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Value addition and waste utilization of Banana: A review

Ravindran, C.[1]*, Kavitha, M[2]., Yazhini. S.P[3]., Dharshni. A[4]., Athina. G.A[5]., Akila. M[6]. And Tamizhvanan. A.[7]
[1]Associate Professor and Head, Horticultural Research Station, Kodaikanal
[2]Assistant professor (Biochemistry), RVS Pamavathy College of Horticulture, Sempatti, Dindigul
[3,4,5,6,7]Research Scholars, Department of Fruit Science, HC & RI, Periyakulam
*Email: ravindran.c@tnau.ac.in

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Abstract

Banana is one of the most widely cultivated fruits globally, with its production generating a substantial amount of agricultural waste. The improper disposal of banana waste, including peel, stem, and leaf, not only leads to environmental pollution but also represents a missed opportunity for resource recovery. Recent studies have focused on the potential of banana waste as a sustainable resource for a variety of applications, including food, bioenergy, bioplastics, and agricultural products. Banana peel, rich in bioactive compounds, offers promising opportunities in food fortification, nutraceuticals, and functional food development. Additionally, banana pseudostems, traditionally discarded, contain fibers that are being explored for eco-friendly textiles and biodegradable materials. The high cellulose content in banana stems and leaves makes them an attractive source for bioethanol production and biocomposites. Furthermore, banana waste has been found to have applications in wastewater treatment, wherein its adsorption properties can be utilized for the removal of heavy metals and other contaminants. This review synthesizes the current state of research on banana waste utilization, highlighting its potential for contributing to circular economy models and addressing the growing global concerns related to waste management, resource conservation, and sustainable development. Future work should focus on scaling up the biotechnological processes, improving cost-effectiveness, and exploring novel applications of banana waste to maximize its potential in various industrial sectors.

Keywords: Banana waste, waste utilization, banana peel, biocomposites, bioethanol, circular economy, sustainable development.

Introduction

Banana (*Musa spp.*) is one of the most widely grown and consumed fruits around the world. It belongs to the Musaceae family and is part of the Zingiberales order. The genus Musa includes both edible and wild species, with the most common varieties being *Musa acuminata* and *Musa balbisiana*, along with their hybrids. While bananas are mainly grown for their fruit, other parts of the plant, such as the pseudostem, leaves, and rhizomes, create a large amount of biomass, much of which often goes unused or is thrown away as waste.

Bananas are an important fruit crop found in tropical and subtropical regions. India, the leading banana producer, generates nearly 26% of the world's total production. Other major producers include China, the Philippines, Ecuador, Brazil, and Indonesia. The extensive cultivation of bananas is due to their high economic importance and nutritional benefits.

In India, banana farming occurs in several states, with Tamil Nadu, Maharashtra, Gujarat, Andhra Pradesh, and Karnataka being the largest contributors. The total area for banana farming in India is about 9.6 lakh hectares, producing around 32 million metric tonnes each year, with an average yield of 34 tonnes per hectare. Despite this significant production, a large amount of banana biomass such as peels, pseudostems, leaves, and rhizomes is discarded, which raises environmental concerns.

Banana farming generates a lot of waste, including peels, pseudostems, leaves, and rhizomes that are often disposed of, causing environmental problems. However, innovative methods to use banana waste provide chances for sustainable practices in agriculture, industry, and environmental protection. Banana compounds that can be valuable in medicine and pharmaceuticals. By utilizing banana waste, pollution can be reduced, a circular economy can be encouraged, farmer incomes can be boosted, and eco-friendly industries can thrive, turning banana waste into a valuable resource rather than just an agricultural byproduct.

Banana Production and Biomass Generation

It has been observed that for each ton of banana fruit collected, around 3 tons of pseudostem, 150 kg of rachis, and 480 kg of leaves are produced, along with 100 kg of discarded fruit. Banana waste, such as pseudostems and leaves, is often returned to the soil to help rejuvenate it, but sometimes it is collected for disposal in large open-air dumps (Subagyo and Chafidz, 2018). Many banana by-products and imperfect fruits end up wasted, raising environmental issues like waste accumulation and contamination. This waste typically goes to landfills, rivers, and oceans, which can draw pests and spread diseases (Martins *et al.*, 2019). Turning banana by-products into biogas can significantly reduce these environmental problems. This approach offers a sustainable solution for tropical developing countries like Malaysia, India, Indonesia, and the Philippines. By producing renewable energy, it promotes economic development and supports industries like fertilizer production and food processing. The potential energy output from banana biomass is estimated to reach up to 950 MW. Biogas consists of about 50% methane and can produce 58.71 mW per liter (How *et al.*, 2019).

