-QTOF-MS/MS study[17] tentatively characterised 24 phenolic compounds (6 phenolic acids, 13 flavonoids and 5 other polyphenols) in Australian banana samples of pulp and peel, confirming the diversity of peel phenolics according to cultivar and fruit part. The peel's phytochemical content includes carotenoids such as β -carotene, α -carotene and lutein and pigments such as anthocyanins, including delphinidin and cyanidin, which add strong antioxidant capacity and potential as a natural colourant [3]. Notably, dopamine and its precursor L-dopa present in the peel have demonstrated antioxidant potency comparable to ascorbate [1], although this does not necessarily imply effective therapeutic benefit against cardiovascular, brain-related, or metabolic disorders in humans.

The process applied to the peel can dramatically affect its phytochemical composition. Drying methods such as blanching, solvent choice, fermentation, extrusion, microwave and ultrasound-enhanced extraction, or simply high temperature for long durations, have all been shown to reduce or degrade the bioactivity of banana peels [5]. Therefore, reporting total phenolic content alone can be insufficient for comparing studies; chemical profiling and antioxidant activity assessments are typically conducted alongside relevant assays such as bioaccessibility and digestion models.

6. BIOLOGICAL, PHARMACOLOGICAL AND NUTRACEUTICAL POTENTIAL

The presence of bioactive components in banana peel suggests it is a promising source of pharmacological properties, including antioxidant, antibacterial, anti-hypertensive and anti-diabetic activity.[5] Compounds in banana peel have also been associated with the prevention of diseases such as cancer, diabetes, obesity and cardiovascular disease [3]. Historical use of banana peel in tropical folk medicine has been extensive for treating a range of afflictions, including wounds, diabetes, dysentery, coughs and diarrhoea [2].

Fibre in banana peel has been shown to reduce blood glucose concentration and hepatic glycogen levels and while fructo-oligosaccharides in banana peel act as a prebiotic, the presence of fiber can also contribute to lowering plasma cholesterol concentrations, representing a potential ingredient for cardiovascular health applications.[4] However, considerable caution is warranted when interpreting these findings.

Antioxidant activity in cell-free assays such as DPPH or FRAP measures chemical reactivity, which does not translate directly to benefits at the cellular, system or organism level. Similarly, demonstrated antimicrobial activity against pure cultures does not necessarily translate into effectiveness in a product formulation at real food pH, water-activity and ionic-strength levels and enzyme-inhibition activity against targets such as α -amylase or α -glucosidase does not guarantee equivalent effects on blood sugar in humans.

Therefore, most current claims regarding anti-inflammatory, antibacterial, prebiotic or antioxidant activities of banana peel derive mainly from in-vitro and animal studies, with clinical, pharmacokinetic or safety data in human participants remaining scarce. A realistic view is to treat current claims as promising evidence warranting further validation in human clinical studies before they can be considered proven treatments.

7. BANANA PEEL AS A FUNCTIONAL FOOD AND NUTRACEUTICAL INGREDIENT

In the last decade, considerable research has focused on developing products containing banana peel flour, powder and extract for use in ready-to-eat foods. One study[18] reported that using 5-10% banana peel flour for partial replacement of wheat flour in breads and pastas improved dietary fiber and fat content without altering the sensory profile, appealing to food industries and health-conscious consumers. Studies with 20% banana peel powder showed DPPH radical scavenging activity as high as 68.3%, while lower levels of inclusion (5-10%) maintained a soft, appealing texture.[19]

Banana fiber has also been used in fermented dairy products such as yogurt as a thickening agent, enhancing probiotic survivability, texture and other sensory aspects. Incorporating banana peel powder into yellow noodles has been shown to enhance texture, colour and vitamin B6, vitamin C and potassium content, while lowering in-vitro starch digestibility relative to standard yellow noodles [1]. Addition of banana peel flour alongside lavender in therapeutic bagel products is a recent development aimed at anxiety relief,[20] beyond improving dietary fibre and antioxidant value.

When incorporated into food, extracted beneficial components (as a separate entity or as an inclusion in ready-to-eat products) are classified as nutraceutical ingredients, ranging from fiber powder and antioxidant or phenolic compound extracts to concentrated antioxidant or pectin-based materials. Developing phenolic-rich products requires overcoming the bioavailability barrier, since phenolic components are often poorly absorbed, rapidly metabolized, or converted in the GI tract by microorganisms.

