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ORIGINAL ARTICLE

# Utilization of banana waste as a resource material for biofuels and other value-added products

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## Abstract
Banana is one of the most important food crops which is generally planted in tropical countries and has beneficial applications in the food industry. A large amount of by-products such as leaves, inflorescence, pseudostem, and rhizomes serves as a source for different industries. Most of these by-products may serve as an undervalued commodity with a limited commercial value, application and in some cases, it is considered as an agricultural waste. This also paves the way to utilize a huge amount of untapped biomass and resolve some of the environmental issues. Most of the edible bananas are cultivated mainly for their fruits, thus, banana farms could generate several tons of underused by-products and wastes. The present review mainly discusses the utilization of banana by-products such as peels, leaves, pseudostem, pseudostem juice, stalk, and inflorescence in various industries as a thickening agent, alternative source for renewable energy, nutraceuticals, livestock feed, natural fibers, coloring agents, bioactive compounds, and bio-fertilizers. Banana waste serves as a potential source for the production of valuable products and preserves renewable resources and provides additional income to the farming industries.

**Keywords** Banana waste · Banana sap · Bioethanol · Renewable resources · Waste utilization · Bioconversion

**Abbreviations**

| | |
|---|---|
| ITO | Indium tin oxide |
| PEDOT | Poly(3,4-ethylenedioxythiophene) |
| PSS | Polystyrene sulfonate |
| PEG | Polyethylene glycol |
| Al | Aluminum |
| CMC | Carboxymethyl cellulose |
| SR | Schopper-Riegler |

## 1 Introduction

Banana (*Musa paradisiaca*, family Musaceae) is a popular fruit crop grown worldwide. It is one of the tallest herbaceous plants with a pseudostem and probably the world's oldest cultured crop [1]. The tough tree-like flexible stem consists of sheathing twisting leaf bases consisting of fibers that provide adequate strength to maintain the tree upright. About 300 varieties of bananas are grown across the world, and the majority of them are cultivated in tropical Asia [2]. Around 1200 seedless fleshy fruit varieties and cultivars of banana and plantain are grown around the world, mostly for food. Although there are significant challenges involved with the use of whole-plant or floral morphology, particularly dealing with somaclonal variation and recognizing clones, morphological identification is nevertheless commonly employed to determine the variety of cultivated banana. The genus Musa contains the majority of edible bananas; approximately, 70 species have been recognized. The majority of edible and cultivated bananas are derived from hybridization between two species: *Musa acuminata* and *Musa balbisiana*. Edible bananas are diploid, triploid, or tetraploid hybrids, containing genetic information from subspecies *M. acuminata* (the "A" genome) and *M. balbisiana* (the "B" genome). An investigation of triploid varieties of banana fruit pulp and peel revealed that it had high nutritional value. Banana inflorescences from *Musa acuminata* and *Musa balbisiana* are rich in anthocyanins. One of the catecholamines, dopamine, was identified in significant concentrations in the pulp of yellow bananas (*Musa acuminata*), red bananas (*Musa sapientum* var. *baracoa*), and Cavendish banana peels. Bracts and male flowers of *Musa paradisiaca* have antioxidant, anti-cancer, and antibacterial activity. Peels of *Musa acuminata* cv. Cavendish have anti-inflammatory, anti-cholesterol, antioxidants, and antibacterial activity. Banana flower (*Musa Paradisaca*), banana fruit

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(*Musa sapientum*), and banana peel (*Musa acuminata*) have anti-cancer activity. There are significant variances in the quality of banana by-product fibers derived from different varieties and cultivars. Banana is cultivated in India, Sri Lanka, Bangladesh, and African countries for the fruits, leaves, and cooked vegetables [3–5]. Banana is considered as one of the most essential fruit crops worldwide. This means that the banana fruit crops are widely cultivated in tropical countries for its valuable applications in the food industry. Banana is the second-largest producer, which contributes about 16% of the total fruit production. Apart from being highly nutritious, this has various other economic benefits as well. Banana leaves serve as food wrappers, weaving mats, and baskets. Furthermore, banana fiber serves as raw material for paper production and making [5–8]. The components of the banana plant include a fleshy rhizome, pseudostem, and long, oblong-shaped leaves. Its oval-shaped inflorescence protrudes from the pseudostem which surrounds the male and female flowers. Its flowers transform or mature into berry fruits which then will develop flesh [9, 10]. Currently, India is the highest producer of bananas, where all year-round production of the banana is possible along with a suitable climate and soil conditions [11]. Deep, rich loamy soil with a pH between 6.5 and 7.5 is most preferred for banana cultivation. Soil for bananas should have good drainage, adequate fertility and moisture. Saline solid, calcareous soils are not suitable for banana cultivation.

Despite different uses of banana plant, it has been observed that large parts of the banana plant are barely discarded as waste, which not only causes environmental hazards but also affects the ecosystem. The various by-products of bananas are a significant source of extremely valuable and required raw materials not just for farming but for various other industries also, through agricultural waste recycling. Most of the edible bananas are cultivated mainly for their fruits; thus, banana farms could generate several tons of underused by-products and wastes. Therefore, without proper agricultural waste management practice, huge amounts of valuable untapped commodities will be lost, thus, causing serious ecological damages. Millions of tonnes of banana pseudostems are disposed of as waste and the farmers are facing problems in disposing of the accumulated banana pseudostems. Hence, there is a need to convert this waste biomass into useful products. The present review mainly describes the use of banana waste (pseudostem) for the production of some valuable products.

## 2 Banana waste

Cultivation of bananas gives rise to a large number of by-products, which include pseudostem, leaves, inflorescence, rhizomes, pith, sap, and fibers. Often considered environmental waste, these by-products have a lot of unused biomass, which can be tapped from various processes and put to good use. These by-products can be obtained from crushed components to replenish the lost nutrients or simply leave these components in an empty area for degradation. Due to copious amounts of gases produced from the by-products left, it is harmful for the current environment. It can also lead to an outbreak of notorious banana fungus, *Fusraium oxysporum* [12]. Reports have shown that banana peel can be efficiently used for the production of alpha-amylase [13]. Various banana by-products can be used for wide applications in different industries as mentioned in Figs. 1 and 2. These by-products can be utilized in the production of enzymes, certain polysaccharides, or even methane for fulfilling the energy requirement [14–18].

Alkaline pretreatment of banana pseudostem fiber has shown the production of good amounts of bio methanol [12]. The fiber obtained from the banana pseudostem has been utilized for making value-added products such as ropes, baskets, and threads [19]. Banana pseudostem sap is used as