Environmental Challenges of Banana Waste

One of the main concerns is the improper disposal of banana waste. When left to decompose in landfills or open spaces, banana peels and plant residues release methane, a potent greenhouse gas that contributes to climate change. Additionally, excessive banana waste, particularly pseudostems and leaves, if not recycled or utilized, can lead to land and water pollution. For instance, banana peel residues can leach harmful chemicals into the soil and water, negatively affecting local ecosystems and reducing soil quality (Guerrero and Munoz, 2018).

Banana waste also contributes to the depletion of natural resources when not repurposed. The burning of banana plant residues, common in some farming areas, leads to air pollution, releasing harmful particulate matter and contributing to respiratory problems in nearby communities. Moreover, the inefficiency of organic waste disposal methods reduces the potential for sustainable practices like composting, which could otherwise enhance soil fertility and reduce the need for synthetic fertilizers (Priyadharshana *et al.,* 2022).

Nutrient Composition and Chemical Properties of Banana Waste

Banana contains various parts, including the peel, leaves, pseudostem, and blossom, have distinct nutritional compositions, making them valuable for agriculture, industry, and human health. The banana fruit primarily consists of 77.19% moisture, 0.3% protein, 0.1% ash, and 22.12% carbohydrates. The peel, often considered waste, contains 8.28% moisture, 4.77% protein, 15.30% ash, 13.15% fat, and 9.4% carbohydrates. Banana leaves, a significant biomass component, have 66% moisture, 14.98% protein, 10.37% ash, 21% fat, and 60-71% carbohydrates. The pseudostem, left behind after fruit harvest, contains 5.0-8.9% moisture, 2.2-5.0% protein, 1.8-7.8% ash, and 20.5-38.8% carbohydrates. The banana blossom has the highest moisture content (90.01-90.23%) with 1.43-1.99% protein, 2.42-3.21% ash, 0.43-0.54% fat, and 95.23-95.61% carbohydrates (Hikal *et al.,*2022).

The mineral composition varies across different banana parts. The fruit contains 308-426 mg of potassium per 100 g, while the peel has 4.39 mg, leaves 3.8 mg, pseudostem 10.63 mg, and the blossom the highest at 553.3 mg. Phosphorus content ranges from 15-29 mg in the fruit, 211.3 mg in the peel, 1.8 mg in leaves, 2.09 mg in the pseudostem, and 10.63 mg in the blossom. Calcium is found in banana fruit (4-7 mg), peel (59.1 mg), leaves (1.2 mg), pseudostem (4.01 mg), and blossom (56.0 mg) (Oyeyinka and Afolayan, 2019).

Trace minerals such as copper, zinc, iron, and manganese also vary. Copper is found in banana fruit (0.025-0.186 mg), peel (0.51 mg), leaves (0.00797 mg), and pseudostem (0.02 mg). Zinc is present in the fruit (0.024 mg), peel (0.033 mg), leaves (0.032 mg), and pseudostem (16.60 mg). Iron content is 0.19-0.41 mg in the fruit, 4.7 mg in the peel, 0.2778 mg in leaves, 30.65 mg in the pseudostem, and 56.17 mg in the blossom. Manganese is found in the fruit (0.116-0.829 mg), peel (0.702 mg), leaves (0.2566 mg), and pseudostem (27.86 mg), but its content in the blossom is unavailable (Pareek S., 2019).

Banana parts also provide essential vitamins. Vitamin A is present in the peel (3.21 mg) but not reported for other parts. Vitamin B1 is found in fruit (0.062 mg), peel (1.79 mg), and pseudostem (0.15 mg). Vitamin B2 is in the fruit (0.073 mg) and peel (1.03 mg). Vitamin B3 is found in fruit (0.672 mg), peel (2.93 mg), and pseudostem (0.73 mg). Vitamin B6 is present in fruit (0.042 mg), peel (2.93 mg), and pseudostem (0.33 mg). Vitamin C content is highest in the fruit (18.4 mg), while the peel contains 1.03 mg. Vitamin E is found only in the peel (1.03 mg) (Kumari *et al.,*2023).

Banana processing

Bananas are a common household fruit, typically consumed fresh. However, numerous processed products are made from fresh bananas and their various components. These banana-based products include items such as bananas in syrup, dried banana slices (non-fried), frozen bananas, dried bananas, banana-based alcoholic beverages and ethanol, banana powder, jellies, jams, compotes, banana slices, juices, nectars, drinks, fried banana slices, and banana vinegar, among others (Pauline *et al.,*2017).