Encapsulation materials such as protein or polysaccharide complexes (pectin, cellulose derivatives, etc.) and nanostructured components (such as protein-polysaccharide conjugates or nanoparticles) have been successfully applied to protect bioactives from deterioration during food processing and storage and to control their release in the appropriate region of the GI tract; however, their potential impacts on food safety, especially the fate of nanoscale components in the GI tract, need to be meticulously assessed (see section 8). These findings show that banana peel powder/extract can be applied as a low-cost functional ingredient in food applications, with limitations that must be managed for certain food matrices to achieve nutritional benefit while maintaining acceptable sensory quality, avoiding excessive dark colour, coarse texture and volume loss.

8. CELLULOSE AND NANOCELLULOSE FROM BANANA BIOMASS

Within the context of food engineering, the carbohydrate matrix of peel, pseudostem and rachis offers a viable, sustainable source from which cellulose, hemicellulose and lignin can be isolated and utilized. This section describes cellulose and nanocellulose recovery; however, most literature has focused on utilization of peel in nutraceutical food applications rather than cellulose and nanocellulose, as already discussed above.

8.1 Types and Production Routes

Banana biomass is capable of yielding three main types of cellulose nanomaterials: cellulose nanofibers (CNFs), nanostructured cellulose (CNC) and cellulose nanocrystals (CNCs), distinguished by structural arrangement and length/width ratio and often grouped together based on shared, nature-driven properties arising from the isolation technique. Bacterial nanocellulose differs, having a distinct chemical origin from nanocellulose extracted from plants. Production of CNCs generally involves physical treatment followed by acidic hydrolysis, alkaline treatment, enzyme-assisted treatment, or oxidative treatment. High-yield cellulose nanofibres from plant matter are more commonly produced via high-pressure homogenization, whereas cellulose nanocrystals are obtained by acid hydrolysis of cellulose to expose a high content of crystalline domains.

A recent advance is a facile and economical method of producing CNCs using microwave-assisted one-pot oxidative hydrolysis combined with mild alkaline assistance on banana peel. One study[21] achieved 85.09% crystallinity of CNCs from processed banana peel by combining microwave technology with a dilute acidic oxidation process (hydrogen peroxide as the oxidizing agent combined with a strong acid such as sulfuric acid). Cellulose nanocrystals extracted from banana peel using alkali treatment, followed by bleaching and acidic hydrolysis, were produced with a yield of 29.9% and characterized by a particle dimension of around 209 nm and zeta potential of -43 mV.[22]

8.2 Food-stabilization Applications: Pickering Emulsions and Encapsulation

Due to unique properties such as high surface area, high water-binding and gelling ability (arising from its fiber network), together with being a naturally available, bio-based agent [6], nanocellulose has attracted attention as a food-stabilizing agent. Nanocellulose can stabilize Pickering emulsions by

forming a barrier at oil-water interfaces and nanocellulose of banana biomass origin has been identified as a viable alternative for stabilizing such emulsions.

Plant-derived materials such as nanocellulose fiber and crystals from banana biomass, together with other naturally extracted banana polymers such as pectin, have emerged as viable encapsulation materials for food delivery systems, protecting entrapped sensitive compounds during food processing, storage and delivery within the human gut. Given the uncertain safety of nanoparticle incorporation into foods, it is prudent to investigate their fate within the human digestive tract before recommending commercial applications.

8.3 Biodegradable Packaging and Active Films

In one study, starch films fortified with cellulose nanofiber from immature banana peel showed improved mechanical properties, including tensile strength and elongation at break, along with reduced water solubility and absorbability. Another study[23] reported enhanced thermal properties of starch film fortified with banana peel cellulose nanofiber in an active-food-packaging context.

Other studies have also demonstrated improved structural, thermal, barrier and antimicrobial properties using nanocellulose/nanocrystals of banana origin in biodegradable matrices such as starch and pectin, valuable findings for developing food packaging materials with barrier layers that prevent food deterioration, antimicrobial active films, or functional composite packaging systems addressing food security and safety concerns. However, issues such as food-contact chemical migration remain to be resolved before full commercial application in the food industry.

8.4 Green Extraction and Process Selection

Production of conventional cellulose requires strong acids, alkalis and bleaching compounds, raising environmental safety concerns and production costs, which has prompted new investigation based on green chemistry principles. Green alternative strategies currently in use and under further research include organic-acid- and enzyme-assisted degradation of plant matter in non-conventional organic solvents, application of low-cost, reusable solvent systems such as deep eutectic solvents and one-pot oxidation processes such as that noted above,[21] along with other combined chemical and physical processes. Selection of the production method depends on the target application, i.e., packaging-grade nanocellulose for mechanical and barrier functions versus stabilizer-grade nanocellulose for specific functional characteristics.