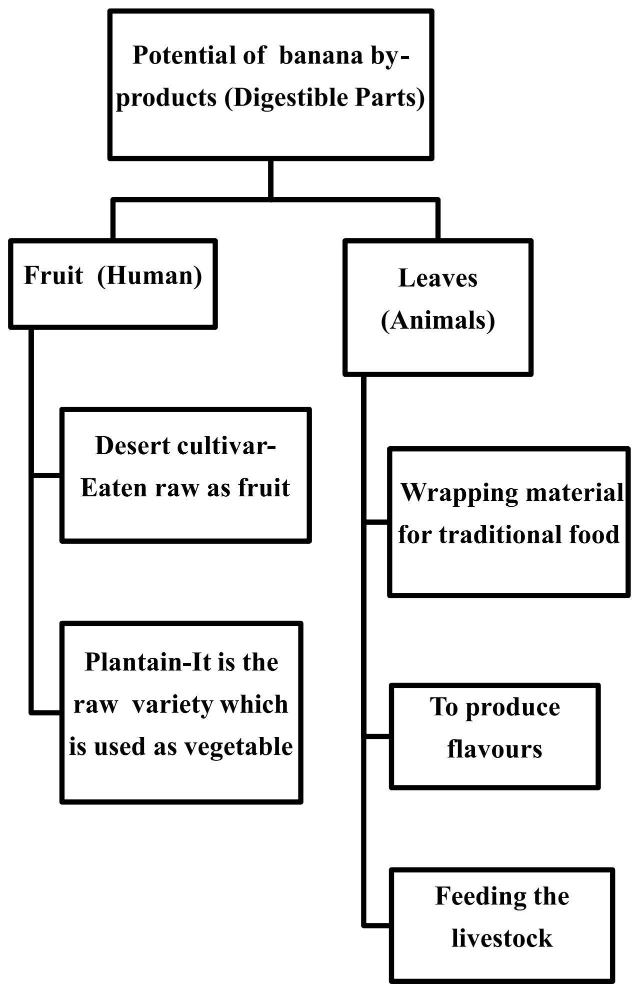


**Fig. 1** Banana by-products (digestible parts) as a potential raw material in different industries

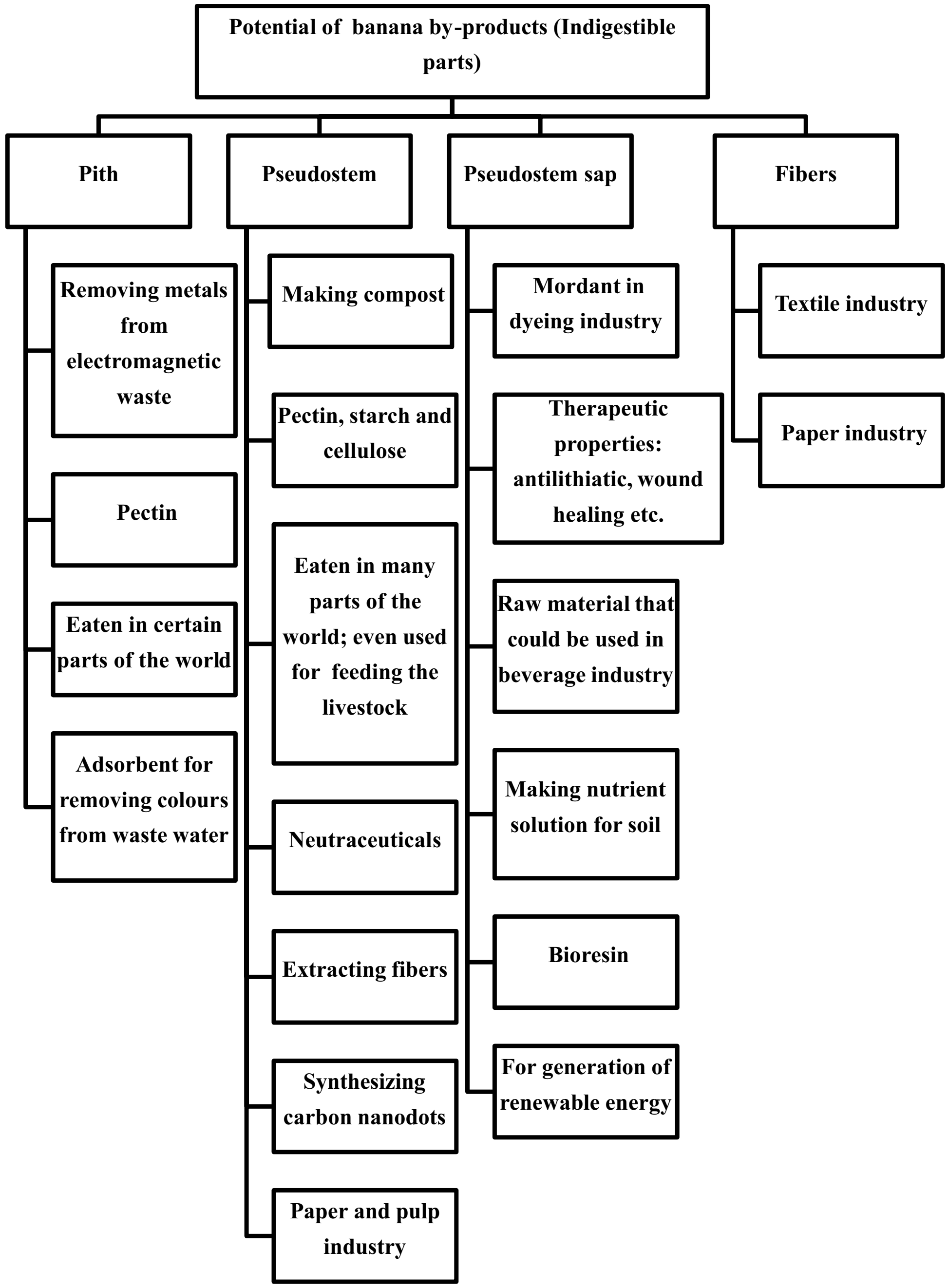


**Fig. 2** Banana by-products (indigestible parts) as a potential raw material in different industries

mordant in the dye industry and as a fertilizer. The banana pseudostem has been used to make pickles, candy, and soft drinks [20]. Ripe banana peel increases ash content, crude fiber, total dietary fiber, and vitamin C to increase the nutritional properties of the cake product. The use of banana peel improves free radical scavenging activity, phytochemical content, and antioxidant activity in the bread to develop functional chapatti. In bread and bakery productions, both ripe and unripe banana peels have been used to substitute (1–30%) other key ingredients like wheat flour, wholemeal flour, maize, starch, rice flour, and brown rice flour. The mixed banana peel and pulp increase dietary fiber content and it could be useful for controlling starch hydrolysis of yellow noodles. Banana peel improved the hardness, cooking yield, water holding capacity, and the dietary fiber content of fish patty. Banana peel has been successfully used in the production of enzymes such as alpha-amylase and laccase [21].

## 2.1 Bioremediation

Banana waste directly or by processing is converted into material that is useful for metal ion removal. Banana peel, stem, and carbon foam made from banana peel have been shown to adsorb heavy metals such as copper, lead, cadmium, and chromium. Fiber derived from the banana adsorbs cadmium, copper, iron, and zinc. Cellulose obtained from banana peel binds a range of heavy metals such as copper, lead, zinc, copper, and cadmium respectively. Carbon isolated from banana pith is an effective binder of mercury, and nickel respectively [22]. Acid or base-activated banana stalks bind to mercury and lead respectively [23]. Treatment of industrial effluents with such banana waste components has shown removal of these toxic metals up to 95%. Banana waste-derived products have been used to remove pesticides from contaminated waters. Activated carbon derived from banana stalk has been used for the removal of carbofuran, 2,4 diphenoxy acetic acid and benzaton from contaminated waters [24]. Charred banana peel treated with phosphoric acid has been used to remove atrazine from contaminated waters [22]. Banana peel and other components have been successfully used in removing dyes from contaminated material. Activated banana pith, banana stalk waste, and a banana bunch have been used successfully for removing methyl orange [25]. Banana leaf and banana empty fruit bunch treated with acid/base have been useful in removing the methylene blue. Banana pith is useful for removing rhodamine B and acid brilliant blue. Different parts of banana plant have been represented in order to improve the absorption of water-soluble radioactive nuclides, cyanides, fluorides, and other toxic elements [26, 27].

## 2.2 Characteristics of the banana waste

Banana fruit is one of the most commonly consumed products in the world. Asian and Latin American countries contribute to the maximum production of bananas. The banana tree generates a tremendous amount of waste which includes peel, pulp, pseudostem, pith, flowers, and leaves. Potential technologies for the utilization of banana waste are mentioned in Fig. 3. Furthermore, a well-labeled diagram of banana parts such as rhizome, pseudostem, inflorescence, pith, and fiber are represented in Fig. 4. Banana leaves are richer in lignin content compared to their pseudo stems. Peels of the banana contains lignin (6–12%), cellulose (7.6–9.6%), pectin (10–21%), hemicelluloses (6.4–9.4%), and starch (3%) [32]. The moisture content in banana peel is about 83% and in pulp 70%. The overall sugar content is quite high in pulp that accounts for up to 40% of the sugar. In both banana pulp and peel, sucrose and cellulose are the major sugar components followed by glucose and fructose [5]. Pseudostem of the banana contains 90% of water and minerals such as sodium, potassium, calcium, magnesium, and chloride [33]. Banana pseudostem, petioles/midrib, rachis, leaf sheath, and floral stalk are good sources of nutrients such as glucose, xylose, galactose, arabinose, and minerals like potassium, calcium, magnesium, silicon, and phosphorus [5]. This has resulted in the development of methods for the utilization of waste in both chemical and biotechnological industries. Banana development creates a huge measure of buildups. The spoiled banana natural product, banana strip, banana pseudostem (BPS), leaves, stalks, rhizome, and organic product bundle stem are regularly delegated banana biomass. Roughly, four tons of pseudo-stems are abandoned in the field for every huge load of banana organic product collected. The assessed banana buildup rate in India is around 1.2 × 107 tones/year. Generally, this colossal measure of biomass is simply unloaded off at removal locales. As a result, the regular decomposition of waste from banana biomass for an open climate discharges harmful gases, like $CH_4$, $H_2S$. There is a requirement for innovative improvement for powerful use of banana squander.