Peel

Banana peel is a significant byproduct of the processing process. Bananas consist of 60% pulp and 40% peel, with approximately 7.25 kg of peel generated from a box of bananas weighing 18.14 kg. The peel is rich in carbon-based organic compounds, including cellulose (7.6–9.6%), hemicellulose (6.4–9.4%), pectin (10–21%), lignin (6–12%), chlorophyll pigments, and other low molecular weight compounds. If not managed properly, these wastes can emit unpleasant odors due to natural decomposition and release gases that contribute to the greenhouse effect (Tibollo *et al.,* 2018).

Pseudostem

Pseudostems are the banana plant's stems that transport nutrients from the soil to the fruits. They consist of two components: the nodes and internodes, which form the floral stem and provide support to the inflorescence. The outer layer is made up of sheaths from several rolled leaves that emerge from the corm's knots and floral stem, arranged in a basal, helical rosette at a 120° angle. The pseudostem can grow between three and five meters in height, with a diameter ranging from 40 to 60 cm. The fiber derived from the dried petioles and pseudostem of bananas is used in paper production (Arafat *et al.,* 2018).

Pulp

Banana pulp is a valuable source of essential phytonutrients, such as phenolic compounds and vitamins (B3, B6, B12, C, and E). It also contains carotenoids, flavonoids, amine compounds, and dietary fiber. Dietary fibers are non-digestible carbohydrate polymers, categorized into two types based on their water solubility: soluble fibers (like pectin and some hemicellulose) and insoluble fibers (such as cellulose, lignin, and resistant starch) (Guerrero *et al.,* 2018).

Machineries used for banana waste management

Banana Waste Shredders

Banana waste shredders are essential for processing banana plant residues like pseudostems, leaves, and peels into smaller, manageable pieces. These machines enhance waste utilization by converting bulky banana biomass into fine particles suitable for composting, biofuel production, or fiber extraction. Equipped with high-speed rotating blades, shredders efficiently reduce waste volume and prepare it for further use. In sustainable industries, they help turn banana waste into valuable products such as organic fertilizer, animal feed, and bioplastics making them key to eco-friendly agricultural and industrial operations (Yamin and Rasyid, 2024).

Banana Waste Cutters

Banana waste cutters are machines designed to slice banana plant residues like peels, stems, and leaves into uniform pieces. By ensuring consistent size, they make waste easier to handle for composting, fiber extraction, or biogas production. The cutting process increases surface area, speeding up decomposition and conversion into raw materials for animal feed, organic mulches, and pulp-based products. Their precision and efficiency contribute significantly to minimizing banana waste (Mowafy *et al.,* 2017).

Banana Waste Crushers

Banana waste crushers are powerful machines that grind banana plant residues into fine particles for easier handling and processing. These crushers are commonly used in industries focusing on biofuel production, composting, and organic fertilizer manufacturing. The crushing process helps release valuable nutrients from banana waste, enhancing its utility in soil enrichment and biogas generation. By reducing waste bulk, crushers simplify storage and transport. With their durable design and efficiency, these machines support sustainable waste management and the eco-friendly use of agricultural byproducts (Zhang *et al.,* 2013).

Banana Waste Evaporators

Banana waste evaporators are specialized machines that remove excess water from banana-based materials through controlled heating. They are widely used to produce banana puree, extracts, and natural sweeteners while improving product quality and shelf life. By converting liquid banana waste into concentrated forms, evaporators make it suitable for food, cosmetic, and pharmaceutical applications. Modern, energy-efficient designs also help minimize power use, making these machines an important part of sustainable banana waste processing (Wang *et al.,* 2022).

Horticultural Applications of Banana Waste

Bio-mulching film:

The resistance of bio-polymer thin films to biodegradation in compost soil, derived from renewable resources like waste banana peel and eggshell in a polymer matrix, represents an innovative advancement in the agricultural sector. These biodegradable bio-mulching films help retain soil moisture and improve nutrient content, supporting healthy plant growth. The films, typically 0.10–0.15 mm thick, use banana peel as a reinforcing fiber and eggshell as a filler. In soil burial tests, films with 10% eggshell composition (EWE) showed visible surface damage, indicating active biodegradation and a gradual decline in physical strength over time (Nik Yusuf *et al.,* 2016).

Nano Fertilizers:

Benefits of using nanotechnology in agriculture involve various applications, such as the creation of nano fertilizers and nano pesticides, which help enhance nutrient levels, boost crop productivity, and contribute to soil and water decontamination, as well as protection against pests and diseases. To produce organic fertilizer, banana peels are crushed and combined with potassium hydroxide, then filtered and heated to 70°C with continuous stirring at 300 rpm. Additionally, Williams banana peel has been used to produce nano fertilizers with particle sizes ranging from 19 to 59 nm. Nano fertilizers enhance plant metabolism and nutrient absorption by utilizing nanometric pores, facilitated by molecular transporters or nanostructured cuticle pores. Studies have shown an average efficiency increase of 18–29% when using nano fertilizers compared to traditional fertilizers (Hussein *et al.,* 2019).