9. NON-FOOD VALORISATION AND THE CIRCULAR BIOECONOMY

In addition to food, nutraceutical and packaging uses, banana peel and biomass fractions can also be used for pectin extraction, natural colorants, fermentation substrates, animal feed and biofertilizer. Non-food valorisation of banana peel into activated carbon and magnetic composite adsorbent materials has recently been tested for removing emerging contaminants such as tetracycline and chromium from wastewater streams [7]. Hydrolysis or enzymatic conversion of banana peel polysaccharide fractions (pectin, hemicellulose and cellulose) into low-molecular-weight oligosaccharides (pectic-, xylo- and cello-oligosaccharides), with prebiotic effects and potential food, feed and pharmaceutical applications, has been observed to be greatly limited by the highly crystalline, recalcitrant structure of cellulose.[15]

New integrated models for food-waste valorisation have gained popularity through integrated biorefinery approaches, in which diverse fractions (food-grade dietary fibre and phenolics, pectin, nanocellulose and residual biomass for energy and biofertiliser) are extracted from the same waste material in sequence, rather than through isolated single-product processes.[12,24] This single-process approach for multi-faceted revenue generation optimizes resource utilization and helps overcome collection, drying and processing limitations of peel.

10. CURRENT TRENDS AND EMERGING TECHNOLOGIES

Five main trends have been observed in recent literature (2021-2026) concerning banana peel and biomass valorisation:

- (i) **Conventional versus green extraction:** studies show a trend away from classical solvent-extraction methods (Soxhlet extraction and maceration) towards innovative green extraction methods, including microwave, ultrasonic and electro-pulsed assistance and enzyme treatments, enabling more efficient recovery of phenolics, flavonoids and antioxidant activity from banana peel while cutting extraction time and solvent consumption.[25,1]
- (ii) **Combined processes for cellulose isolation:** an advance from traditional stepwise delignification, bleaching and hydrolysis towards single-stage, simultaneous hydrolysis using combined techniques, especially microwave-assisted mild oxidative hydrolysis, to produce nanocellulose of high crystallinity with reduced processing time, reagent use and yield losses [21].
- (iii) **Addition of value beyond fiber fortification:** traditional use of banana peel as a dietary fiber fortificant is increasingly complemented by investigation of nanocellulose- and pectin-based Pickering emulsions, encapsulation matrices and nano-emulsions for delivering bioactives with low solubility and/or oxidative instability in functional foods [6].
- (iv) **Synergy in active and biodegradable packaging materials:** researchers are increasingly applying nanocellulose/nanocrystals extracted from banana peel, pseudostem and rachis as a specific, novel additive in packaging formulations, in combination with other bio-materials such as starch and pectin.[23,13]
- (v) **Non-food environmental products:** research has explored bio-environmental applications such as activated carbon and magnetic adsorbent materials for pollutant removal, competing with nanocellulose applications [7]. Selection between these technologies and combined applications, depends on lignocellulose availability and the desired characteristics of the final food or non-food product.
- (vi) **Integrated biorefinery and circular bioeconomy:** studies are moving from single-product valorisation towards integrated models generating multiple fractions and value streams from a single waste matrix, such as food-grade fractions, pectin, nanocellulose and residual bioresource for energy generation, biofertiliser, animal feed and biofuel production.[12,24]

Together, these five trends signify a maturing field seeking integrated approaches to producing high-value products from banana peel and biomass while addressing associated nanotechnology issues, though with comparatively less focus on scale-up, standardized safety and product development (section 12).

11. PRACTICAL PATHWAYS TO IMPLEMENTATION

Successfully translating laboratory research findings into industrial applications of banana peel and biomass for human food consumption requires several coordinated strategies. First, drying and stabilization methods need to be standardised to prevent loss of bioactive compounds, maintain sensory quality and inhibit enzymatic browning (catalyzed by polyphenol oxidase) and microbial growth prior to further processing (peel flour, extraction material, or cellulosic products). Second, food-grade processing incorporating 5-20% banana peel flour into conventional food products such as baked goods, noodles, bread and dairy products allows use of existing food technology, delivering the fastest route to market for a new value-added product.

This approach is expected to be more economical, requiring minimal changes to industrial production lines. Third, green extraction methods should be adapted for small and medium-sized enterprises (SMEs) in local contexts (such as local hubs in Tamil Nadu, India), providing cost-effectiveness through minimized transportation costs and resource use.[12] Fourth, integrated value creation from banana biomass should adopt biorefinery and circular-bioeconomy frameworks that combine food and other value-added products through simultaneous extraction of nutrients, bioactive compounds and fibres, with residues directed to bio-fertilizer, animal feed and bioenergy production. This would enable higher economic returns[5,24] per tonne of peel processed.