## 2.3 Cellulose, pectin, and starch source

By-products such as pseudostem pith and green culled bananas (which are rejected at the time of selection of the edible fruits) can be used as a primary element of pectin, cellulose, and starch. Banana starch has relatively low amylase

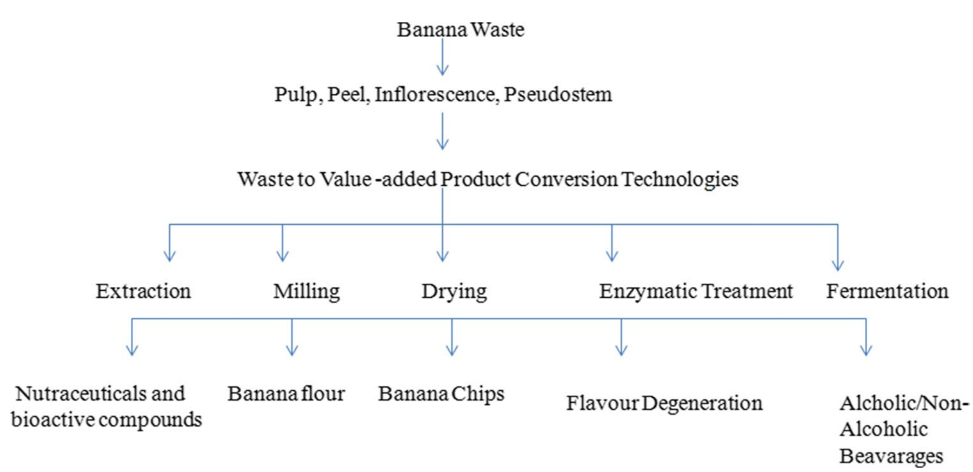


**Fig. 3** Potential technologies for utilization of banana waste

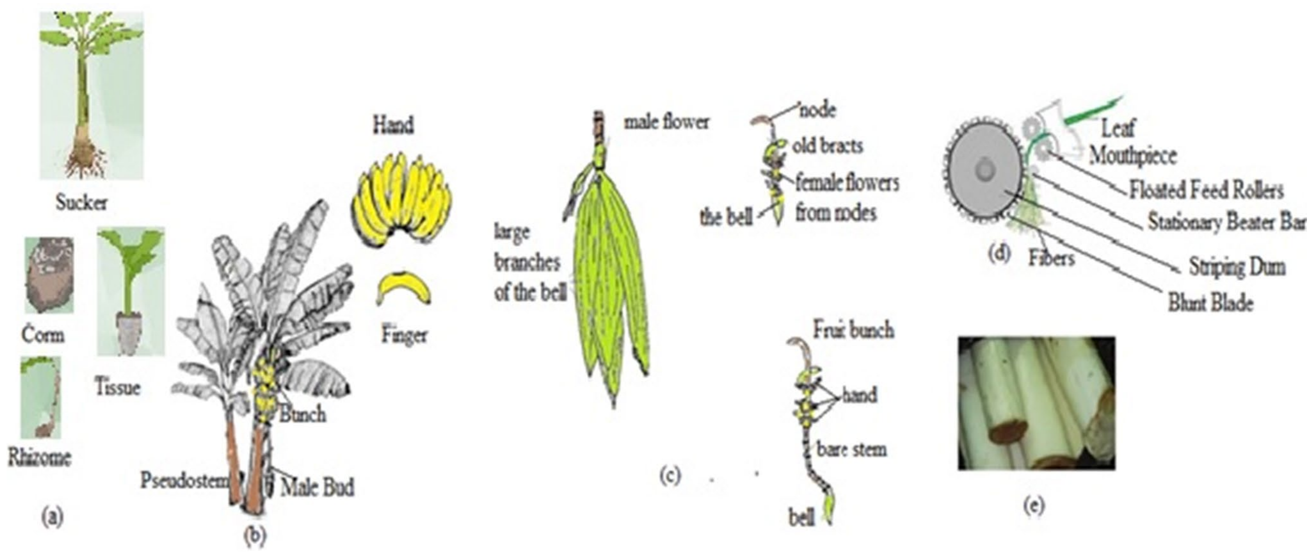


**Fig. 4** A well-labeled diagram of different banana by-products (**a**) rhizome of banana [28], (**b**) pseudostem of banana [29], (**c**) inflorescence/blossom/heart of banana [30], (**d**) fibers of banana (82), (**e**) pith of banana [31]

content and resistance to heat and amylase attack, low swelling and solubility properties, and is superior to corn starch [34]. The pectin content in a banana is less than the pectin isolated from citrus peels like lime and pomelo [35]. Elanthikkal et al. obtained the microcrystalline cellulose from the waste of the banana fibers with the help of acid hydrolysis [36]. These three substances, including cellulose, pectin, and starch, have a huge need in the food sector as a thickening agent, gelling agent, etc. Pectin can be extracted from banana peels through various extraction methods. Similarly, cellulose can also be isolated from the banana waste fiber using different extraction processes [34, 37, 38]. Cellulose, pectin, and starch isolated from banana by-products have many applications. In the human diet, starch, cellulose, and pectin are of great nutritional importance as they are major carbohydrates. Emaga et al. [39] reported that the pectins isolated from banana peels contain various monosaccharides such as glucose, galactose, arabinose, rhamnose, and xylose. From an industrial perspective, starch and cellulose serves as a major feedstock for bioethanol due to the relative ease with which it can be converted into fermentable sugars [40].

Jadhav et al. [40] examined the production of amylase from the potato and banana peel by *Aspergillus niger* and *Bacillus subtilis*. Also, Oshoma et al. [41] reported that banana peel is primarily a substrate for the production of amylase and single-cell proteins assuring the possibility of banana peel waste into proteinaceous food along with enzymes. Studies also revealed that banana peel can be used as a substrate for the production of lactic acid [42]. Lactic acid is an organic acid with a wide range of applications in the food (as preservatives, pH regulators, flavoring agents, etc.), chemical (neutralizers, cleaning agents, chiral intermediates, etc.), cosmetic (moisturizers, skin lightening, anti-acne agents, etc.), and pharmaceutical industries (mineral preparations, prostheses, controlled drugs, etc.) [43]. Banana peel has been successfully used in the production of enzymes such as alpha-amylase and laccase. Distinct groups of fungi such as *Aspergillus*, *Penicillium*, and *Saccharomyces* are known to grow on a banana peel. Several of the bacterial species are also known to grow on the peel. The growth of such a broad range of organisms helps in fermenting the peel and production of several important biomolecules at the industrial level [20].

## 2.4 Source for Anthocyanins

Anthocyanins are naturally found in fruits and vegetables [44]. Other than that, current research has found that anthocyanins have an inhibiting effect on digestive enzymes. Due to its anti-inflammatory, antioxidant, and chemoprotective qualities, anthocyanin has the potential to prevent chronic and degenerative diseases [45]. Few research studies were conducted to develop anthocyanin-fortified foods [46]. Banana bracts have a lot of promise as a banana waste product, especially because of the attractive color of the pigments. UV–visible spectroscopy, physicochemical reactions, HPLC, and electrospray mass spectrometry were used to interpret anthocyanins extracted with acidified methanol, purified using C-18 resin, and characterized by UV–visible spectroscopy, physicochemical reactions, HPLC, and electrospray mass spectrometry. Furthermore, it is a useful tool in anthocyanin identification since it contains the six most prevalent anthocyanidins: cyaniding, delphinidin, pelargonidin, petunidin, peonidin, and malvidin [47]. Sutikno et al.

[48] effectively built organic solar cells with a layer structure of ITO/PEDOT: PSS/PEG/PEG + Anthocyanin/Anthocyanin/Al/ITO, demonstrating the potential of banana flowers as electron acceptors. Based on parameters such as pH and solvent concentration, Ove et al. [49] extracted and evaluated the anthocyanins derived from the banana bracts as a natural colorant that can be used as a natural colorant in different food sectors instead of synthetic colorants which have a carcinogenic effect. Six different anthocyanin pigments, petunidin-3-rutinoside, delphinidin-3-rutinoside, malvidin-3-rutinoside, cyanidin-3-rutinoside, peonidin-3-rutinoside, and pelargonidin-3-rutinoside, were identified from wild bananas of Thailand by Kitdamrongsont et al. [50].