Organic fertilizers:

Bokashi is a widely used organic fertilizer that helps improve soil fertility. Its production process is relatively quick and involves various materials, such as chicken manure, black earth, ash, or coal. The final product is grayish in color, with a sandy appearance. To prepare the materials, banana peels and pseudostems are chopped into 2–5 cm pieces and shade-dried for three days. The soil is sifted to remove impurities like stones and sticks. Molasses is then mixed with water, much like preparing yeast for bread. All ingredients are layered and mixed to form a trapezoidal pile, which is turned regularly for even blending until it reaches about 90 cm in height (Alzate Acevedo *et al.,* 2021).

Waste of Banana in Textile and By-Products.

Paper Production

Another use of banana by-products is the use of pseudostems in the paper industry as an alternative to wood pulp which is environmentally friendly. Treatment of the pulp with lower temperature by using formic acid helps improve the pulp. Banana residues produce paper that is stronger, more durable and water resistant since it does not absorb water. Banana leaves and peduncles present high-quality short-fiber pulp that has fiber properties equal to those of traditional sources, which offers high burst factor, tear index, stretch and tensile strength (Shini *et al.*, 2024). When 20 percent banana stem pulp is mixed with 80 percent commercial bagasse pulp, high-grade writing and printing paper is obtained. Banana sheaths contain high levels of pentosan, and thus, this gives them thickness, which is resistant to grease. Pseudostem pulp that has been processed using kraft or soda can successfully substitute wood pulp with kraft being more effective. The use of a carboxymethyl cellulose (CMC) coating at 3-5% to coat 70deg SR pulp is highly effective to increase grease resistance (Ramdhonee & Jeetah, 2017).

Biomethane

Waste banana peels, pseudostems, and stalks present a good potential of renewable energy production through biogas. Microorganisms break down the biomass under anaerobic digestion to produce methane. Banana peels are also good in producing briquettes whose combustion efficiency is also good and left-over waste can be used as a compost in order to enhance the fertility of the soil. Mesophilic (37-40 °C) and thermophilic (50-55 °C) fermentation of banana stem slurries (2-16% solids) provide greater yields of methane at 2% total solids; both at mesophilic and thermophilic. Despite being a faster process, thermophilic digestion produces a little less gas. Digestion under controlled pH and temperature conditions results in large losses of organic solids and COD, which proves the usefulness of biomethanation of banana residues (Gupta *et al.*, 2023).

Bioethanol

The banana residues are also promising feeds to bioethanol, which is a renewable source of energy and is manufactured by fermentation of cellulose using microorganisms. Banana peels contain high levels of fermentable sugars and the quantity of ethanol produced is dependent on the concentration of the substrate, the length of fermentation, and the type of microbial strain. *Clostridium thermocellum* CT2 and *Clostridium* *thermosaccharolyticum* HG8 have been used to ferment pseudostems and leaves and Saccharomyces cerevisiae is a good fermenter of peel-derived glucose into ethanol. Fermentation is enhanced by pre-treating the pseudostems, leaves and fruits with enzymes or mild chemicals, with pseudostem substrates produced as high as 17.1 g/L ethanol (Sawarkar *et al.*, 2022).

Sources of Cellulose, Pectin and Starch.

Pseudostem pith and green culled fruits are banana by-products that are useful in the extraction of cellulose, pectin, and starch. Banana starch is heat resistant and has low amylose content as compared to corn starch and can be used in food and industrial applications. Even though the pectin content in the banana residues is less as compared to citrus sources, it is still useful in thickening and gelling processes. With the help of acidic hydrolysis, microcrystalline cellulose may be extracted out of banana fibers. Starch, cellulose, and pectin are vital biopolymers in the food, pharmaceutical, and biofuel sectors because they could undergo a transformation into fermentable sugars to form bioethanol (Verma *et al.*, 2024).

Phenolic Compounds

Banana wastes contain a high concentration of bioactive phenolics and flavonoids. Examples of hydroxybenzoic acids include vanillic, gallic and p-hydroxy benzoic acid that is found in the sap of banana and hydroxycinnamic acids such as ferulic, caffeic, p-coumaric, chlorogenic and synapic acids found in plant parts. Anthocyanins (petunidin-3-rutinoside in the bracts), flavonols (quercetin in the flowers and sap, kaempferol and myricetin in the peel and pulp), flavones (apigenin and rutin), and flavanones (such as naringenin) are all flavonoids. A powerful antioxidant, catechin is present in large amounts in the pulp. These are the compounds that make banana by-products antioxidants and therapeutic (Vu *et al.*, 2018).

