ijlpr 2022; doi 10.22376/ijlpr.2023.13.1.SP1.P37-45

International Journal of Life science and Pharma Research

ISSN 2250-0480

Review Article

Mechanical Properties
Mechanical Properties of Banana

Mechanical Properties and Waste Management Approaches of Banana in India

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Abstract: Around 27% of the contribution to the world's banana production is done by India only. This directly leads to an increase in waste loss. Despite its tremendous utilization, nutritional & health benefits, and mechanical properties of fibres which allows the growth of the economy in the country, the problem of waste management in India is big. Usually, the leaves, pseudostems, rachis and banana peel are the major solid waste-loss of bananas which corresponds to its maintenance and harvesting practices. Its waste loss amounts to roughly 114 million metric tonnes worldwide, contributing to environmental issues such as the excessive emission of greenhouse gases. Thus, this review paper focuses on the the mechanical properties of pseudostem fibres which offer a significant bioresource to create a variety of high-value goods, including rope, cordage, fishing nets, mats, packaging materials, paper sheets, textile fabrics, bags, tablecloths, handicrafts, absorbent materials, and polymer composites. The research on banana fibre-reinforced composite materials is a new field of research and is still open to be explored. These composite-based fibres have a good potential to be used in various sectors like construction, automotive, machinery, etc., due to their high mechanical strength. Many advancements in the manufacturing techniques of its fibres are under process to ease the process. However, still, hand layup, compression moulding, and filament winding are the processes which are followed. Thus, this review paper focuses on the mechanical properties & utilization of banana pseudostem fibres and approaches to combat the main challenges of waste management and to provide sustainable solutions to achieve social, economic, and environmental benefits.

Key Words: Production, Trade, Nutrition, Tensile Strength, Contraindications, Waste Management

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Received On 18 October 2022
Revised On 06 December 2022
Accepted On 13 December 2022
Published On 01 January 2023

Citation Jindal Heena, Saxena Tanya, and Sawal Kartik , Mechanical Properties and Waste Management Approaches of Banana in India.(2023).Int. J. Life Sci. Pharma Res.13(1), P37-45 http://dx.doi.org/10.22376/ijlpr.2023.13.1.SP1.P37-45

1. INTRODUCTION

With its diversity in culture, religion, languages, and fruits and vegetables, India is a vast nation in Southern Asia. Every Indian state is well-known for its customs and plantations. Fruits are a crucial component of a healthy lifestyle, a centric issue for the youth nowadays. USDA recommends two cups of fruits daily, especially whole fruits, to be adopted by humans in their daily diet. India is becoming the 'Epitome of the World' in its production and plantation techniques. Several fruits, including berries, apples, oranges, and others, are rich in vitamins and other nutrients, but bananas are by far the most well-known and favoured of all of them. It is a tropical fruit cultivated worldwide and ranks as the fourth-most significant agricultural food crop after rice, wheat, and corn. It is used as a functional ingredient in various culinary products and is eaten as a raw or cooked staple food. In addition to being high in carbohydrates, dietary fibre, vitamins, and minerals, bananas are also known to be high in several health-promoting bioactive phytochemicals.[1–3] An herbaceous flowering plant of the family Musaceae, the Banana is a member of the genus *Musa* (Fig. 1). The fruits are seedless, thus classified under parthenocarpic fruits. The two primary species of edible bananas are *Musa acuminata* Colla and *Musa balbisiana* Colla. The hybrid from these species, *Musa x paradisiaca* L., is also readily accessible today.[4,5] Banana plant is primarily and abundantly planted following the monsoon season, i.e., in October-November, which, with reliable irrigation techniques, can even be grown in February and March. The only crop that can be used for food, fodder, and roofing is this one. The tissue culture techniques are utilized all year long to suit market demand, apart from extreme cold or heat. The fruit can vary in shape, colour, and firmness but is typically recognized as elongated and curved with soft flesh, rich in starch covered by peel that can be green, yellow, red, purple, or brown when ripe.[6]

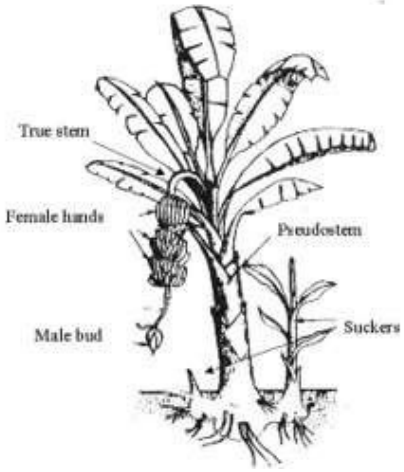

Fig. 1. Banana plant with labelled parts [6,8]