### 2.5 Flavor creator

Banana leaves are rich in lipoxygenase, which is a membrane-bound enzyme having many applications in the food industry. This enzyme can be used to produce different flavors like oolong tea, melon, and cucumber when treated with oils (soyabean oil, linoleic oil). Thus, using banana leaves for the generation of flavors in the food industry can pave new ways for handling the huge amount of banana leaves that are usually thrown as waste [17]. Bananas have a particular aroma and flavor. They contain different nutrients, which will aid in the development of banana-based drinks. Chen et al. [51] investigated the physicochemical flavor and sensory characteristics of banana juice and wines at different stages of the fermentation process. Post-fermentation banana wine had a lower pH and higher brix, as well as more reducing sugar, alcohol, and total acid than primary fermentation banana wine. Hasbullah et al. [52] examined the sensory properties of banana peel analog coffee (Modern American coffee shop located in the Capitol Hill neighborhood of Seattle. Serving a rotating cast of exceptional local roasters and Fresh Breeze Organic dairy) and the impact of banana peel maturity along with oven time. The study concluded that banana peels had the potential to be utilized as an alternative to coffee. Consumer acceptability and production potential will be determined by the sensory characteristics of analog coffee.

### 2.6 Source of several nutrients

Banana pith from the pseudostem as well as inflorescence have long been eaten which is an important part of the culinary culture of the people of southeast Asia. It has been shown that banana pith and inflorescence have a substantial amount of dietary fiber, protein, and amino acids. Banana peels are also quite high in potassium [53, 54]. Potassium is abundant in bananas, which offer 23% of our daily potassium requirements. Potassium aids in the reduction of blood pressure and risk of stroke. The peel of a banana is high in carbs and fiber. Bananas include a variety of vitamins, including A, $B_6$, C, and D, which help to keep the body healthy in many different ways. Peels relieve constipation and aid in the treatment of diarrhea and dysentery due to their high fiber content. Bananas are intended to help children with worm issues. At a concentration of 158 mg/100 g dry weight (DW), gallocatechin is found in banana peel [55]. Bananas contain around 20% sugar and are a good source of vitamin B and calcium. It has around 116 kcal energy/100 g of ripe banana. Leucocyanidin is a flavonoid that thickens the mucus membrane in the stomach and protects against ulcers, heartburn, and hangovers [1]. Major nutritional components such as lipids, proteins, and carbs are abundant in banana peels, accounting for 91.50% of the dry weight. It also contains high content of indigestible fiber [56].

### 2.7 Source of phenolic compounds

Several natural phenolic compounds are present in banana by-products exhibiting anti-bacterial, anti-oxidants, anti-cancer, and anti-inflammatory activities which are presented in Table 1. Banana peel is rich in many antibacterial compounds (12-hydroxy stearic acid, ß-sitosterol, and malic acid). Studies have also shown that bananas are rich in antioxidants, which furthermore enhances its food preservation capacity [57, 58].

Epigallocatechin and its derivatives have been found in the male banana flowers. Studies have also detected (+)-catechin, gentisic acid, protocatechuic acid, ferulic acid, caffeic acid, and cinnamic acid in the banana pseudostem [59, 60]. Studies have shown that compounds such as caffeic acid, gallocatechin, catechin possess unique medicinal properties such as antimicrobial activity, antioxidative properties, neuroprotective features, chemo-preventive properties, and anti-cancerous properties [60–63]. Other components such as anthocyanins also have many notable properties such as antioxidant anti-inflammatory and anti-cancerous properties which can be explored to their full potential. Usually found in the pulp, dopamine is a catecholamine that also has anti-inflammatory properties [10, 64, 65]. Bananas can furthermore contribute to the food industry as the bioactive components present in them can be used for food preservation. Different parts of the banana plant such as banana fruit, pulp, peel, stem, flower, sap, leaf, and pseudostem have shown antioxidant activities (Table 2). There is a strong link between phenolics content and the ability to scavenge oxygen radicals and reduce free radicals [66]. Based on the presence of the individual phenols, they can be grouped into phenolic acid and hydroxycinnamic acids. Moreover, banana by-products also exhibit extracts that show selective anti-bacterial activity in some of the studies against a wide range of bacteria such as *B. subtilis*, *E. coli*, *S. aureus*, *V.cholerae*, *Micrococcus*, *Klebsiella*, *Salmonella*,

**Table 1** Natural phenolic compounds present in banana by-product

| Phenolic acids | Source | Banana by-products | References |
|---|---|---|---|
| Hydroxybenzoic | Vanillic acid | Banana sap | [123] |
| | Gallic acid | Banana sap | [123] |
| | p-Hydroxybenzoic acid | Banana sap | [123] |
| Hdroxycinnamic | Ferulic acid | Banana pulp, peel, sap, and leaves | [123, 133, 134] |
| | Caffeic acid | Banana sap | [123] |
| | p-Coumaric acid | Banana sap | [123] |
| | Caffeoylquinic acid | Banana sap | [123] |
| | Chlorogenic acid | Banana sap | [123] |
| | Synapic acid | Banana peel and pulp | [133] |
| Flavonoids | | | |
| Anthocyanins | Petunidin-3-rutinoside | Banana bract | [50] |
| | Delphinidin-3-rutinoside | | |
| | Malvidin-3-rutinoside | | |
| | Cyanidin-3-rutinoside | | |
| | Peonidin-3-rutinoside | | |
| | Pelargonidin-3-rutinoside | | |
| Flavonols | Quercetin | Banana flower, sap | [82, 135] |
| | Kaempferol | Banana peel, pulp, and sap | [82, 133] |
| | Myricetin | Banana peel, pulp, and sap | [82, 133] |
| Flavones | Apigenin | Banana sap | [82] |
| | Rutin | Banana flower | [135] |
| Flavanones | Naringenin | Banana sap | [82] |
| Flavanols | Catechin | Banana pulp | [136, 137] |

**Table 2** Antioxidant activities of banana by-products

| Type of banana by-product | Activity | Applications | References |
|---|---|---|---|
| Banana fruit extracted with aqueous, methanol, ethanol, and acetone extracts | To scavenge free radicals either by lipid peroxidation or chelating metal ions | Fruits contains antioxidant | [138] |
| Banana pseudostem and rhizome juices | Electron transfer or hydrogen donors | Functional beverage | [139] |
| Banana pseudo stem and flower extracted with chloroform, acetone, and methanol solvents | Prevent lipid oxidation via chain breaking reaction | Nutraceutical for the replacement of synthetic antioxidants | [140] |
| Banana sap extracted with methanol and ethanol solvents | Strong antioxidant | Preparation of formulations in pharmaceutical industries | [141] |
| Banana leaf extracted with hexane, ethyl acetate, and methanol solvents | Inactivate lipid free radicals | Helps to understand the use of *Musa* species in traditional medicine as an antioxidant agent | [142] |
| Banana pulp, seed, and peel extracted with hexane, ethyl acetate, and ethanol solvents | Free radical terminators | Potential source of bioactive compounds | [143] |

and *P. aeruginosa* (Table 3). A large number of studies have been conducted that have effectively shown the antibacterial activity of various plant parts of banana extracts by organic solvents. Furthermore, various parts of the banana have been tested for anti-proliferative/anti-cancer activity on various cancerous cell lines presented in Table 4. The extracts show distinct activity with defined $IC_{50}$ values. Other than cell lines, studies have been done by various groups to demonstrate the enhancement of immunomodulatory activity of the immune cells using various banana extracts [67, 68]. All the natural phenolic compounds present in banana by-products are bioactive compounds mentioned in Table 5. Due to the presence of these bioactive compounds, banana by-products such as pulp, fruit, peel, and sap showed various therapeutic

