Review

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Exploiting waste derived from *Musa* spp. processing: Banana and plantain

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Abstract: Banana and plantain (*Musa* spp.) are among the most popular crops especially in tropical and sub-tropical zones. *Musa* spp. is a unique, perennial, single-harvest plant that after fruit harvesting is decapitated and generates large amounts of waste and by-products: leaves and pseudostem. Fruit processing also generates waste peels and discarded pieces. Recent research has demonstrated that this type of organic substrate represents a potentially valuable resource that can be developed into high-value products. These developments are critically reviewed in this article, which includes a summary of the composition and biocompounds contained in pseudostem and peel, the use of *Musa* spp. waste in animal and human feed and the obtention of fiber to make paper, rope, handcrafts and combustion materials. On the other hand, the potential for polysaccharides to be fermented and transformed into ethanol, methane or hydrogen, the obtention of single-cell protein (microbial protein) and the use of solid residues for composting or as a substrate for mushrooms cultivation have also been evaluated. The applications described represent great opportunities for economic benefits from this agro-industrial waste. A scheme for the integrated utilization of *Musa* spp. waste in a biorefinery approach is presented as well. © 2023 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: by-products; biorefinery; biocompounds; compost; energy; biomaterial

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Introduction

Plantain and banana, also known as *Musa* spp., are giant monocotyledonous plants that grow in tropical and subtropical areas and are a source of food for millions of people around the world.[1] Plantain (*Paradisiacal muse*) is one of the most important fruit crops in the world, with an annual production of 43 116 591 ton in 2020.[2] Historical reports have shown Asia to be the origin of plantain production, but its adaptability has led it to be one of the most cultivated plants in Central and South America.[3]

Specifically, plantain is the name of a group of 100 cultivars. In the case of banana, the Cavendish variety represents around 47% of the global production. This fruit can be consumed raw as it is sweet and easily digested when ripe. In contrast, mature plantain is usually cooked owing to its high starch content.[4]

Plantain and banana crops are mainly descendants of the Musacea family, coming from two wild species called *Musa acuminata* and *Musa balbisiana*. They are important for the Latin American and Asian economies owing to the characteristics of the tropics, such as the diversity of agroecological conditions, availability of land and wide diversification of sectors. In addition, *M. acuminata* and *M. balsisiana* are classified as the fourth crop at an international level, as the resulting fruit is considered a basic product. The production of bananas and plantain promotes employment and income in tropical and subtropical countries, and produces large export volumes. Major export destinations include the USA, Canada, Europe, Russia, and part of the Asia-Pacific region. The main plantain-exporting countries are Ecuador, Costa Rica, and Colombia. Bananas are produced in Asia, Latin America, and Africa. In Asia the biggest producers are India and China, with 40 million tons per year, and the production serves the domestic markets. Other large producers are the Phillippines, Ecuador and Brazil, with 15 million tons. The market generates around US$8 billion per year. Concerning plantain, a production of approximately 98 million tons per year is estimated in a market of more than US$4306 million per year.[4–6]

Among the parts of the plantain and banana tree, leaves, fruits (pulp and peel), rachis, acorn and pseudostem stand out.[7] Nutritionally, they contain carbohydrates in the form of starch, potassium (K) and vitamins B, C and A.[8] As for the residues generated during processing of plantains and bananas, it is important to highlight that from the whole fruit the only consumable fraction is the pulp. Specifically, when a bunch of plantains is harvested only 20–30% is consumed[9]; the rest is represented by pseudostem, foliar residues, rachis and peels. Regarding the peels, it is estimated that 78% are generated in homes, restaurants and the processing industry (the latter being the largest generator of banana waste in a markedly localized manner). In addition, *Musa* spp. is the only perennial plant that must be discarded and reseeded after harvest to allow the growth of young plants, so, at the end of the productive phase, a high volume of crop residues is also generated.[3] These activities generate large amounts of waste, which, in addition to not generating economic benefits to producers, have become a source of pollution, causing phytosanitary and environmental problems, thus contributing to the degradation of the surrounding ecosystems. Although there might be other management methods, these agro-industrial wastes are generally dumped in landfills and occasionally transformed into organic fertilizer or used for animal feed, not generating significant economic contributions to producers.[10] The management of such waste requires improvement according to current stringent regulations and, therefore, it is important to promote sustainable alternatives for the use of such types of organic agro-industrial waste. Owing to their compositional analysis, recent research has demonstrated that such substrates represent a potentially valuable resource that can be developed into high-value products. Table 1 summarizes the composition of the pulp, leaves and peels derived from *Musa* spp. as reported in the scientific literature. In the specific case of *Musa* spp. peel, this organic waste represents 30% of the weight of the fruit and it is rich in dietary fiber, protein, fatty acids, essential amino acids and potassium. It also contains a wide variety of antioxidants, such as gallocatechin, dopamine, anthocyanins and carotenoids, among others.[7] Some studies have shown that banana pulp and peel have antifungal and antibiotic properties, because of the chemical structure of

