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SUSTAINABLE BIOREFINING PATHWAYS FOR BANANA (MUSA ACUMINATA) PEEL BIOMASS: FROM STRUCTURAL MACROMOLECULES TO FUNCTIONAL BIO-BASED PRODUCTS

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Abstract

Bananas (Musa acuminata) *are among the key intercontinental economic crops and one of the world's most purchased fresh fruits. Banana peel, the outer shell of banana fruit is a major by-product left after banana utilization, contribute significantly to agricultural waste but also hold significant potential as a useful resource. This review paper focuses on the nutritional profile and value addition of banana peels with focus on how they can contribute to waste management and sustainable food system. Nearly 30 to 40% of the total fruit weight is of banana peels which are rich in dietary fiber, carbohydrates, proteins, minerals, and vital bioactive compounds which include phenolics, flavonoids, tannins, and antioxidants. These components provide important functional and health promoting properties such as antimicrobial, antioxidant, anti-inflammatory, and cholesterol lowering effects. Various fiber extraction techniques such as chemical treatment, enzymatic processing, and eco-friendly extraction methods have been developed to obtain high quality cellulose and dietary fiber from banana peel. Functional properties of extracted fibers can be further enhanced through the implementation of biorefining and modification techniques, enabling their application in food as well as in non-food industries. In addition to food applications, banana peel can be used for enzyme production, water purification, nanoparticle synthesis, and in animal fodder. Banana peels can also be utilized as a low cost biosorbent making it a useful tool for removing heavy metals and pollutants from contaminated water. The utilization of banana peel contributes to waste reduction, promotes sustainable resource management and zero waste concept. Banana peels waste conversion into valuable products supports circular bioeconomy principles and offer economic and environmental benefits. Further research can be carried out to improve processing techniques and expand the commercial utilization of banana peels.*

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INTRODUCTION:

Banana (*Musa acuminata*) is a long fruit varying in size, color, and firmness. Bananas are typically oblong and curved, with soft, starch rich flesh covered in a peel that can take on a range of coloration until fully mature. According to Singh *et al.* (2016) because of delicious taste of bananas, their nutritional value and potential to improve mental health, they are most widely consumed through the globe. According to the Food and Agriculture Organization (FAO) of the United Nations 2020 report about 120 million tons of bananas were produced globally, and this value is expected to increase further. A research by Zou *et al.* (2022) revealed that banana harvesting and consumption give rise to huge amount of by products, which include stems, banana leaves, and banana peels, all of which can be utilized by further processing to transform and incorporate them into innovative food products. With the objective to utilize the by-products and to introduce high-value functional products, research especially on banana peel has mostly concentrated on the extraction of active compounds, fibers, pectin content and other components. Report by Ashka *et al.* (2025) stated that Banana cultivation results in large quantities of by products, mainly banana peels and pseudo stems. Banana peels make up approximately 35 percent of the fruit weight, which are rich source of soluble fibers and insoluble fibers. Beside fiber banana peels also act as a reservoir of phenols, antioxidants, and bioactive compounds namely flavonoids, tannins, alkaloids, and terpenoids. These compounds contribute significantly to health by exhibiting antibacterial, antihypertensive, antidiabetic, and anti-inflammatory properties; rendering banana peels as an active source in controlling microbial growth and many disease as stated by Zou *et al.*, (2022). A study on fiber by Wachirasiri *et al.* (2009) indicated that fruit fiber has superior quality compared to other fiber sources because of its high quantity of soluble and total fiber, its ability to withhold water and oil, and by reducing phytic acid and caloric values, as well as adding to intestinal fermentability. Research by Hikal *et al.*, (2022) showed that banana peel has high dietary fiber content and value calculated was about 50 g/100 g which is considered as a healthy source if processed and utilized properl.