Therapeutic Applications

Banana by-products exhibit various pharmacological functions. The bananas are green and contain antidiarrheal effects, and the pulp assists in reducing the cholesterol levels. Banana meal and peel have antioxidant activity and green plantain fruits enhance wound healing. Ripe and unripe banana ingredients exhibit anti-allergic characteristics. Banana sap has antimicrobial, antioxidant and wound-healing activities as well as possible antidiabetic and antilithic activities. These therapeutic effects underscore the prospects of banana residues in coming up with natural health supplements and pharmaceutical formulations (Choudhary *et al.*, 2023).

Carbon Nanodots

Banana pseudo-stem biomass converted into carbon nanodots (CNDs) has been of interest in biomedical and environmental applications. They are biocompatible, photostable and low-toxicity, fluorescent water-soluble nano-particles, ideal in bioimaging and biosensing. The CNDs produced using one-pot hydrothermal reaction can be used to detect Fe3+ as fluorescent probes. More so, green banana starch is cross-linked with citric acid to produce nanoparticles that can encapsulate hydrophobic agents such as b-carotene to release them at the intestine. Gold nanoparticles prepared using banana pith also exhibit bacteriostatic activity as well as have the possibility of being used in eliminating textile dyes present in wastewater (Kaur & Verma, 2022).

Textile Applications

In the textile industry, banana fiber has replaced cotton as a sustainable alternative to this textile because of its strength, stiffness and biodegradability. The fibors may be softened by boiling in distilled water, and then mixed with cotton, in proportions of 5:95, 10:90, and 15:85 and spinned into yarns by ring-spinning. Banana-cotton blends have tensile strength that is 14 percent stronger, elongation which is 18 percent higher and yarn quality which is 43 percent higher than that of 100 percent cotton ones. The 15% tensile strength, 22% tear resistance, 15% increased air permeability and 30% abrasion resistance are also proved in woven fabrics of these blends. Such properties make banana fiber a prospective, sustainable substitute of cotton in the production of apparels (Khan *et al.*, 2022).

Bioplastic

Bio-plastic can also be made using banana residues. The renewable polymers are one that is biodegradable and decomposable to microbial activity, which is an alternative way to petroleum-based plastics. The bioplastics are broadly categorized into three, which are petroleum-based biodegradable polymers, hybrid bio-petroleum plastics, and renewable resource-based polymers. These materials greatly minimize carbon footprints, greenhouse gas emissions and energy consumption in the manufacturing process and environmental pollution to the minimum. They are also characterized by favorable physical qualities like increased water vapor permeability, lessened texture, lowered oily, improved printability and tactile feel. Starch and cellulose of banana are among the major raw materials to build these bioplastics that are environmental friendly

(Alcivar *et al.*, 2022).

Medicinal and Pharmaceutical Potential of Banana

Bio-Oil

Bio-oil is a dense, oxygen-rich liquid offering a sustainable alternative to fossil fuels. With a density of 1200 kg/m^3, it provides economic and environmental advantages over other thermal conversion methods (Bridgwater *et al.*, 1999). Slow pyrolysis of banana pseudostem (BPS) increases biochar yield, enhancing soil fertility and carbon sequestration, while rapid pyrolysis produces higher-value products. A study revealed that BPS bio-oil showed superior yield and performance compared to other biomasses, and pre-treatment to reduce ash content further improved its quality (Taib *et al.*, 2021).

Minerals

Banana stems are rich in essential macronutrients such as potassium (K), calcium (Ca), phosphorus (P), magnesium (Mg), and sodium (Na). Potassium and sodium regulate acid–base balance, calcium and phosphorus strengthen bones and teeth, and magnesium supports nerve and muscle function (Ho *et al.*, 2015). Banana stems and leaves also contain carotene, riboflavin, thiamine, and nicotinic acid. Incorporating freeze-dried whole green banana flour as a 30 % substitute for wheat flour significantly enhances the dietary fibre, macronutrient, and mineral content of bread (Amini-Khoozani *et al.*, 2020).

Dietary Fibres:

Bananas are valued for their high dietary fiber content, including cellulose, hemicellulose, pectin, and lignin non-starchy polysaccharides that support detoxification and weight management (Sujithra & Manikkandan, 2019). Banana pseudostem flour, due to its rich fiber composition, serves as an effective functional food ingredient for fiber-enriched products (Li *et al.*, 2018).

Polyphenols and Flavonoids:

Plant extracts rich in antioxidants have shown significant antimelanogenic effects. The ethanolic extract of banana stems has demonstrated a reduction in melanin content in melanocytes, indicating its potential to inhibit melanin production and reduce gingival pigmentation, offering a promising natural alternative for periodontal depigmentation (Vu *et al.*, 2019; Sowmya *et al.*, 2022).