Table 1. Composition of pulp, leaves and peel from *Musa* spp. (expressed in dry basis).

Parameter	Pulp	Leaves	Peel
Total sugar (%)	3.3 ± 1.1[11]	n.a.	35.4 ± 4.2[14]
Starch (%)	80.4 ± 2.1[11]	n.a.	12.8 ± 0.9[13]
Ash (%)	2.9 ± 0.2[11]	12.2 ± 0.3[12]	15.3 ± 0.1[13]
Protein (%)	3.6 ± 0.6[6]	n.a.	8.6 ± 0.1[13]
Fat (%)	0.5 ± 0.1[16]	n.a.	13.1 ± 0.2[13]
Net heating value (MJ/kg)	15.3 ± 0.0[6]	19.8 ± 0.6[12]	15.1 ± 0.0[6]
Cellulose (%)	2.4 ± 0.0[6]	26.7 ± 0.9[12]	23.0[13]
Hemicellulose (%)	1.1 ± 0.3[6]	25.8 ± 0.9[12]	23.0[13]
Lignin (%)	12.3 ± 3.5[6]	17.0 ± 0.3[12]	29.9[13]
Total dietary fiber (%)	1.1 ± 3.5[17]	42.2 ± 1.9[15]	50.3 ± 0.2[13] 42.4 ± 13.4[14]

Abbreviation: n.a., not available.

the antioxidants, and also contain neurotransmitters such as norepinephrine, serotonin and dopamine.

The composition of the main products and by-products can be influenced by the production conditions, crop varieties and/or cultivars.[18–22] Authors such as Maseko *et al.*[21] have studied the multi-elemental fingerprints of N, P, K, Mg, Ca, Zn, Cu, Mn, Fe and B and the chemometrics, and have found significant variation among samples, which allows the classification of *Musa* spp. considering genomic and sub-genomic groups. In addition, the identification of elements such as carbon, hydrogen, oxygen and nitrogen in bananas grown under different conditions showed differences in their composition and characteristics. Specifically, the elemental composition of bananas was found to be mainly influenced by local rainfall and soil types. At the same time, the geographical origin of the fruit can be distinguished by applying principal component analysis.[19]

Figure 1 shows the annual number of publications on ScienceDirect containing the terms "By-product and waste banana and plantain". The number of such publications has doubled in the last 10 years. This indicates that the use of by-products and residues derived from *Musa* spp. processing has taken on importance, in accordance with the objectives of sustainable development and bioeconomy. In this context, previous work has demonstrated the possibility of using banana waste to obtain charcoal, ethanol and methane as fuel, while its antioxidant capacity in the prevention of carcinogenic diseases, Parkinson's and Alzheimer's has also been studied.[7] However, despite the existing alternatives for the use of by-products and waste generated from *Musa* spp., these are not usually applied at the industrial scale, which frequently leads to the accumulation of organic waste at processing and production sites. For that reason, the main purpose of this work is to describe and discuss the viability of diverse and novel alternatives to valorize residues derived from *Musa* spp. processing. Moreover, such processes have been integrated in a biorefinery approach with the purpose of promoting circular production processes and contributing to the mitigation of the environmental impact derived from one of the main agro-industrial sectors worldwide.