1.1 Production & Trade

Bananas are primarily produced in Asia, Latin America, and Africa. The largest producers of domestic consumption are India and China. It is a major fruit crop in tropical and subtropical regions. Since 2005, India's banana production has been gradually rising. Banana production in India reached 20 million metric tonnes in 2006 and finally exceeded the 30 million metric tonnes threshold in 2020. Every year, India's production of bananas grows rapidly. Andhra Pradesh, Maharashtra, Gujarat, Tamil Nadu, and Karnataka contribute much to the production. According to 2021-22 statistics of the National Horticulture Board, Maharashtra is the largest banana-producing state in India, with a share of around 18%, followed by Maharashtra and Gujarat at 14% and 12%, respectively. India is also exporting the fruit worldwide, majorly to Iran, Qatar, United Arab Emirates and Saudi Arabia. The banana exports from India have grown from 61 thousand tonnes in 2010 to 330 thousand tonnes in 2022.[7–9] (Fig. 2)

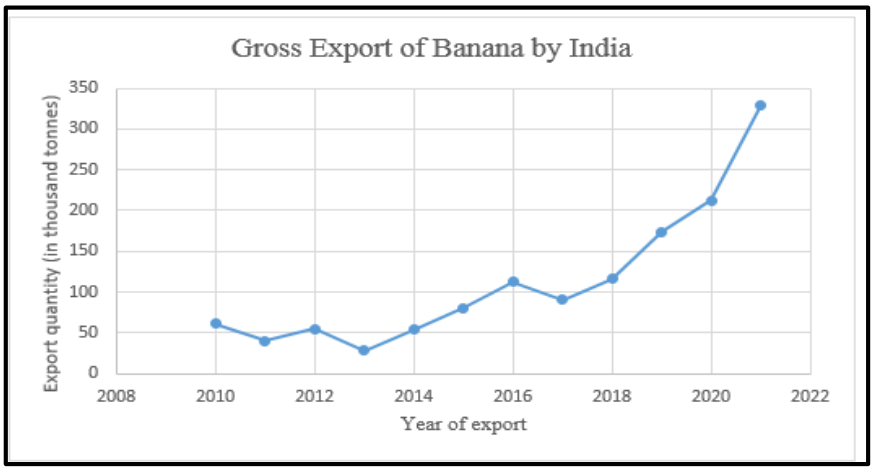

Fig. 2. Gross export of bananas by India from 2010 to 2022

1.2 Nutritional Aspects & Health Benefits

Due to their versatile nature, Banana provides enormous benefits and helps maintain a healthy lifestyle. While eating banana fruit, we consume carbohydrates and dietary fibres, majorly with 23g and 2.6g, respectively, along with a nice amount of Vitamin A, B6, C and D, minerals, natural sugar (20%), and other plant components per 100g. Potassium (358mg) is one of the important minerals found in banana fruit which results in improving heart health and controlling blood pressure. In contrast, carbohydrates and fibres help maintain gut health by converting them into butyrate through fermentation. It contains several bioactive components, including phenols, carotenoids, biogenic amines, and phytosterols which are particularly desirable in the diet since they have a variety of beneficial impacts on human health and well-being. Numerous of these components have antioxidant properties and work well to defend the body from various oxidative stressors. Bananas are effectively used to treat various diseases, including reducing the risk of hypertension, stroke, cholesterol, kidney stones, chronic neurodegenerative disorders, cardiovascular disorders, and certain cancers. The Banana can also be employed as an energy and immunity booster; laxative; and protects against stomach ulcers and heartburn due to its antacid nature.[10–15]