**Table 3** Applications of banana by-products based on antimicrobial activities

| Type of banana by-product | Activity | Applications | References |
|---|---|---|---|
| Banana leaf extracted with petroleum ether, chloroform, and ethanol solvents | Chloroform and ethanol showed inhibition against all the tested bacteria (*E. coli*, *B. subtilis*, *P. aeruginosa*, and *S. aureus*) whereas petroleum ether did not show any activity | Antiseptic and disinfectant formulations | [144] |
| Banana peels extracted with ethanolic extract and aqueous extract | Ethanolic extract showed inhibition against all the tested bacteria (*B. subtilis*, *E. coli*, *P. aeruginosa*, and *S. aureus* Micrococcus, *Klebsiella*, and *Salmonella*) whereas aqueous extract does not show activity against *Salmonella*, *S. aureus*, and *Micrococcus* | Medicinal plant with antimicrobial activity | [145] |
| Banana sap extracted with aqueous, methanol and ethanol solvents | Only *Streptococcus* showed activity against all the solvents out of the tested bacteria | Preparation of antibacterial formulations in pharmaceutical industries | [141] |
| Banana inflorescence extracted with aqueous, chloroform, methanolic, and ethanolic solvents | *V. parahemolyticus* showed no inhibition in case of aqueous and chloroform extract, chloroform extract showed activity against *B. cereus* and *S. aureus* whereas methanol and ethanol extracts showed activity against all the tested bacteria *B. cereus*, *S. aureu*, *V. parahemolyticus*, and *L. monocytogenes* | Bacteriostatic as banana inflorescence is a source of natural antibacterials | [146] |
| Banana pulp, seed, peel extracted with methanolic solvent | Pulp and peel showed activity against all the bacteria *S. aureus*, *B. subtilis*, *E. coli*, and *P. aeruginosa*, *Shigella*, *Vibrio*, and *Salmonella* whereas seed showed no activity | Treatment of dysentery and diarrhea | [147] |

applications (hypocholesterolemic, wound healing, anti-allergic, and antioxidant, etc.) presented in Table 6. Lupeol is a dietary triterpene reported to have a therapeutic role as an anti-inflammatory and anti-cancer agent [69]. Hydroxybenzoic and hydroxycinnamic acids are the derivatives of phenolic acids. Hydroxycinnamic acids are present in the bound form [70]. Hydroxybenzoic acid such as gallic acid is the component of hydrolyzable tannins whereas p-hydroxybenzoic acid and vanillic acid are the components of lignins [71]. Due to the presence of polyphenolics, gallic acid has high free radical scavenging activity [72]. Caffeic acid is the most important hydroxycinnamic acid which is found in foods primarily as chlorogenic acid. Hydroxycinnamic acids due to their antioxidant activity play a role in the prevention of diseases associated with the risk of oxidative stress such as cardiovascular diseases and cancer [73]. Gulcin [74] reported that caffeic acid is the superior antioxidant when compared with p-coumaric and ferulic acids in inhibiting the LDL oxidation and quenching of singlet oxygen and radicals. Apigenin is a bioactive flavonoid that helps to protect against cancer and monitor cardiovascular conditions [75]. Rutin, also known as vitamin P, and Quercetin-3-o-rutinoside has been reported to protect organs against the free radical agents and can be used for the treatment of gastrointestinal diseases and hepatotoxicity [76]. Quercetin, kaempferol, rutin, and myricetin act as antioxidants and have therapeutic effects in the treatment of inflammation, allergy, viral infection, and cancer [77]. Naringenin is a flavanone and has anti-cancer, antioxidant, antiproliferative, anti-inflammatory, antiatherogenic, and antimutagenic activities and is found in fruits such as grapefruit and oranges [78]. Dopamine plays a role as a neurotransmitter in the brain, precursors for epinephrine and norepinephrine, an accumulation of the oxidized products of dopamine is associated with Parkinson's disease [79, 80]. Kanzawa et al. [81] reported that bananas contain dopamine which acts as a strong antioxidant due to the o-dihydroxy structure and its amino residue which is responsible for the hydrophilic character. N-acetyl serotonin and furthermore metabolite serotonin have a role in the ripening period due to the melanin production [82]. Serotonin is responsible for feelings of well-being and happiness. In bananas, serotonin benefits to overcome or prevent depression by altering mood and calming the body [83].

## 2.8 Source for animal feed

The banana by-products will be an inexpensive source of animal feed along with the high nutritive value. It possesses a significant amount of nutrition in the form of proteins, lipids, carbohydrates, and fibrous content as well as other essential minerals such as calcium, potassium, iron, and manganese, which makes it a suitable choice as an animal feed [20, 84]. Akinyele and Agbro reported the increase in

**Table 4** Applications of banana by-products based on anti-cancer activities

| Type of banana by-product | Effects | Applications | References |
|---|---|---|---|
| Banana peel, pulp extracted with hexane, water, and ethanol | Hexane extracts of peel and pulp showed high cytotoxicity against HCT-116 and MCF-7 whereas water and ethanol extracts showed least activity with HCT-116 and MCF-7 cell lines | Pulp and peel has biological activities lead to therapeutic applications | [148] |
| Banana peel, pulp extracted with mixture of ethanol–water | Pulp and peel showed anti-cancer activity against A549, MCF-7, HepG2, and HT-29 cell lines | Prevention and treatment of different cancers in different ways | [149] |
| Banana flower extracted with ethanol solvent | Flowers exhibited good cytotoxic effect with both HeLa and CHO cell lines | Natural source for the development of an anti-cancer lead molecule | [150] |
| Banana peel extracted with ethanol solvent | Peel showed cytotoxic activity against MCF-7 cell line | Banana peel as a source of antitumor and anti-cancer agent | [151] |

**Table 5** Bioactive compounds obtained from banana by-products

| Banana by-product | Bioactive compound | Applications | References |
|---|---|---|---|
| Banana peel | Myricetin, quercetin, kaempferol, rhamnetin | Strong antioxidant and metal chelating properties | [152] |
| Banana sap | Lupeol, ferulic acid, vanillic acid, trans-cinnamic acid, p-hydroxybenzoic acid, p-coumaric acid, rutin, catechin/epicatechin, chlorogenic acid, gallic acid, caffeic acid, and nicotiflorin | Antidiabetic activity | [123] |
| Banana sap | Apigenin glycosides, myricetin glycoside, myricetin-3-O-rutinoside, naringenin glycosides, kaempferol-3-O-rutinoside, quericitin-3-O-rutinoside, dopamine, and N-acetyl serotonin | Inhibition of cancer cell lines, neurodegenerative disorders, anti-estrogen, anti-inflammation, antivenom, capillaries strengthening | [82] |
| Banana flowers | Rutin, quericetin | Treatment of gastrointestinal diseases | [135] |
| Banana pulp | Ferulic acid, synapic acid | Inhibiting LDL oxidation | [133] |
| Banana peel | Isorhamnetin, kaempferol, quericitein, myricetin, and methylmyricetin | Treatment of inflammation, allergy, viral, and cancer | [133] |
| Banana bract | Anthocyanin | Antioxidant activity | [50] |

**Table 6** Therapeutic applications of banana by-products

| Banana by-products | Therapeutic applications | References |
|---|---|---|
| Green banana | Antidiarrhoeal activity | [153] |
| Banana pulp | Hypocholesterolaemic activity | [154] |
| Banana meal | Antioxidant activity | [155] |
| Green plantain banana fruit | Wound healing activity | [156] |
| Banana (peel, flesh) and ripe banana (peel, flesh) | Anti-allergic activity | [157] |
| Banana sap | Antioxidant and antimicrobial | [1] |
| Banana sap | Wound healing activity | [121] |
| Banana sap | Hyperglycemic effect | [124] |
| Banana sap | Antilithiatic | [157] |

protein and sugar content by solid-state fermentation by incubating the banana peels with *Aspergillus niger*, *A. flavus*, and *Pennicilium* sp. These fungi can break down the banana peels non-starchy polysaccharide content, converting it to simple sugars with a large increase in protein. According to the findings, fungal biotechnology is a useful method for improving the nutritional content of agricultural by-products. This gives rise to the notion of incorporating these biodegradable by-products into the diets of chickens, pigs, and goats to reduce the amount of maize consumed by these species [84]. This enhancement through microbial degradation will furthermore increase the nutritional value of the animal feed. In a feeding experiment, where the livestock was given leaves and pseudostems of banana, it was found that banana leaves possess many superior qualities as compared to the conventional fodder. Features such as low partition factor, high ATP, and last but not the least, high microbial biomass benefitted the organism. The study indicated that bananas are a potent source of ruminant feed [85]. Banana peel included low amounts of anti-nutritive chemicals, such as hydrogen cyanide, a toxic toxin, which was determined to be less than the acceptable limit (0.5–3.5 mg/g). Other anti-nutrient chemicals, such as oxalate and phytate, are reduced in comparison to maize and sorghum, which are typical animal feed. As a result, the banana peel has been utilized in the production of animal feed [56].