Antioxidant Activities:

Banana peels contain higher concentrations of phenolic compounds such as gallic acid, catechin, epicatechin, gallocatechin, and anthocyanins than many other fruits. Notably, the gallocatechin content in peels is five times higher than in pulp. These compounds contribute to strong antioxidant activity, as measured by FRAP, ABTS, and DPPH assays. Antioxidant potential increases during ripening and decreases once the fruit becomes overripe, emphasizing the role of phenolic compounds as the primary antioxidants (Dahham *et al.*, 2015).

Antimicrobial Agent:

Banana peel extracts show significant antibacterial activity against bacteria such as *Bacillus cereus*, *Staphylococcus aureus*, *Bacillus subtilis*, and *Escherichia coli*. This activity is attributed to 2-Methyl-5-(1-methylethyl)-phenol. Methanolic extracts from Nigerian bananas inhibited *S. aureus*, *P. aeruginosa*, and *E. coli*, while ethanol and ethyl acetate extracts from Bangladeshi bananas were effective against both Gram-positive and Gram-negative bacteria, including *Bacillus megaterium* and *B. subtilis* (Mordi *et al.*, 2016).

Anti-Cancer Activities:

Ethanol extracts from banana inflorescence have demonstrated selective cytotoxic effects against human colorectal cancer cell lines (HT29 and HCT116), with minimal toxicity to normal human umbilical vein endothelial cells. These findings suggest selective anticancer potential. Morphological changes, including cell shrinkage, membrane blebbing, and detachment, indicate apoptosis as a probable mechanism of cell death (Revadigar *et al.*, 2017; Arun *et al.*, 2018).

Livestock and Animal Feed Potential

In tropical areas, banana plants and their byproducts, such as leaves, stalks, and pseudo stems, are good sources of food for animals. People use these plant parts in many ways, such as fresh, sun-dried, or ensiled with things like molasses or rice bran. Banana leaves have 10–17% crude protein (CP) and about 15% dry matter (DM). Pseudo stems have 3–5% CP and 5–8% DM. Both parts are high in fiber, with neutral detergent fiber (NDF) levels between 50 and 70% and acid detergent fiber (ADF) levels between 30 and 40%. (Kramer, 2014).

Ruminants, especially cattle, can keep positive balances of nitrogen, calcium, and phosphorus when given chopped whole banana plants. However, for the best productivity results, it is wise to add supplements that are rich in energy and phosphorus. In one study about bulls that were fed chopped banana plants for 30 days: these animals reached 84% of the required DM intake and maintained both weight and health. Crossbred bullocks fed banana plants ad libitum also met their maintenance requirements but with some occasional cases of diarrhea. The pseudo stem digestibility was higher than that of leaves because of differences in water and lignin content. Also, tannins from banana leaves may affect digestibility as well as have anthelmintic effect. (Ezaddin & Salih, 2023).

Another by-product that has potential as livestock feed is the banana peel, which makes up about 30% of the weight of the fresh banana fruit. The ripe peel contains carbohydrates like 13.8% soluble sugars and 6.2% ether extract, as well as 8% CP. Banana peels can replace up to 30% of the diet in ruminants such as goats and cattle without any adverse effects on growth or milk yield. On the other hand, in non-ruminants such as pigs and poultry, inclusion levels should be limited to below 20%, since higher proportions might negatively affect their growth performance. In rabbits, banana peel can effectively replace maize up to a level of 30%, providing nutritional and economic benefits. (Babu, 2016).

Banana waste by-products

Banana pseudostem fibres

Banana fiber is widely utilized as a blending material in the textile industry, particularly in countries such as the Philippines, Malaysia, Japan, and Korea. Being a natural fiber, it blends well with other fibers like jute and mesta, making it versatile for various industrial products (Fig 1). These products include gunny bags, door mats, carpets, yarn, ropes, geo-textiles, luggage carriers, and interior decorative crafts, as well as paper items like tissue paper and paper bags, where high strength is essential. In addition to its textile applications, banana fiber serves industrial purposes such as a natural sorbent, a base material for bioremediation and recycling, and as a natural water purifier. Furthermore, banana fiber is used in the production of socks and gloves in some European countries (Mohiuddin *et al.,*2014).

Hard board making

Banana fiber is used in the production of hard paper and boards, often combined with scutcher, cotton rags, waste paper, and paddy straw in varying proportions. This blend creates a type of board that is increasingly being used as an alternative to traditional boards available on the market (Fig 1) (Mohapatra, 2010).

Handicrafts

Banana fiber is used to create a wide range of handicraft items. These include decorative wall hangings, bags, coasters, table mats, pillows, jajim, tosok, sofa sets, dolls, keychains, and more. This sector offers a valuable opportunity for women to enhance their economic and social conditions by actively participating in its development (Fig 1) (Manandhar, 2010).