Uses of *Musa* spp. waste in the food industry

Production of human food

Several researchers have reported the use of the residues and by-products derived from processing *Musa* spp. for the elaboration of food, especially from the rachis, pseudostems and low-quality fruit. Mazzeo *et al.*[23] evaluated the viability of rachis flour for the preparation of biscuits, human food formulation and bread. They reported that the flour presents similar physicochemical characteristics to other flours of commercial use derived from wheat, rice, and corn, while the nutritional value of *Musa* spp. flour is higher owing to its fiber content. Moreover, *Musa* spp. flour showed good acceptance by the evaluating sensory panel, which makes it a product with high potential to be competitive in the food market. Nevertheless, the commercialization of such a promising product is still markedly reduced, making research on new management alternatives to promote this type of flour necessary. For example, the production of *Musa* spp. flour might be scaled and incorporated into food matrices that could function as dietary supplements for vulnerable countries, contributing to societal development and protection of the environment. In fact, Campuzano

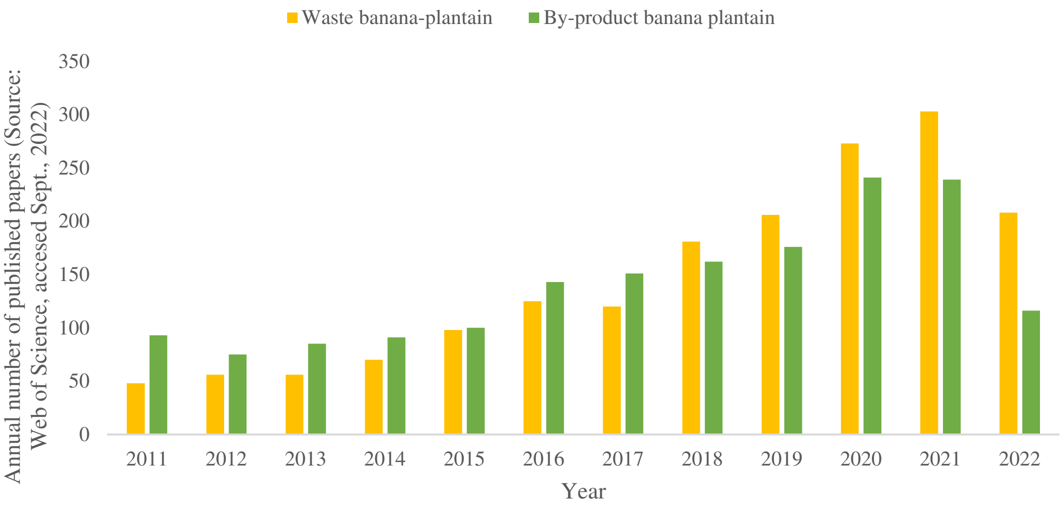

Figure 1. Web of Science bibliometric study related to waste and by-products derived from *Musa* spp. (September 2022).

et al.[24] found that *Musa* spp. flour can be used as a functional ingredient as it increases antioxidant activity and reduces the glycaemic index by increasing the amount of undigestible starch, especially in bakery products. It also has high viscosity and high starch content, and its pseudoplastic conditions make *Musa* spp. flour suitable for making meat emulsions. Consequently, it would be interesting to standardize and improve the management of *Musa* spp. flour to take advantage of its functional properties and to incorporate it in the food industry as a food booster, leading to new market trends that might be geared toward more conscious and responsible consumption.

In addition, the high content of lignin and cellulose in the composition of *Musa* spp. peel makes it a possible source of dietary fiber to be incorporated in highly demanded products such as bakery, culinary and meat products, juices and derivates.[25] In this context, Alarcón *et al.*[26] performed a characterization and reported that the fiber obtained from banana peel has high potential for use in processed food matrices such as meat. Specifically, such fiber has antioxidant capacity and a total phenol content that protect the protein fraction of the main product; for example, it can lead to the reduction of substances reactive to thiobarbituric acid, as well as to a decline in oxidation changes.[27,28] Moreover, peel fiber improves the dietary fiber levels of meat products. However, the shelf-life of the final product was affected since it showed variability in tone, which increased over the course of the experimentation. In addition, regarding the physical properties, the product was affected in variables such as texture, hardness, elasticity, cohesiveness, gumminess and chewability, bringing uncommon characteristics to the meat that might cause its rejection by consumers. This demonstrates the need to deepen the research on fiber production and management, for it to be used as a food matrix, making its shelf life longer and avoiding the changes during storage that may provide unfavorable characteristics. Conversely, its use in the non-food industry might be also advisable because its elasticity and biodegradability characteristics give evident value to by-products and allow it to be used in other processes.[29] In this context, it is important to promote institutional support to carry out the scaling of such valorization processes and, in this way, obtain products that generate positive impacts on society and in turn give value to the research that has been carried out and transfer it to industry. In addition, process design should include a detailed analysis of water and energy requirements to improve sustainability by reducing excessive consumption and reusing residual fractions if possible.