Banana Peel Composition:

Kusuma *et al.* (2018) claimed that banana peel is a treasure of minerals, bioactive compounds, and dietary fiber. According to a study by Zhang *et al.* (2019) banana peel is an agricultural waste that has antioxidant properties and is composed of dietary fiber, minerals, vitamins, and phytonutrients. Yusuf *et al.* (2016) study showed that banana peel can be utilized as an inexpensive source of superior quality starch estimated about 13 percent, crude protein within 6 to 9 percent range, crude fat about 4 to 11 percent, vitamins and certain bioactive compounds along with trace amount of micronutrients namely Potassium, Calcium, and Magnesium. A study by Bishnoi *et al.*, (2023) stated that chemically banana peel is composed of cellulose, hemicellulose, lignin, and simple sugars. As banana peels are widely available, it has tremendous potential to be utilized as an ideal substrate for the production of value added products. Adding to the study Mishra *et al.* (2022) provided detailed composition analysis. According to the study banana peel is composed of almost 70 percent carbohydrates, around 3 percent protein, 5 percent fiber, 5 percent fat, and moisture content of nearly 20 percent. However, on dry basis it was concluded that Banana peel has around 9 percent cellulose, nearly 21 percent pectin, 9 percent hemicellulose, 12 percent lignin, and another few low molecular compounds. Due to the presence of carbon rich organic chemicals, banana peel waste might take up to two years to break down and biodegrade.

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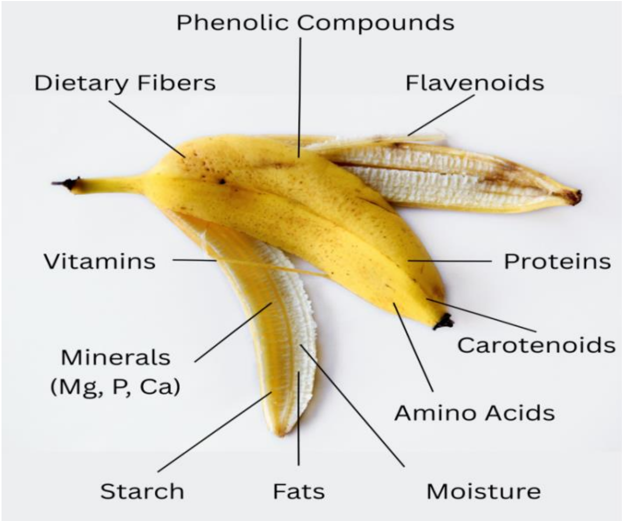

Figure 1. Composition of Banana Peel

Fiber Extraction:

Numerous methods can be used to extract fiber from banana peel. These methods include Chemical Extraction (Alkali Treatment) in which Banana Peels are treated with chemical like Sodium Hydroxide (NaOH) or Sulfuric Acid, that cleave the lignin and hemicellulose bonds, leaving behind pure cellulose fibers that are used in the production of variety of products as used by Yoshimoto *et al.* (2005). One of the general procedures mentioned by Safdari *et al.* (2021) to extract fibers from the banana peels is to cut banana peel into smaller pieces and then dry it in oven at 103°C.Then grinding it using a grinder. Once the powder is obtained, keep it in polyethylene containers at 25°C. Next take 3 g of dried powdered sample and mix it with distilled water in a hot water bath at 60, 75, and 90°C with continuous stirring and heating by a magnetic stirrer for about 50, 100, and 150 minutes. After that is done, filter the samples twice, and spin it in a centrifuge at 4000 rpm for 20 minutes to separate the suspended particles. After centrifugation, pass the solution through filter paper to separate the solid particles from the liquid supernatant extract. Next place fiber containing extract in refrigerator after mixing with 96% ethanol in 1 : 2 ratio. To separate fiber from the liquid do centrifugation at 4000 rpm for 15 minutes. Remove the supernatant and wash the remaining precipitate with 70% ethanol and then with 96% ethanol solution in order to remove impurities. In the final step, use freeze drying method to dry the samples and once dried, pack it in polyethylene bags and stored at refrigerated conditions for prolong usage and evaluation.

As the world is moving toward sustainable processes thus charcoal ash solutions are developed as alternative extraction method to chemical extraction. A research conducted by (Phirom-On & Apiraksakorn, 2022) used an environmentally friendly technique that replaces harsh chemicals like NaOH with a natural alkaline solution made from wood charcoal ash to extract cellulose from banana peels. This method implied reduces production costs, environmental impact, and aligns particularly with the food industry demands for chemical free dietary fibers extracted from banana waste (40% of fruit by weight). It also looks into zero waste uses for the wastewater generated during the process.