### 2.9 Source of natural fibers

Banana pseudostems produce fibers that offer a wide range of value-added products such as ropes and baskets. Pickles, sweets, and soft beverages can also be made from the stem's inner core [86]. Studies have shown that banana by-products also have an exponential capacity to be used as the substituent of natural fibers. Fibers from the fruit stalk, pseudostem, and the leaves have been extensively studied for their potential [87–89]. Zuluga et al. [88] examined the potential of cellulose microfibrils extracted from banana rachis vascular bundles. The impact of the treatment on the morphology and structure of the resultant products was studied using SEM, ion chromatography, ATR-FTIR, TEM, electron, and X-ray diffraction. The partial elimination of hemicelluloses was verified using ATR-FTIR. The strong link of xyloglucans and cellulose appears to be the reason for non-cellulosic components. Furthermore, the appearance in all ATR-FTIR spectra is due to the presence of xylans related to hemicelluloses. Diffraction, 13C NMR, and ATR-FTIR results indicate that the cellulose microfibrils isolated from banana rachis belong to cellulose IV1 and are very close to cellulose Ib. Cherian et al. [89] proposed a unique technique for synthesizing natural fiber nanofibrils from banana fibers. Different contemporary methods were used to analyze the produced nanofibrils. The primary components of these fibers were discovered to be cellulose during the chemical analysis. The IR analyses show that the fibers disintegrated and transformed chemically during steam explosion, as well as when the fibers were furthermore treated for steam explosion in an acidic media. The modified fiber size and crystallinity were investigated using XRD. The XRD experiments furthermore indicated that during steam explosion in an alkaline medium, fiber size is reduced to the nanometer range, and with repeated steam explosion in an acidic medium, fiber size is reduced to the nanoscale range. The scanning force microscopy (SFM) study also reveals that the size of banana fibers has decreased to the nanometer range (below 40 nm). The evidence for the development of nanofibrils in banana fibers by repeated steam explosion in acidic circumstances is furthermore supported by transmission electron microscopy (TEM) examination. Oliveira et al. [87] extracted dioxane lignin (DL) from banana plant leaf sheaths. The HGS type (having a 12:25:63 molar proportion of p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S) units) lignin isolated from the leaf sheaths has a specific lignin fraction rich in H and S units that is strongly structurally linked with aliphatic chemicals. It is suggested that lignin from the banana plant's leaf sheath is chemically linked to suberin-like components of cell tissues via ester bonds involving hydroxycinnamic acid residues. The composite structure of banana fibers has been discovered through research. The use of cellulosic fibers, such as banana fiber, as a filler in the plastic industry helps to reduce costs. Furthermore, by combining banana with glass fiber in the fabric form, the requisite high tensile strength can be achieved. The impact of the composites on strength improves as the number of layers and fiber volume fraction increase [90]. Furthermore, researchers have also shown that fibers extracted from the pseudostem enhance the epoxy composites, i.e., increase/raise the tensile potency of epoxy by almost 40% [91]. These fibers obtained from pseudostem have been in use since a long time in making traditional handicraft and clothes. Banana fibers have a huge potential to be used as textile fibers after degumming through microorganisms. *Streptomyces lydicus* was used for the production of poly-galacturonase for converting the raw banana fibers into processed and modified fibers that could be used in the textile industry [92].

### 2.10 Pulp and paper production

Banana by-products are widely used as raw materials in the paper industry. Pseudostems are utilized in the processing of pulp and paper. Preparing the pulp at a lower temperature and utilizing formic acid yields better quality of the pulp [93]. Papers manufactured from these by-products were found to be water-resistant and stronger as compared to the traditional paper made from wood pulp. It was their low water absorption capacity that made them resistant to water. In a comparative study conducted between three agricultural wastes, it was found that banana leaf and the peduncle are excellent sources of short fiber pulp. Its fiber characteristics are at par with those that are obtained from other woody and non-woody sources. The features of the fibers from the agricultural wastes performed well in terms of burst factor, tear index, stretch, and tensile properties and have a huge potential in various industries [94]. Nassar et al. [95] optimized banana stem pulping parameters to replace softwood pulp in writing and printing paper. A furnish mix ratio of 20 to 80%, banana stem pulp, and commercial bagasse pulp was used to produce high-quality writing and printing paper.

The increased pentosan content of particular banana plant sheaths, along with gums and mucilage, makes it a suitable source for making grease resistant paper. With the help of kraft and soda processes, pulp from banana pseudostem waste was used to manufacture grease resistant paper. On the basis of yield, it was concluded that the kraft process is safer and more efficient than the soda process [96]. For the manufacturing of greaseproof paper, banana pseudostem fiber pulp can successfully substitute wood pulp. In comparison to base paper produced with a higher degree of pulp refining, base paper produced with a lower degree of pulp refining will require a greater quantity of coating per unit area. Only the carboxymethyl cellulose (CMC)-coated paper surpassed the other two coating materials in terms of grease resistance. The handsheets generated with 70° SR pulp freeness in conjunction with a 5% CMC coating yielded the best results. When the amount of coating absorbed per unit area of the sheet is considered, handsheets generated with 70° SR pulp freeness and 3% CMC coating appear to be more efficient [97].

### 2.11 Carbon nanodots

Carbon nanodots are nanoparticles that have the property of fluorescence which are used to track biological processes occurring inside the living cell [98]. Banana pseudostem has been used for the manufacture of these carbon dots. These carbon dots exhibited water solubility, high photostability, high cell permeability, low toxicity, and above all, high biocompatibility which has made them an attractive choice. These nanoparticles were prepared using one-pot hydrothermal treatment. Furthermore, studies conducted depict that these carbon dots can be used for cellular imaging by using it as a fluorescent probe for $Fe3^{+}$ [99]. Nanoparticles were made using starch extracted from a green banana. Citric acid was used to cross-link these nanoparticles. Thus, demonstrating that it is a powerful chemical alteration for encapsulating extremely hydrophobic compounds like β-carotene. This study confirmed that these cross-linked nanoparticles are suitable as vehicles for intestinal-specific targeting [100]. As banana pith extract has a high bacteriostatic effect, gold nanoparticles made from it can be utilized in biomedical applications. Moreover, nanoparticles were shown to be effective in degrading Malachite green dye, suggesting that they might be utilized for bioremediation of Malachite green dye-containing textile industry effluent [101].

## 3 Production of renewable fuels

Renewable resources, also known as biomass, are a naturally plentiful resource that can comprise any biologically derived elements such as plants and animals, agricultural products, and biological leftovers or wastes [102]. These resources can be converted into raw materials or products that are recyclable and quickly biodegradable, with good environmental acceptability or "green label" qualities as well as commercial feasibility [103]. Excessive consumption of the non-renewable resources has put a big question mark over the duration for which they can be used. Hence, alternative forms of energy are required to meet societal needs. Not only has demand been fast depleting non-renewable resources, but it has also resulted in the abundant generation of harmful gases which have led to the deterioration of the earth's natural resources. Utilization/transformation of biomass such as agricultural waste into renewable fuel is one of the environmentally friendly approaches. The general methods adapted in this technology are dependent on enzymatic hydrolysis and microbial fermentation of solid matters [104]. Renewable resources have opened the way for industry and have been utilized to replace non-renewable resources, such as petroleum and gas products, precious metals, and minerals, for decades. In order to ensure a sustainable development of technology, it is critical that the use of low-cost agricultural by-products and biological wastes be spread to all relevant sectors. This may provide an extra source of income for farmers and processing companies while also reducing non-renewable resource depletion [105]. Additional useful outputs from present farming activities may be able to prevent our important forest from being destroyed to generate similar commodities. Green technology refers to an approach that is environmentally friendly and focuses on conserving natural resources while providing the least amount of risk to existing species on the planet, including humans. There are a number of food processing methods available for food processing. Few of those methods are canning, fermentation, air-drying food, blanching, and preserving in salt or sugar. Because using agro-food based items to drive green technology would eventually result in food instability, ethical concerns, and unsustainable energy returns, the technology should be independent of the present agro-food stock market [106]. Banana by-products are widely available as a source of raw materials for the green technology industry due to its abundance of biomass. The fact that bananas have been consumed by humans for a long time without any major negative effects provides some reassurance that these by-products are free of harmful phytochemicals. However, compared to other plants with potent and harmful chemical ingredients, by-product harvesting, handling, and storage may require less vigilance. Therefore, it is not dependent on the present agro-food-based market, the utilization of banana by-products for industrial purposes could promote "green technology," which may not pose any food security or ethical difficulties. Furthermore, except for the accessible banana plantation for fruit, it does not need supplementary planting space [10].