Eco-bag

Eco-friendly bags, also known as environmentally degradable bags, can be made from banana fiber. When blended with cotton, these eco-bags are more durable, wrinkle-resistant, and resistant to absorbency compared to bags made from cotton alone. To enhance their appeal, various designs and color patterns are incorporated, improving both the aesthetics and quality of the eco-bags (Manandhar,2010) (Fig 1).

Yarn

Banana fiber is used to create yarn for rope making, referred to as banana fiber yarn. Rope making is a fundamental process that transforms linear materials into a usable form. Ropes are made by twisting or braiding fibers together to enhance their strength, making them ideal for pulling and connecting. While ropes possess tensile strength, they lack the compressive strength needed for heavy-duty tasks. The banana tree's decaying bark consists of three layers, each with a specific use. The outer layer, being the toughest, is typically used for weaving, while the middle layer is ideal for making ropes used in thick cloth production. The inner, silkiest layer is spun into yarn for fine clothing, such as sarees, three-piece suits, T-shirts, and undergarments (Mohapatra, 2010) (Fig 1).

Synthetic dyes

Synthetic dyes are widely used in chemical assays, the textile industry, and various commercial products. However, several synthetic dyes commonly found in these products have been linked to health issues, highlighting the importance of removing these dyes from wastewater. The banana pseudostem (Musa paradisiaca cv. 'Pisang Awak' ABB) can effectively absorb methyl red from aqueous

Fig 1: Banana byproducts

solutions. The ability of banana stalk waste to remove methylene blue from water. Natural, low-cost absorbers made from renewable banana by-products offer a more affordable alternative to synthetic and inorganic absorbents, although they may not perform as effectively under extreme conditions (Mohapatra.,2010).

Waste water treatment

The World Wildlife Fund (WWF) reports that over 1.1 billion people around the world lack access to drinking water, a situation driven by the increasing population's demand for reliable water sources. A variety of organic and inorganic substances are regarded as toxic pollutants, often discharged into the environment, particularly in surface waters (Alzate *et al.,*2021).

Banana utilized as adsorbent against pollutants

The uncontrolled disposal of heavy metal ions has raised global concerns due to the contamination of aquifers with water-soluble pollutants. Even at low concentrations, these heavy metal ions are toxic to both aquatic life, including plants and animals, as well as to humans. The surface properties and adsorption capacity of pyrolyzed and dried activated banana peel were compared to commercial activated carbon (F-400) in removing Cu(II) ions from an aqueous solution. Pyrolytic activation of dried banana peels resulted in larger mesopores (49 Å) but a smaller surface area (38.49 m^2/g), with predominantly negative surface charges. In contrast, commercial activated carbon (F-400) had smaller mesopores (30 Å) and a significantly larger surface area (819 m^2/g). When comparing the adsorption capacities, the activated banana peel (38.4 mg/g) outperformed the commercial activated carbon (F-400) (2.39 mg/g), despite its smaller surface area. This enhanced capacity was attributed to the opposite charge on the surface of the banana peel adsorbent. The banana peel-derived adsorbents achieved a removal efficiency of 96% at lower initial concentrations. The adsorption data best fit the Langmuir isotherm, and the sorption kinetics followed a pseudo-second-order model for both adsorbents. The adsorption mechanism was explained through ion exchange and electrostatic interactions (Ahmad and Danish, 2018).

Dye removal from waste water using banana waste

Natural dyes have a long history of use, but in modern industries such as paper and pulp, textiles, plastics, leather, cosmetics, and food, synthetic dyes have become more prevalent. However, synthetic dyes are known for their slow degradation rates, which can have significant negative effects on the aquatic environment. Under specific conditions of pH (4.0–8.0) and temperature (20°C), the maximum adsorption capacities of dried banana peel powder and activated banana peel carbon were determined to be 18.647 mg/g and 19.671 mg/g, respectively. As the initial concentration of the dye solution increased, the sorption capacity of both adsorbents (dried banana peel powder and activated banana peel carbon) also increased. The adsorption isotherm data revealed that methylene blue adsorption onto activated banana peel carbon followed a multilayer pattern, adhering to the Freundlich isotherm, while adsorption onto dried banana peel powder followed a monolayer pattern, fitting the Langmuir isotherm. The adsorption kinetics of methylene blue for both adsorbents followed the pseudo-second-order model. Surface characterization through Fourier-transform infrared spectroscopy (FTIR) analysis identified the presence of amine, hydroxyl, and carbonyl functional groups, which serve as active binding sites for the biosorption of dye molecules from aqueous solutions (Amela *et al.,*2012).