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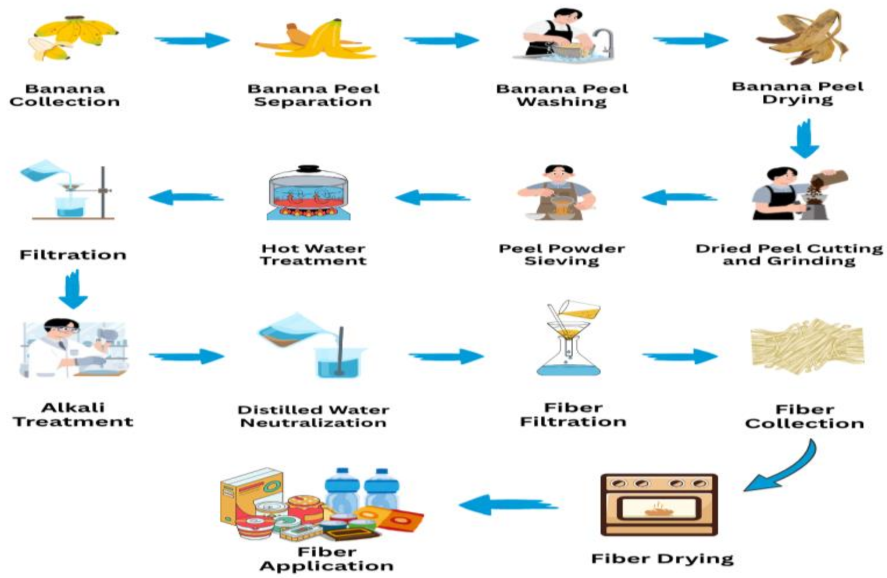

Figure 2: Flow diagram of Fiber Extraction from Banana Peel

Biorefining and Fiber Modification Techniques:

According to Bishnoi *et al.* (2023) biorefining is the conversion of organic matter, obtained from living or recently deceased organisms, resulting in variety of products that include fossil fuels, chemicals, energy, and other materials. As stated by Herzyk *et al.*, (2024) in order to biorefine banana peels extracts it passes through a series of processes, such as decoction, separation techniques which include supercritical fluid extraction, solvent extraction, and antisolvent extraction method. As a result of passing through stated processes enzymes, protein, ethanol, biogas, and other worthy substances can be obtained as final products. Modification of extracted fiber is necessary because natural fibers are usually high in cellulose content which is calculated to be around 70 percent. Beside cellulose it is also composed of approximately 20 percent lignin and other minor constituents that include pectin and waxes as mentioned by (Gupta *et al.*, 2020).

In order to modify extracted banana peel fiber different physical and chemical methods can be applied. Prominent chemical methods that are widely used include alkaline pretreatment, acid pretreatment, peroxide pretreatment and enzymatic hydrolysis according to Shimizu *et al.* (2018). Bio refining affected overall properties of the dietary fiber extracted from banana peels as evident from the results obtained from the study of Zhang *et al.* (2019). The dietary fibers water holding capacities were elevated and were found to be about 7.50 and 6.91 g/g each. Swelling capacities reached to about 4.8 ml/g by treatment of the obtained fiber with sodium hydroxide and sulfuric acid respectively. An increase in oil holding capacities approximately 5.52 g/g and improved sodium cholate adsorption capabilities were observed in the dietary fibers synthesized by sequential treatment with trypsin followed by sulfuric acid treatment.