1.3 Adverse Effects & Contraindications

The high carbohydrate content and the tryptophan level in bananas are thought to influence brain function and sleepiness and even cause depression.[15,16] The consumption of bananas may worsen migraine headaches.[17] Few people have also experienced allergic reactions from eating bananas, with symptoms ranging from oral allergy to severe anaphylaxis.[18] Further, WHO has mentioned the dietary potassium intake for adults to be at least 90 mmol (3510 mg) per day.[19] Having high potassium content, bananas are frequently a wise choice to lower the risk of cancer, heart disease, or stroke. However, eating too many potassium-rich foods can be problematic if someone takes some medications. For example, a study found that postoperative cardiac surgery patients who consumed a lot of bananas along with treatment with angiotensin-converting enzyme inhibitors (ACEI) and potassium-sparing diuretics, which may have contributed to their life-threatening hyperkalaemia despite having a normal renal function.[20] Another study revealed that individuals who consumed bananas along with beta-blocker medicines also had higher potassium levels.[21] Though bananas contain tyramine, which is harmful when combined with monoamine oxidase inhibitors (MAOIs), an antidepressant, studies have shown that bananas do not raise tyramine levels to dangerous levels.[22] Therefore, it is anticipated that patients with diabetes and impaired renal function may have diet-related hyperkalaemia more frequently. Thus, it is advisable to limit the intake of bananas and other potassium-rich foods when consuming these medications.

2. MECHANICAL STRENGTH OF BANANA FIBERS – A UNIQUE PROPERTY

Banana pseudostem fibres are quite crystalline and lustrous in appearance. It is a promising fibre material with an average fineness of 2400 Nm. It has a low density, good elasticity, tensile strength, stiffness, low strain at break, powerful moisture absorption, and releasing quality. (Table 1) Although banana pseudostem fibre looks quite similar to ramie and bamboo fibre, it has far superior spin ability and fineness compared to them. The fibre is multicellular and scaly in structure. It appears as bundles, each of which has many fibrils. (Fig. 3) Due to the hollow structure design of the banana pseudo stem, the fibre has high insulating and absorbance qualities. Environmental issues, including changing seasons and pollution, significantly impact the natural fibre. This issue can be solved by treating the fibre with either alkali or acid, which results in good-quality fibres. Typically, the fibre is first treated with 10% NaOH solution for 1 hour, followed by another hour of soaking in HCL solution to remove the impurities on the fibre and boost its strength and wettability. The banana fibres are biodegradable and can be stored for three months. [23–27]

Fig. 3. Pseudostem structure of banana[28]; (a) transverse section, (b) cross-sectional view, and (c) bundles of pseudostem fibres

Table 1: Chemical & Mechanical properties of Banana fibers[29]

S.No.	Parameter	Average value ± Standard deviation
1.	Cellulose (%)	50.77 ± 15.22
2.	Hemi cellulose (%)	16.52 ± 12.37
3.	Lignin (%)	11.89 ± 5.5
4.	Extractives (%)	6.50 ± 3.55
5.	Ash content (%)	6.26 ± 4.13
6.	Moisture content (%)	12.55 ± 5.13
7.	Diameter (µm)	138.06 ± 86.28
8.	Density (g/cm^3)	1.34 ± 0.025
9.	Tensile strength (MPa)	458.1 ± 257
10.	Tensile modulus (GPa)	17.14 ± 10.72
11.	Elongation (%)	4.18 1.69

2.1 Banana fibre-reinforced polymer composites

The term "composite" refers to a material comprised of two or more parts, one of which serves as the reinforcement and the other as the matrix material. Banana natural fibres can be employed as reinforcing materials in composites with epoxy, polyvinyl chloride, polyester, polyethene, etc., as the matrix/binder system. The additional environmentally acceptable and biodegradable matrix systems now employed in the composite are polylactic acid (PLA), polyester amide (PEA), polyhydroxybutyrate (PHB), and polyhydroxybutyrate-co-b-hydroxy valerate (PHBV).[30,31]

2.2 Manufacturing techniques & their advancements

Among the natural fibres, banana fibre has a high tensile strength of 600 MPa. Its tensile strength rises to 891 MPa when the banana fibre is combined with virgin fibre. These two fibres must therefore be combined with an appropriate resin. Compression moulding is the method used for this technique. The best and least expensive way to make fibre is this way. Other methods of preparing the composite fibre include filament winding and hand layup.[32]

2.2.1 Hand Layup

A moulding technique is known as "hand layup" involves placing fibre reinforcements by hand before pouring polymer resin on top of them. The second layer of fibre reinforcements is placed on the polymer resin surface. A roller is moved slightly under tension while rolling over the reinforced fibre to avoid air between the layers. Each polymer resin and fibre undergo the same procedure until the required layers have been layered. This was held at ambient temperature under pressure for 24 to 48 hours. This procedure requires additional cycles to produce the desired material and provides an excellent surface finish on one side only.[30]