The extraction of starch is another possibility to valorize *Musa* spp. waste. Starch is composed of amylose and amylopectin, making it a renewable, biodegradable and low-cost substrate. In addition, after hydrolyzation, products of higher commercial value can be generated. In fact, residual materials derived from *Musa* spp. processing have been studied as an alternative source of starch and their potential has been highlighted owing to their physical, chemical, and functional properties, digestibility, chemical modification, and industrial uses. Melo-Sabogal *et al.*[29] reported the obtention of starch from the pulp and peel of *Musa* spp. as the first step for the enzymatic conversion to maltodextrin. In the case of pulp starch, a yield as high as 16.11% was obtained, while 14.30% was reported for producing maltodextrin from peels. Furthermore, the starch obtained complied with the physicochemical and rheological properties required to make it a feasible and promising alternative to be exploited. In the case of maltodextrin, a yield of 6.00% was obtained with rheological characteristics not suitable for drying by atomization; therefore, it was recommended to evaluate the efficiency of hydrolysis to improve the characteristics of this product and thus expand its applicability. As mentioned, starch has multiple applications, within the contexts of both food and non-food, so this use is an alternative that might generate high profitability. However, it is necessary to promote research into this field of study and implement techniques and technologies that allow increasing extraction efficiency at low energy expenditure and the use of such renewable resources.

Another alternative use of *Musa* spp. waste and by-products is to obtain its protein fraction. Deb *et al.*[30] have recently extracted, classified, and characterized the protein fraction from banana peel. Samples were dried at 60°C and then ground, defatted, and fractionated for protein, albumin, globulin, prolamin and glutelin for physicochemical and functional characterization. Protein values as high as 89.76% were obtained, with albumin reaching the highest proportion (62.4%), water holding (1.86 ± 0.12 g/g), oil (1.97 ± 0.12 g/g) and emulsifying capacities ($59.27 \pm 1.25\%$).[30] Additionally, the peel is a source of polysaccharides: pectin, hemicellulose and cellulose (Table 1). Pereira *et al.*[31] reviewed the possibility of transforming these carbohydrate fractions into oligomers with application in the development of prebiotics. However, it is necessary, depending on the matrix in which it is to be included, to carry out the respective effectiveness tests established by the local authorities.[32]

Animal feeding

The implementation of the residues generated in *Musa* spp. cultivation within animal feeding might be an alternative for producers that allows the nutritional characteristics of this type of residual biomass to be taken advantage of. However, Canto & Castillo[33] reported that it has low nutritional properties for animal feeding. In the case of leaves, they have a high ash content and low concentration of organic matter, which is related to a lack of energy and protein content. Consequently, although animal feeding with this type of waste has been a trend for many years, it does not really provide significant nutritional value, leading to the necessity of including other supplements in the diet. Diniz *et al.*[34] found that the inclusion of 50% hay made with banana or *Musa* spp. leaves or pseudostems can improve ruminal fermentation based on grass, even though it shows lower degradability when compared with guava or mango leaves. Additionally, the authors reported that the use of these materials in monogastric animals diet should be restricted. Although the implementation and use of by-products can bring benefits for the composition of the diets, they stated that additional studies are necessary on monogastric digestibility, nutrient consumption and ingestion behavior to determine the efficiency of use of the product. In this context, bioprocessing or pre-treatments including fermentation is an alternative to use *Musa* spp. in animal feed. Specifically, Nannyonga *et al.*[35] compared the solid-state fermentation (SSF) using *Saccharomyces cerevisiae* and the anaerobic digestion (AD) of banana waste. The waste was pretreated by alkaline-delignification and thermal pre-treatment prior to SSF and AD, respectively. The SSF was found to be a more economical and efficient bioprocess than AD under the study conditions. The protein content increased by approximately 7.9% after SSF and by 6.7% after AD; the lipid contents increased by 5.9 and 5.4%, while the mineral contents increased by 6.3 and 7.5%, after SSF and AD, respectively. These results suggest the possible use of the upgraded wastes as animal feed supplements and/or nutrient-rich fertilizers, but further research is still required.