Peel Extract Applications and Health Benefits:

1. Rich Source of Dietary Fiber:

Cellulose a type of dietary fiber extracted from banana peel is resistant to digestion and absorption by the human body can help in body weight management and can also act as a prebiotic if its solubility can be improved according to (Phirom-On & Apiraksakorn, 2021). Food products incorporated with soluble fiber provide superior health benefits that include

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blood glucose and cholesterol management stated by (Jovanovski *et al.,* 2019). Further sequential studies by Tamargo *et al.,* (2019) demonstrate that it can substantially minimize the risk of heart disease and function as a fermentable substrate. These claims were also backed by studies conducted by Bishnoi *et al.* (2023) stating that dietary fiber from banana peel is composed of two fractions namely soluble fraction composing of pectin and gums and secondly insoluble fraction which compose of cellulose, lignin, and certain hemicelluloses, both of which have favorable influence on human health, such as safeguarding against diverticulosis, colon associated cancer, irritable bowel syndrome, constipation, and cardiovascular diseases.

2. Protein and Essential Amino Acids:

Study by Mohapatra *et al.* (2010) revealed that presence of all essential amino acids except for lysine in banana peel is higher than FAO standard. (Khawas & Deka, (2016) termed banana peels as great suppliers of amino acids as it contain nine essential, and nine non-essential amino acids at different developmental phases, making total of 18 amino acids. Banana peels carry around 8% of bioactive protein and their composition is highly affected by maturity and banana variety (Budhalakoti, 2021). Further studies by (Yasmin & Saleem, 2014) have shown that banana peels protein possess excellent antimicrobial and antifungal characteristics. According to study by Rahimizadeh *et al.,* (2020) the extracted proteins can be used in food and beverage industry as emulsifier, foaming agent, and thickening agent in products such as baked goods, confectionery, and protein shakes.

3. Antioxidant and Phenolic Compounds Source:

Zaini *et al.,* (2022) stated that as banana peels are rich in polyphenols, flavonoids, and carotenoids, it make them an excellent source of antioxidant nature by giving it ability to neutralize free radicals, reduce oxidative stress and due to above properties they have also been utilized for treatment of numerous medical conditions that include diarrhea, burns, ulcers, and inflammation according to further study by Saeed *et al.,* (2024). Banana peels possess relatively high amount of phenolic compounds as compared to other fruits byproducts according to studies by (Vu *et al.,* 2018; Zaini *et al.,* 2022). Banana peel is a powerhouse of numerous phenolic compounds such as gallic acid, catechin, epicatechin, tannins and anthocyanins stated by (Sidhu & Zafar, 2018) that support previous studies. Further findings by Sulaiman *et al.,* (2011) study highlighted that phenolic and antioxidant activities in peel extracts are higher comparative to banana pulp with few exceptions.

4. Industrial Enzymes:

According to study by Unakal *et al.* (2012) high value industrial enzymes can be produced from banana peel such as amylase enzyme, that is widely used for multiple purposes across various industries including baking, culinary, textile, brewing, detergent, paper, and pharmaceutical industry. Study by Bhavani *et al.* (2023) also suggested that extraction of enzymes like alpha amylase and cellulase can occur from banana peels. According to Mondal *et al.,* (2022) amylase enzyme hold critical role in complex compounds hydrolysis such as converting starch into simpler and smaller units known as glucose in food, beverage, and baking industries. Thereby, enzyme amylase is utilized to prepare cakes, cookies, beer, juice, and digestive syrups.

5. Water Purification:

As population growth and industrialization is on peak, the demand for pure water is inclining day by day (Vorosmarty *et al.,* 2000). In order to overcome this scarcity, significant efforts are being made to find alternatives for water supply, and to treat and reuse industrial wastewater through purification. Another study by (Akpomie & Conradie, 2020) stated that due to abundance, banana peel can be utilized as cost effective, biodegradable biosorbent for efficiently removing pollutants such as dyes, heavy metals, and oils from water. According to (Nodeh *et al.,* 2016) usage of biomass waste materials is most

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preferred for biosorption as it is cost effective, require no technicality, and as it is biodegradable so turns out to be environment friendly. A research by Reddy *et al.*, (2015) concluded that banana peels can be used as biosorbents to remove nitrates from fluids.