2.2.2 *Compression moulding*

Common compression moulding equipment includes top and bottom heating stages that can be heated and cooled to the desired temperature. Thermoplastic sheets may be sandwiched or laminated with natural fibre mats pre-heated for a predetermined time and at a predetermined temperature. To sufficiently melt the thermoplastic sheet and avoid uneven resin flow or ripping of the natural fibre mat, pre-heating is a crucial step. To allow the resin to infuse into the natural fibre mats, the materials are pre-heated before being compressed at a specific pressure. To maximize resin impregnation into the fibres and minimize thermal deterioration of both the fibres and resin, a balance between temperature, pressure, and moulding time during the compression stage is critical. After then, chilled water is pumped into the heating stages of the mould to cool it while maintaining pressure. The extra resin on the sidewalls of the mouldings can then be removed by grinding or trimming once the moulded item has adequately cooled and set.[32,33] (Fig. 4)

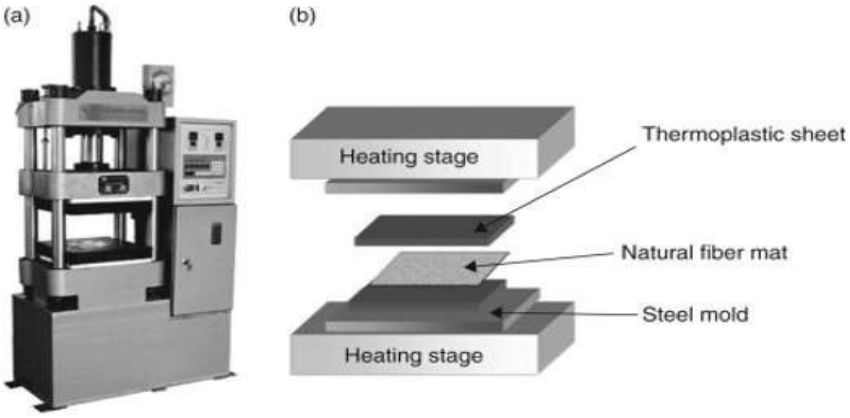

Fig. 4. (a) Compression moulding machine, and (b) schematic compression process[33]

2.2.3 *Filament winding*

The three main winding patterns used in filament winding are circumferential, helical, and polar. A comb device, which can gather and merge the fibre bundles with a tension device, is used in the filament winding method to pass through many continuous fibre rovings. Fibre tows are wound onto a revolving mandrel in a variety of fibre orientations under the control of the filament winding machine control system after passing through a resin bath, nip roller device, and pay-out eye. Fibre strands are thoroughly impregnated with resin in a resin solution. The roller device uses two stainless steel rods to press out surplus resin, ensuring filament-wrapped composite products with a high fibre volume fraction. The pay-out eye is the final stage before the fibre tows are twisted around the mandrel in the pay-out eye. The pay-out eye may move both linearly and rotatory, which can satisfy the demands of the filament winders. Comparing filament winding to other common composite fabrication techniques, filament winding rapidly overtakes them as a significant method of fabrication, helping to advance the usage of composite materials in forthcoming new market sectors.[34] (Fig. 5)

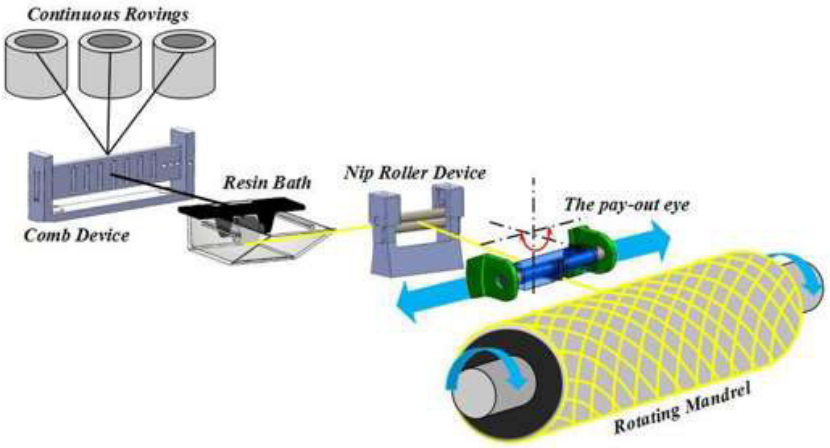

Fig. 5. Filament winding process[34]