12. LIMITATIONS OF CURRENT TECHNOLOGY AND SAFETY ISSUES

Value creation from banana peel and biomass for food, nutraceuticals and materials faces numerous constraints that impede scale-up to industrial technology. Browning caused by endogenous polyphenol oxidases consistently complicates preservation of nutraceutical and sensory properties during processing and physical and microbial degradation are facilitated by inherent moisture content.[2] Critical obstacles include the limited number of detailed toxicological studies, since raw peels are prone to microbial contamination, fungal toxin formation, accumulated heavy metals and the presence of biogenic amines that can affect human use of derived products.

Regulatory frameworks for utilization of banana waste in food products were generally not designed with these hazards in mind and are particularly sparse regarding nanomaterials in food-contact applications and their gastrointestinal fate. Capital costs and technical expertise, often lacking among SMEs in banana-producing nations, can prevent acquisition of advanced extraction equipment.[24] EU standards classify ingredients derived from banana peel as "novel food," making the safety-assessment process time-consuming and costly.[24] Consumer perception poses a further challenge, as, ironically, waste-based foods can provoke aversion even in cultures accustomed to their use.

It remains essential to treat claims from in-vitro bioactive, antimicrobial and anti-enzyme assays as preliminary findings warranting caution before conclusive claims of human efficacy can be made [24].

13. RESEARCH GAPS AND FUTURE PERSPECTIVES

Several research gaps should be prioritized. Comprehensive physicochemical characterization and detailed safety and toxicological studies of banana peel-derived ingredients are lacking, limiting scale-up of nutraceutical uses of the material.[3] A lack of standardization in cultivar-specific or origin-specific extraction/stabilization processes makes it difficult to compare yield, bioactive and nanocellulose production data across studies.[12] Validation of the reported health benefits of peel bioactives, most of which derive from in-vitro or animal studies, must be pursued through clinical trials.[5]

For the cellulose fraction specifically, three areas need immediate research focus. Systematic research is needed into the particle-size-dependent fate, absorption and safety of banana-biomass nanocellulose targeted as a stabilizer or encapsulant in food systems, even though it shows favorable crystalline characteristics and functional properties at laboratory scale.[22,21,6] There is currently no systematic techno-economic or life-cycle assessment comparing green versus conventional nanocellulose extraction routes from banana biomass, so insufficient data exist to establish which green extraction process is most viable. Laboratory testing has shown positive results for nanocellulose in packaging applications, but data on likely migration in food-contact situations and on end-of-life biodegradability remain lacking.

Future work on scaling up green extraction techniques should prioritize small-scale producers, who predominate in most banana-producing countries (including India and, within it, Tamil Nadu), by ensuring processes are inexpensive and energy-efficient; this, combined with techno-economic and life-cycle analysis, can establish priority technologies for wider adoption.[24] Finally, region-specific research on the effects of different banana cultivars, such as Poovan, Rasthali and Karpuravalli, which predominate in Tamil Nadu,[11] would help localize global research findings for locally feasible food-additive and cellulose-production applications.

14. CONCLUSION

Banana peel, along with other banana biomass fractions, has shifted from being regarded as waste to being valued as a nutritional product in recent literature, owing to its high content of dietary fiber, minerals, pectic compounds and polyphenols and their documented preclinical health properties (antimicrobial, antioxidant, antidiabetic and anti-inflammatory). Its applications in baked goods, cereal-based products and dairy products make it a commercially valuable ingredient, particularly for major producing regions of India and, to an extent, the whole nation.

Applications identified for its cellulose/nanocellulose fraction, such as stabilizing Pickering emulsions, encapsulating bioactives and enabling active biodegradable food packaging, can add further significant value. However, further work on extraction and standardization of banana bioactives and nano/cellulose is needed to enable utilization supported by comprehensive safety studies (including for nanocellulose), human clinical studies for nutritional claims and proper regulatory clearance.

Once these issues are addressed, use of banana peel and biomass can prove beneficial for food security, nutritional improvement and a range of environmental benefits supporting sustainable growth of the bioeconomy.

Declarations

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Conflict of Interest

The authors declared no conflict of interest.

Data Availability

Data sharing is not applicable to this article as no new data sets have been created or analyzed in the current study. All data have been included in reference articles.

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