6. Usage in Animal Feed:

Banana peels could be used as valuable energy source in livestock diets that support metabolic activities and growth due to its high carbohydrate profile (Tsado *et al.*, 2021). According to Bishnoi *et al.*, (2023) banana peel possesses variety of micronutrients and amino acids, that are essential for livestock health and well-being. Banana peel can be harnessed as cost efficient source of feed for animals but improvement through hydrothermal processes is required in order to elevate its nutritional content and to enhance its digestibility. Feeding time of lactating cows can be reduced by including banana peel up to 60 percent in the diet with sorghum silage which results in enhanced milk production capacity of cows due to feeding efficiency and reducing rumination on dry matter (De Angelis, 2025). Egg production and weight gain in chickens can also be optimized through by addition of 25 percent banana peel powder to corn based feed according to study by Araya *et al.*, (2021).

7. Nanoparticle Production:

Kokila *et al.*, (2015) study suggested that nanoparticles can be produced by utilizing banana peels as a principal source. Besides its applications in medical and pharmaceutical industry, noble metal nanoparticles such as silver, gold and platinum are widely incorporated in shampoos, soaps, detergent, shoes, toothpaste and cosmetic products that directly get in contact with the human body. According to study by Gopi *et al.*, (2014) nanoparticles of palladium, gold, silver, cadmium sulfide, and hydroxyapatite can be produced using banana peel because of its rich profile in polymers such as hemicellulose, lignin, and pectins. A research by Goh *et al.*, (2023) utilized banana peel extract as reducing and capping agent for development of environment friendly silver nanoparticles (AgNPs).

8. Components and Their Health Benefits:

Below table show the summary of Banana peel components and its effects on health.

COMPONENTS	HEALTH BENEFITS
Dietary Fiber	Improves gut health (Oliver *et al.*, 2021)
Phenolics	Antioxidant (Zeb, 2020)
Flavonoids	Anti-inflammatory (Ginwala *et al.*, 2019)
Potassium	Heart health (Aburto *et al.*, 2013)
Iron	Prevents anemia (Andersen *et al.*, 2023)
Tannins	Antimicrobial activity (Villanueva *et al.*, 2023)

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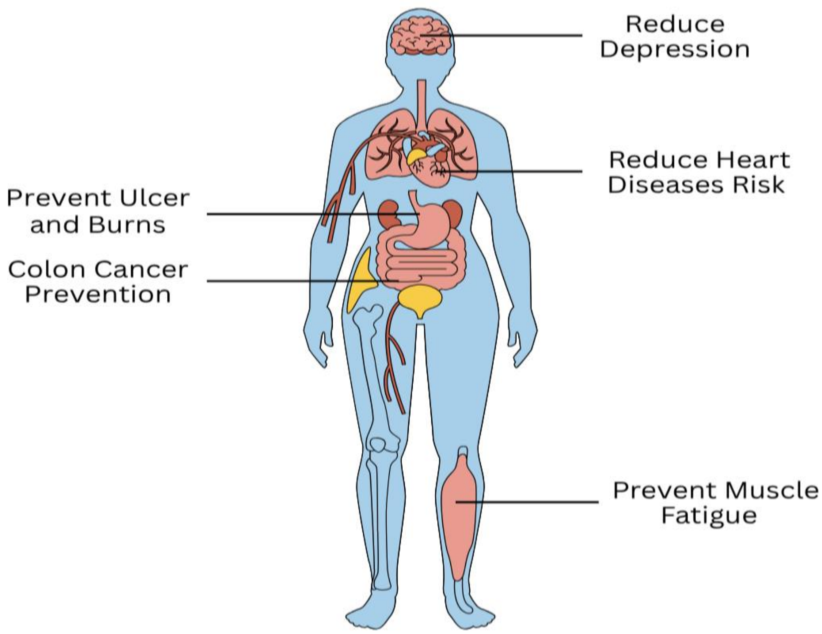

Figure 3: Health Benefits of Banana Peel Extract

CONCLUSION

Banana peels can act as sustainable and economical source for various components with significant functional and health promoting potential. Its utilization aligns with sustainable development goals, zero waste and circular bioeconomy concepts. With proper processing and standardization, banana peel derivatives can serve as innovative ingredients in functional food development which is a game changing way to protect the ecosystem and recover cost incurred from trash.

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