In general, the different investigations reported so far into the use of *Musa* spp. wastes and by-products for human and animal feeding show the necessity of carrying out pre-treatments that facilitate and enable their use in food formulations. However, the inclusion of thermal pretreatments and the use of solutions for acidic or alkaline hydrolysis can generate polluting wastewater that should be properly treated. The peel contains several anti-nutritional components such as tannins, oxalate and phytate, which can cause reduced growth and nutrient intake and damage to vital body organs. However, authors such as Zaini *et al.*[25] reported that the concentration of oxalate in banana peel is below the admissible values (40–50 mg/day), making possible its modification by hydrolysis or thermal treatments.[36] In the case of phytate, banana peel contains a safe amount that is comparable with the values reported in cereals, which contain the highest concentrations of phytic acid.[37] Those compounds can also be modified by hydrolysis or thermal treatments that release digestible sugars and, in turn, inactivate substances such as tannins and other anti-nutrients until they reach safe levels for consumption.[25,3618] However, such treatments could be expensive and hinder applicability at a large scale. Another alternative is the extraction of fiber to be used as a prebiotic in human or animal food. Andrade *et al.*[38] reported that some groups of bacteria such as *Akkermansia*, *Bacteroides* and *Faecalibacterium* act as commensals in the intestine and promote the generation of prebiotics and probiotics, generating symbiotic systems with multiple benefits to the host.[32,38–40] Yet as mentioned before, it is also important to deepen the research carried out in that field of study.

Non-food industry applications

Paper manufacturing

The production of paper from pseudostem and peel derived from *Musa* spp. processing was studied as both substrates are rich in cellulose. Ramdhonee & Jeetah[41] made absorbent paper from banana peel fiber with different formulations, including as raw material recycled paper and peel fiber. The paper containing 100% banana fiber was the most absorbent one (2.15 s), showing the highest resistance to abrasion (180 turns) and the lowest fold recovery angle (32.5°). From these results it was possible to demonstrate that banana peel contains an adequate quantity of cellulose, along with low lignin concentration, making it ideal as a low-cost alternative material for paper production. The pseudostem was also used for the manufacture of paper. Specifically, Mazzeo *et al.*[23] evaluated the obtention of paper using three different methods: two of them through chemical processes and one artisanal. The authors obtained a rigid material with all the methods implemented. The yield reached for fiber was higher for extractions by chemical methods (80–81%), while the third artisanal method allowed a value of up to 35% to be reached. This last artisanal method was characterized by extracting fiber only with water and the compaction of the obtained product without adjuvants. However, they recommended a refinement of the processing method to facilitate the extraction of lignin, and thus improve softening to meet the characteristics required at industrial level. In addition, the conduction of further physicochemical tests is required to determine the characteristics of the product. On the other hand, Canto & Castillo[33] reported the use of *Musa textilis*, *Musa balbisiana*, their hybrids and some varieties of *Musa acuminata* to produce fiber. The authors found that the fiber strength depends on the variety used. Generally, the strongest fibers are used to make ropes for boats, while the light ones meet the requirements for handicrafts, paper pulp and some packaging. As for the process of making paper, a traditional methodology was followed, cutting the plant material (pseudostems) and heating it in alkali solution (sodium hydroxide). Subsequently, the mixture was washed with water to neutralize the pH, and ground to pulp, which was separated by filtration and placed in a thin flat film. As it dried naturally, the pulp formed paper, which, owing to its characteristics, might be used in handicrafts. The production of paper pulp might be a valuable alternative for valorizing coffee wastes and by-products owing to the high demand for paper nowadays, especially considering the need for sustainable production processes and the growing trend toward using ecological paper, which provides an interesting market either for printing or packaging. However, it is necessary to increase the number of studies on the standardization and definition of the optimal production conditions using *Musa* spp. wastes and by-products as raw materials. The resistance of the final product and the cost effectiveness of the full process should be considered. This is essential to achieve market competitiveness as alternative non-wood fiber sources to the traditional processes for producing paper.[41] Because of diversifying production, a decrease in the demand for fiber derived from scarce forest resources could be achieved, while non-wood resources and agricultural waste would be valorized.[42] However, the processes to obtain and transform *Musa* spp. fiber into paper pulp should be optimized through appropriate life cycle assessments to reduce their environmental impact, as highly polluted and non-biodegradable wastewaters are usually generated in the production process. A compromise needs to be reached encompassing electricity consumption, water recycling and transportation costs.[43]