### 3.1 Production of bioethanol

Ethanol is extensively utilized in the industry as a renewable fuel as well as a solvent. Bioethanol production has been one of the major applications of banana waste. Bioethanol is produced through a fermentation process using either bacteria or yeast by converting cellulosic materials into ethanol [107]. It has been found that banana peels are an extremely good substrate for the production of ethanol by using microorganisms. The yield is affected by different parameters such as the substrate concentration,

**Table 7** Ethanol production with different parts of banana by-products

| Source of fermentation | Amount of ethanol | References |
|---|---|---|
| Whole banana | 0.009% | [110] |
| | 0.009% | [110] |
| | 7.45% | [158] |
| Banana peel | 6.54% | [159] |
| | 45% | [160] |
| | 3.56% | [161] |
| | 1.309% | [162] |
| | 0.16% | [163] |
| | 3.6–5.8% | [111] |
| | 2.1% | [164] |
| Plantain peel | 20% | [158] |
| Chiku and banana peels | 2.66–78.9% | [165] |
| Banana pulp | 28.45% | [166] |
| | 0.008% | [110] |
| Banana stem hydrolysate | 0.2% | [167] |
| Rotten banana | 0.113% | [168] |
| Banana fruit mash | 7% | [169] |
| Banana pseudostem | 84% | [170] |
| Banana sap | 0.014–0.3% | [118] |

fermentation conditions, and the organism performing the process of fermentation [108]. The yield of ethanol obtained from different parts of banana in several studies is mentioned in Table 7. Harish et al. reported the production of ethanol from banana pseudostem and leaves by using thermophilic fungi *Clostridium thermocellum* CT2 co-cultured with *Clostridium thermosaccharolyticum* HG8 [109]. Hammond et al. [110] reported ethanol yields of 0.091, 0.082, and 0.006 L/kg from whole fruit waste bananas. Green, normal ripe, and overripe green whole bananas yielded 0.090, 0.082, and 0.069 L/kg of ethanol by enzymatic hydrolysis, respectively. Brooks [111] investigated the abilities of five yeast strains obtained from ripe banana peels. Saccharomyces cerevisiae R-8 had the finest ethanol-producing characteristics because it was extremely flocculent. On maltose, S. cerevisiae T-7 and S. cerevisiae R-2 had rapid fermentative activity. *Debaryomyces hansenii* B-2 and *Saccharomyces kluvveri* K-6 fermented 40% (v/v) glucose at 30 °C to produce 3.6 and 5.8% ethanol, respectively. The pseudostem of banana has been utilized in producing up to 17.1 g/L of ethanol. In many of the cases, the pseudostem can be pre-treated along with a mix of enzymes or chemicals that can result in substrate hydrolysis. Pretrated banana leaves and fruits have also been proved to produce ethanol upon fermentation.

### 3.2 Production of biomethane

Methane is a very useful fuel that is currently used in industries and households. However, with a growing population, more of this fuel is required. As of now, sewage is used to generate methane gas, but banana waste has tremendous potential to be used in the production of methane gas. First, the plant material needs to be digested by anaerobic bacteria in an air-tight container. It is a completely natural process that does not require the external supplementation of any sludge or sewage [14, 112]. Except banana pseudostem, banana peel, stalk, and waste have been successfully shown to produce biogas. Even the briquettes prepared from the banana peel had a less burning rate, and equivalent briquette strength to the existing ones. Banana by-products can also be used for making compost by solid-state fertilization. Utilizing this as soil manure greatly enriched the nutrition content and resulted in an increased yield [10]. Biomethanation of banana peel and pineapple wastes was achieved with 0.76 v/v and 0.93 v/v gas output per day and 36% and 58% substrate utilization, respectively [113]. Kalia et al. [114] investigated the high organic content (83%) as well as the lignin and cellulose content of 15–20% (w/w), all of which contribute to the sheath-like structure of banana peels. In batch culture, banana stem slurries (BSS) containing 2–16% total solids (TS) were anaerobically digested under mesophilic (37–40 °C) and thermophilic (50–55 °C) conditions. Under mesophilic conditions, ultimate biogas yields of 267–271 L/kg TS fed were reported with 2–4% TS slurries. Biogas yields of 212–229 L/kg TS fed were obtained with 2–8% TS slurries in the thermophilic range. Thermophilic digestion rates, on the other hand, were 2.4 times quicker than those obtained from the mesophilic rates. In both temperature ranges, methane production was highest at 2% TS BSS. The method resulted in organic solid reductions of 45–50% and COD reductions of 40–55%. Biogas generation from banana and plantain peels was reported by Ilori et al. [115], with gas produced from feedstocks of 8800 $cm^3$ and 2409 $cm^3$, respectively. The digester produced a total volume gas of 13,356 $cm^3$ and used equal amounts of banana and plantain peels in combination as feedstock. The physical chemistry of the digested feedstocks indicated an initial decrease in pH to the acidic region, followed by a gradual rise up to 7.4 and the temperature remained consistent in the mesophilic range of 32–35 °C.

## 4 Banana sap

Banana stem juice or banana sap is an exudate of the banana plant that oozes out when the stem is cut. Initially, it is transparent, changes to a pink color when exposed to air, and later changes into brown. Also, it is the sap which constitutes about 90% of the weight of the pseudostem [116]. The watery content of the banana pseudostem is referred to as banana sap. Banana sap has many unique properties. Its constituents include carbohydrates, lignins, tannins, and alpha-cellulose [117]. Banana sap can be put to numerous uses as well. The sap can be utilized to develop liquid fertilizers and nutrient spray solution, mordant for natural dyes [4]. Banana sap/banana stem juice discarded into the environment has the potential to produce ethanol. By combining the banana sap with other industrial wastes such as corn steep liquor, spent wash, and yeast extract production of ethanol can be significantly increased [118]. Furthermore, studies reported the enhanced methane/biogas production via co-digestion of banana sap/banana stem juice (BSJ) with agricultural residue washings such as bagasse washing (BW) and wheat straw washing (WSW). Biomethanation potential was demonstrated by BSJ alone, as well as in combination with BW and WSW [119]. Among the unique medicinal properties it possesses, the notable ones are the following: it can be used for the treatment of epilepsy, fever, leprosy, insect bites, digestive ailments, and hemorrhoids along with astringent properties [1]. Various studies conducted to analyze the therapeutic properties of the pseudostem sap have shown antimicrobial properties. Also, it showed substantial antioxidant activity [1]. In a study, it was found that the sap has hemostatic properties with non-specific action on the coagulation cascade. Tannins present in the sap might be an important factor for mediating the interaction between the sap and proteins in serum which leads to the formation of a network thus effectively reducing blood loss. This network not only traps the red blood cells but the leukocytes also and inhibits their movement. Another important factor is the astringent properties of the sap in determining its hemostatic properties. The sap also showed vasoconstriction properties. It was a combination of the two that helped in reducing the time of clotting [120]. The banana sap is rich in phenols and certain aromatic amino acids; dopamine was found in the sap, which is a potential vasoconstrictor. The presence of dopamine can explain the medicinal properties of the sap where it was often used to stop the bleeding from an injury. The sap was also found to contain N-acetylserotonin, whose function remains unclear. Apart from these, it is also responsible for antioxidant activity. Naringenin was found to have beneficial effects such as lowering the cholesterol level in blood. Other compounds such as kaempferol and quercetin also possess unique therapeutic values such as anti-inflammation and anti-venom. Myricetin, also found in the banana sap, is said to reduce the risk of neurodegenerative disorders in critical diseases such as Alzheimer's disease. Another compound extracted from the sap, apigenin, is also said to have anti-cancerous properties as it promotes cell division and apoptosis [83]. Research has shown that the banana pseudostem juice is quite effective in the stimulation of wound healing whose action was quite comparable to that of silver sulphadoxine [121]. Banana stem sap (BSS) has a higher potential for improving wound healing in diabetic mice than virgin coconut oil (VCO) [122]. Banana stem sap was found to have hypoglycemic effects [123] and hyperglycemic effects as depicted in the in vivo studies conducted by Singh et al. [124]. Mordant is any chemical substance that is crucial for the establishment of dye (color) in a particular material. Using banana pseudostem sap as mordant not only gave efficient results, it was also cost-effective. Tannins present in the sap are the main chemical compound responsible for the dyeing action of the sap [117]. Scientists have also found out that banana sap can also be effectively used as an anti-corrosive agent. Mixing the concrete with banana sap can amplify the steel reinforcement thus enabling it to withstand harsh environmental conditions [116]. To enhance the nutritional value of sap, researchers tried to find out whether the plantain stem juice could be blended with fruit juice. Results showed that banana juice can be added to grape fruit juice that will increase the nutritional content and antioxidant activity. This will open up the novel view point for the utilization of the plantain stem juice. Furthermore, this will also produce a low-cost blended average required by the consumers [125]. It was found out that banana sap had all the requirements of raw material for a sports drink. However, other ingredients including water, sodium, and sugar need to be added. It shows that this sap has the potential to be exploited as a sports drink, although more research needs to be done to assess its safety, i.e., whether it is safe for human consumption or not [23]. In another study, the banana sap was mixed with non-digestible gluco-oligosaccharides and D-allulose. Dextransucrase enzyme transfers D-glucose moiety of sucrose into α-(1–6) linked oligosaccharides in the presence of an acceptor. These oligosaccharides are beneficial as they promote the growth of good bacteria in the mouth. Furthermore, calcium alginate has been studied as one of the most efficient carriers for glucan sucrase immobilization. It was seen that dextransucrase-based biocatalytic reactions could change the sucrose into probiotic oligosaccharides in the banana pseudostem juice. These could function as probiotics because non-digestible gluco-oligosaccharides act as an apt substrate for the growth of beneficial bacteria. D-allulose has many beneficial effects. It has almost zero calorific value and has positive health impacts, some of which are anti-diabetic, anti-dyslipidemic, anti-hyper glycemic, and neuroprotective [126]. The stem juice has an antilithiatic activity which was confirmed while conducting a study to assess whether the juice can dissolve kidney stones. Results indicated that the juice could dissolve calcium, phosphate, and oxalate ions from the stones and exerted a beneficial effect in cases of kidney stones [127]. In the industrial field also, the banana sap has been tried as a unique resin that was environmentally friendly. The hybrid bio-based resin that was prepared had many unique features such as improved strength of the resin, completely biodegradable, and has a significant potential to be used in the automobile industry. Results showed that resins with 50% banana sap by weight had the best strength and preferable qualities [128].