Removal of pesticides from contaminated water using banana wate product

The use of synthetic pesticides in agriculture and residential areas has risen significantly, leading to their gradual presence in surface and groundwater. The contamination of water with pesticides poses a serious threat to both wildlife and human health. Phosphoric acid-treated charred banana peel was utilized as an adsorbent for removing atrazine from aqueous solutions. The adsorption process was found to be dependent on both pH and temperature. The adsorbent effectively removed more than 80% of atrazine from water within a pH range of 2.0 to 8.0, indicating that charred banana peel is suitable for both acidic and basic solutions. The adsorption data followed the Langmuir isotherm model, with a maximum monolayer adsorption capacity of 14 mg/g. The standard Gibbs free energy (DG) and standard enthalpy change (DH) values indicated that the adsorption process was both spontaneous and endothermic. Additionally, the mass transfer model demonstrated that both external mass transfer and intraparticle diffusion played significant roles in the scavenging mechanism (Chaparadza and Hossenlopp, 2012).

Banana waste-derived adsorbents for the removal of water-soluble radioactive nuclides

The use of banana peel-derived nano-sorbents to remove radioactive elements, specifically Uranium and Thorium, from mine wastewater. The banana peel nano-sorbent was characterized for crystallinity, surface functional groups, particle size, and surface morphology before and after adsorption. The adsorption efficiency was influenced by pH and temperature, with optimal removal occurring at pH 4.1 for uranium and pH 3.0 for thorium. Results showed that 0.01 to 0.3 g of the nano-sorbent removed 99.99% of thorium but only 70% of uranium. The nano-sorbent's higher adsorption capacity was attributed to its enhanced surface area and smaller particle size, achieved through mechanical milling. Functional groups like amine and carboxylic acids played a key role in binding the radioactive elements. Thermodynamic analysis indicated that the adsorption process was endothermic and spontaneous. The maximum adsorption capacity, based on the Langmuir isotherm model, was 27.1 mg/g for uranium in synthetic solutions and 34.13 mg/g for uranium in mine wastewater, while for thorium, it was 45.5 mg/g in synthetic solutions and 10.10 mg/g in real wastewater. This study demonstrated the effectiveness of banana peel-derived nano-sorbents in removing radioactive contaminants from water (Oyewo *et al.,* 2016).

CHALLENGES AND FUTURE PROSPECTS OF BANANA WASTE MANAGEMENT

Banana cultivation generates a substantial volume of waste, including peels, pseudo stems, leaves, and rejected fruits, posing significant disposal and management challenges. The absence of efficient waste processing infrastructure in many banana-growing regions further limits large-scale utilization. Additionally, the inherently high moisture content of banana biomass complicates its storage, transportation, and processing. A major barrier is the low awareness among farmers and industries regarding the potential value and processing methods of banana waste. Economic and market constraints, such as limited demand and underdeveloped markets for banana waste-derived products, also discourage investment in waste utilization technologies. Technical challenges, including the need for advanced and expensive machinery for extracting fibers, biofuels, and compost, further hinder progress. Moreover, improper disposal practices can lead to methane emissions, contributing to environmental pollution and climate change.

In spite of these difficulties, there is hope for the future in managing banana waste. Better anaerobic digestion technology can now turn banana waste into biofuels and biogas more easily, which helps cut down on the use of fossil fuels. Studies and new ideas are making it possible to create useful products like bioplastics, textiles, and paper from banana plants. Changing banana leftovers into natural fertilizers and animal feed gives green answers for better soil health and cheaper feed options. Plus, the active compounds found in banana trash could be very important for use in drug, health food, and beauty product companies. New processing tools such as good shredders and crushers can help improve the way waste is used. Good government rules and money help are very important to push a lot of people to use green waste management methods. In the end, putting banana waste use into a closed-loop economy plan will change waste into useful stuff, helping both eco-friendliness and economic strength.

Conclusion

Banana waste, including peels, stems, and leaves, offers valuable bioactive compounds, fibers, and cellulose, making it useful for food, bioenergy, bioplastics, and environmental management. Converting these resources supports circular economy models, reduces pollution, and creates high-value products. Research shows promise in areas like functional foods, biodegradable materials, and bioethanol production. However, further optimization and scaling of extraction methods are needed for commercial viability. Collaboration and technological advancements will be crucial to advancing banana waste utilization, contributing to sustainability and resource conservation globally.

Declaration of Competing Interest

The author, Dr. C. Ravindran, Associate Professor (Horticulture), declares that there are no financial or personal relationships with other people or organizations that could inappropriately influence the work described in this manuscript. The author has no conflicts of interest related to the research, the data presented, or the findings of this study. The manuscript has not been submitted for publication elsewhere, and all sources of funding and acknowledgements are appropriately cited within the manuscript.

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