After an environment-friendly enzymatic treatment, the banana fibres can be used to create a yarn that can be knitted. Enzymatic therapy for banana fibre is effective in improving cleanliness and fibrillation. In this procedure, lengthy fibres that have been removed are chopped into 50 mm lengths and refined in an enzymatic bath. The best enzyme for treating banana fibres is poligalacturonase (Biopectinase K), which exhibits high specific activity, is specific for substrates, and doesn't harm the fibres' cellulosic structure when used under ideal conditions of 45°C temperature, 4.5 pH for six hours, and bath replacement every three hours. By removing pectin and hemicellulose, enzymatic treatments increase the thermal stability of fibres while slightly decreasing their mechanical properties, probably due to defibrillation.[35] It was discovered that hybrid composites exhibited superior resistance to water absorption than un-hybrid composites because of the hybridization of banana and kenaf fibre-reinforced hybrid composites. The woven hybrid composite of banana/kenaf fibres has greater tensile, flexural, and impact strengths than the constituent fibres alone. Through improved interfacial bonding, sodium lauryl sulphate (SLS) treatments seem to improve mechanical strength.[36,37]

2.3 Utilization

Due to its vast properties, the banana pseudostem fibres can be used to create a variety of high-value goods, including rope, cordage, fishing nets, mats, packaging materials, paper sheets, textile fabrics, bags, tablecloths, handicrafts, absorbent materials, and polymer composites.[23,2838] The research on banana fibre-reinforced composite materials is a new field of research and is still open to be explored. These composite-based fibres have a good potential to be used in various sectors like construction, automotive, machinery, etc., due to their high mechanical strength.[24–26,2939] Its pseudostem sap can be used as a mordant for fixing colour and organic liquid fertilizer, while the central core can make pickles, candies, and soft drinks. The scutcher can be used to make compost and vermi-compost.[23,28,38] (Fig. 6)