## 5 Challenges and future prospects

Waste management and by-product handling in the agriculture sector generate environmental and sustainability issues [129]. It may be difficult to dispose of this garbage due to the following factors: pathogen development and biological stability. Many types of garbage already include a large number of bacteria or will be rapidly transformed by microbial action. The present techniques for furthermore utilizing product-specific waste have been established along conventional lines and are inextricably linked to the agricultural origins of the raw materials themselves.

In modern agriculture, bananas are classified as fruit crops or cash crop commodities. These commodities generate a large quantity of cellulosic waste, often known as agricultural waste or biomass. It is a constant challenge to invent new approaches to overcome such a large volume of agricultural waste or biomass. Recent trends emphasize the use of this biomass for value-added applications to meet needs in renewable energy, fiber composites and textiles, food alternatives, and animal feed [130].

Several researches have been conducted to enhance the utilization of banana by-products in order to fulfill the rising demand for raw materials in various sectors [14–17]. These studies paved the door for new and innovative approaches to develop consumer items and applications using a value-added strategy while recycling banana agricultural wastes. As a tool to promote a productive community, there is an ongoing need to generate and invent new technologies with value-added capabilities from alternative bio-resources. Because of the rising need for food, energy, and other essentials, a gradual shift in present technical progress toward the use of alternative resources in many sectors is required to meet the demands of the world's growing population.

To establish economic impacts and fulfill the demands of the market, it is highly preferable to convert the waste biomass and by-products into highly beneficial products [131]. There is a long way to go before banana waste can be efficiently used to meet the needs and requirements of diverse fields. Although the products from banana wastes such as papers, bio-resins, biofuels, and fibers will be of extremely good quality, there is a need to take initiative and spread awareness so that these banana by-products can be made widely and easily available. Furthermore, the quality of the product generated from the banana by-product should be comparable or better as compared to the competition existing in the market. Before releasing the product into the market, it has to be assessed for its purity and ensured that it fulfills all the criteria and regulations set by the regulatory bodies. Coming from the customer's point of view, the product should be suitable for the consumer in every way. Food products developed from banana by-products need to be fortified on this aspect as well.

Considering the fact that the immediate issue will always be research innovation in order to provide high-value, high-quality products with low costs. Bananas, which cover a wide range of well-known varieties and cultivars, have been explored, and by-products such as pseudostems, rhizomes, leaves, fruit stalks, and peels from common varieties have been identified as potential raw materials in the food and non-food industries, with each application providing a unique solution. Banana by-products that have been evaluated and found to have potential applications for food additives, nutraceuticals, food supplements, feeds, renewable fuel, fibers, bioactive and other organic chemicals, fertilizers, and contaminant absorbers should be furthermore addressed for their safety aspects to meet market demand. In order to make these unprocessed raw materials available for industrial scale processing, a standardized collecting system and processing of banana by-products had to be resolved. The trend of using more sustainable and economical by-products is increasing along with the current situation of worldwide population expansion. It gives a suitable and significant reason for the development of sustainable goods from banana by-products and waste, making it a long-term income-generating commodity. Income source from waste, such as banana by-products, should be considered as one of the most significant methods to ensure an environmentally sustainable future for future generations.

There exists a huge variety of cultivars of banana that need to be studied to identify which species gives the best raw material that can be furthermore processed. Moreover, more detailed research is required to develop molecular markers or any other technology that can easily identify and differentiate between the different varieties of banana species. This can be followed by the use of genetic engineering techniques as well as marker assisted breeding to generate products that have better features and are tuned to the needs of the consumer. Efforts are needed to be taken for educating the farmers as well as the managers who supervise the collection of by-products as well as their processing. Recently, there has been a shift toward adopting agricultural waste as a renewable source of energy which lowers the cost and has beneficial effects on the environment. Land degradation is prevented as well as the waste is utilized into something productive. In this way, the stress on the environment is also reduced. This will also help the banana farmers by generating extra income. There has been very limited research conducted to explain the relationship between the quality of the banana by-product and the geographic location as well as the climate of that particular location [132]. More research and assessment is required to calculate the cost of modern equipment that will be in use to convert the by-products into the feasible processed compound. More regulation is required concerning the collection of the by-products and sorting them so that the product does not start to decay. For example, lignocellulosic materials will start degrading if a certain period of storage interval is exceeded. The storage and handling procedures need to be standardized so that the quality of the by-product remains the same without fluctuating. Efforts are needed to be taken for educating the farmers as well as the managers who supervise the collection of by-products as well as their processing. With the non-renewable resources declining, it is time to look for alternate sources of energy in nature only. The agricultural wastes provide a lucrative option. It is also essential to exploit the various fields in which banana waste products can be used, i.e., as food additives, nutraceuticals, in the paper-making industry, making sports juice, renewable energy, compost, resource of bioactive, and other organic chemicals. This approach will help us in leaving a greener and healthier sustainable future to the generations.

## 6 Conclusions

The banana by-products such as pith, leaves, pseudostem, and fibers have great potential to fulfill the need of the raw material in different industries such as pulp, paper, beverage, and textile industries. The banana by-products such as pseudostem, peel, pulp, sap and flowers are reported to possess bioactive compounds having anti-bacterial, anti-oxidants, anti-cancer, and anti-inflammatory activity. It can also be used for the generation of biofuel (bioethanol and methane). Banana waste by-products can be investigated for use in foods as food additives or pharmaceuticals as a bacteriolytic or fungicidal agent, or separated into various phenolic-rich fractions or specific phenolic compounds as these are potent sources of anti-angiogenic and anti-cancer agents. It may have a key function in lowering the risk of neurodegenerative and cardiovascular diseases. Individual compounds and enhanced fractions can be utilized as food fortifiers or as functional agents in pharmaceutical products. As a result, the banana industry can acquire better significance. Even though there is a long way to go in terms of optimizing the use of biomass waste, biomass-derived adsorbents have a bright future in terms of societal and environmental sustainability. The best part of the products developed from the banana is that it will reduce the amount of biomass that is wasted, and will result in the utilization of the by-product into something good for the environment. Furthermore, studies should be conducted to assess the feasibility of utilizing the banana sap in various industries.

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**Data availability** All relevant data are included in the paper.

## Declarations

**Conflict of interest** The authors declare no conflict of interests.

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