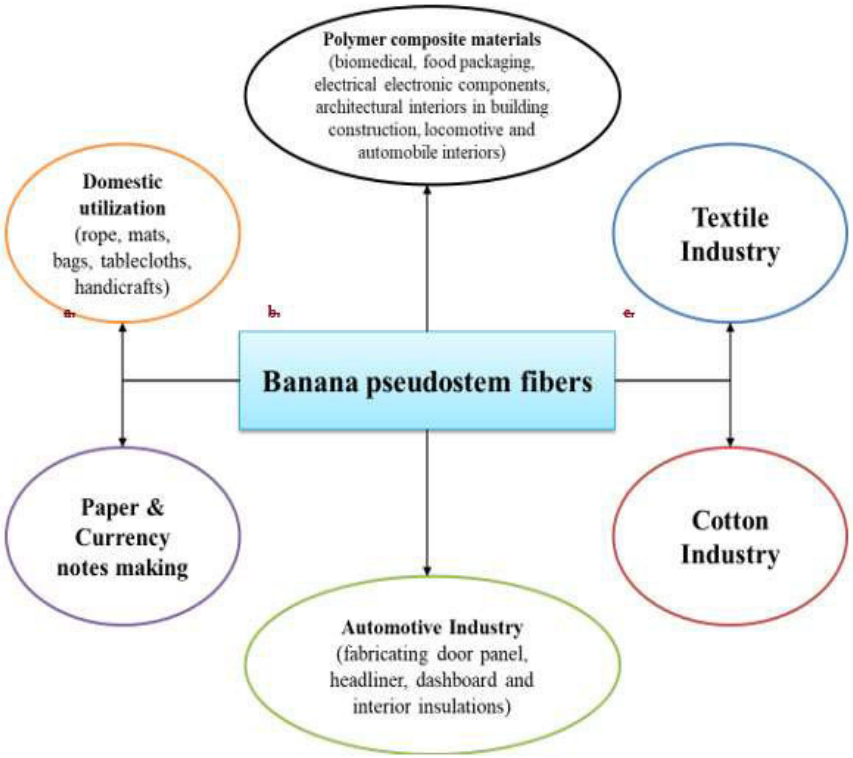

Fig. 6. Potential of banana pseudostem fibre as a rich bioresource material

3. *WASTE-LOSS & MANAGEMENT APPROACH*

The primary trades from the banana industry derive from fresh banana sales. Thus it is associated with producing large amounts of solid waste loss resulting from maintenance and harvesting practices, highlighting the leaves, pseudostems, rachis and banana peel. Almost 60% of banana biomass is estimated to be wasted after harvest. Its waste loss amounts to roughly 114 million metric tonnes worldwide, contributing to environmental issues such as the excessive emission of greenhouse gases.[30,31,40,41] The implementation of recycling and reuse techniques in production and supply chains is a key component of the United Nations Sustainable Development Goal-12 ("Responsible Consumption and Production"), which aims to reduce food losses.[32,42] Due to the difficulty of disposing of food waste in landfills, new methods for managing food waste, such as composting or incineration, are emerging.[33,43] The banana wastes are rich in cellulose, hemicellulose, and natural fibres, which various processes can alter, like bacterial fermentation and anaerobic degradation, thus extremely important to the industrial world.[3141] Due to this, various initiatives or sustainable solutions have been developed worldwide to combat the problem of banana waste loss, such as the production of bioplastics[34–36,44–46], organic fertilizers[37–39,47–49], and biofuels[40–45,50–55]. Additionally, these can be employed in wastewater treatment techniques by creating inexpensive biofilters and getting activated carbon from rachis and banana peels.[46–48,56–58] Banana pseudostems can also be used to develop silver nanoparticles beneficial in cancer treatment and the nanometric fibres often utilized in nanotechnology applications.[49–51,59–61] (Refer Table 2)

Table 2: Worldwide industrial applications and products obtained from banana waste

Industrial applications	Products	Banana waste employed	References
Bioplastics manufacturing	Biodegradable utensils, films, and planting bags	Pseudostems, leaves, peels	34–36,44–46
Organic fertilizers production	Compost, vermicompost	Pseudostems, leaves, peels	37–39,47–49
Biofuels	Bioethanol, Biodiesel, Hydrogen	Pseudostems, peels, Rachis	40–45,50–55
Wastewater treatment	-	Pseudostems, peels, Rachis	46–48,56–58
Nanotechnology	Nanosilica, Silver nanoparticles, Nanocellulose fibre	Pseudostems, leaves, peels	49–51

In terms of managing banana waste sustainably, India is staying caught up. On February 10, 2021, the ICAR-National Research Centre for Banana, Trichy, in collaboration with IIIT-DM, Kancheepuram, and Industry Gencrest, Mumbai, launched a significant initiative to manage this enormous amount of biowaste. These organizations were brought together at the request of Dr Mylswamy Annadurai, known as the Moon Man of India, to develop pilot-scale machinery for extracting banana fibre and use the sap, central stem, and scutcher to produce a variety of products that could be utilized in textiles, as acoustic, aircraft panels, self-healing composites, major stem-based juices, biscuits, etc. (as functional foods).[52,5362,63] A similar

programme was also started in Karnataka by the CSIR-CFTRI (Central Food Technological Research Institute) to create a model called "Trash to Wealth" that delivers commercial value to waste by producing vermicompost, stem-juices, and fibre extraction from banana waste.[5464] A new pilot-scale operation has been launched in Chhota Udepur, Gujarat, to produce hand-made, colourful papers from leftover banana stems. Due to their great tensile strength, banana papers can be used for documentation, packaging material, and art decoration.[5565] Furthermore, a study on the use of banana pseudostem in textiles has been conducted at the Maharaja Sajajirao University of Baroda in Vadodara with funding from NABARD (National Bank for Agriculture and Rural Development, Mumbai) to take the banana fibres to fabric stage by softening them and making them more flexible to be spun into fine yarns and then construct a banana textile grade fabric.[5666] Scientists at the IASST (Institute of Advanced Study in Science and Technology), Guwahati, have devised a method for producing non-toxic activated carbon from tea and banana waste. This carbon can be utilized for various tasks, including odour removal, water purification, food and beverage processing, and industrial pollution control. The banana plant extract contains oxygenated potassium molecules that activate the carbon produced from tea residue. Recently, this novel procedure received an Indian patent.[57,67]

4. CONCLUSION

To conclude, Banana's waste management approaches provide solutions to prevent the exploitation of nature and establish an interconnection of biotechnological processes in the production of various bio-products. Further, its mechanical strength properties offer a significant approach to raising the economic GDP of the country.

5. AUTHOR'S CONTRIBUTION STATEMENT

Mrs Heena Jindal conceptualized and curated the original draft; Ms Tanya Saxena and Mr Kartik Sawal gathered the data regarding the work and provided valuable inputs towards designing the manuscript. Mrs Heena Jindal has further incorporated the necessary expert comments and finalized the manuscript.

6. CONFLICT OF INTEREST

Conflict of interest declared none.

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