Biocompounds

Sugars, minerals, organic acids and dietary fiber might be considered among the most important plant metabolites, while in the case of bioactive compounds phenols, alkaloids, terpenoids and flavonoids can be highlighted. These types of secondary metabolites are the result of a number of chemical, physical and biological processes that occur in plants.

Each biocomponent has specific biological and structural characteristics. Specifically, some of the most common active components include phenols and polyphenols.[44] Tannins and flavonoids are included in this broad group, and they are distinguished by some general characteristics, including 12–16 phenolic groups and five to seven aromatic rings. The structural characteristics of proanthocyanidins, condensed and hydrolyzable tannins must also be considered.[45] Tannins are specifically water-soluble phenolic compounds of rough and bitter taste that are present in roots, plant barks, fruits and leaves at low concentration. Tannins are also called antinutritive substances, because, if found at high concentrations, they can limit the absorption of some nutrients such as nitrogen, phosphorus, potassium, zinc and magnesium, among others. However, tannins have other characteristics that make them important, such as anti-inflammatory and astringent properties. These compounds are credited with antioxidant action, as they are capable of trapping radicals.[46,47]

More than 40 phenolic compounds have been identified in the case of *Musa* spp., but their composition varies depending on various factors that include maturity, plant variety and crop conditions.[48] It is worth noting that tannins predominate, especially in the peel, and they are more abundant in green fruits than in ripe ones. In this context, the extraction of such biocompounds has emerged as an alternative in the treatment of degenerative and carcinogenic diseases. Table 2 summarizes the main biocomponents obtained through different procedures from *Musa* spp. waste, as reported in the scientific literature. As can be seen, *Musa* spp. peel has a high antioxidant activity, which makes it a promising source for extracting bioactive compounds. Specifically, *Musa* spp. is considered among other fruits such as mango, papaya, watermelon and avocado as having the second highest content of phenolic compounds (total phenolic content within the range of 5–47 mg gallic acid equivalent/g dry matter). In contrast, the peel has an antioxidant capacity above 90%.[49] However, although the management alternatives described previously might be considered of special interest to various demanded types of industry, such as pharmaceuticals or nutraceuticals, their application at industrial scale has been scarcely implemented in most cases. In addition, further subsequent steps would be required for the treatment and valorization of the residues resulting from the extraction process of such biocomponents. The extraction systems used include the generation of waste streams rich in solvents with different recovery and disposal needs. In fact, in some cases they are considered hazardous wastes that must be carefully managed. Consequently, the initial design of the specific extraction processes should include a detailed evaluation of the type of solvent to be used, prioritizing those framed within green chemistry.[50,51]

Table 2. Biocomponents obtained from *Musa* spp.

Biocomponent	Biomass and conditions	Main results	Reference
Antioxidant phenolic compounds	freeze-dried banana peel (0.15 g) extracted with different solvents (3 mL): methanol, ethanol, acetone, water acidified with hydrochloric acid (pH 3.0) or mixtures (1:1, v:v) of organic solvents and water	The best solvent for the extraction was found to be water–acetone (1:1). The highest value of extractable components was 54% (3.3% phenols; 4.34 g/g of cyanidine 3-glucoside equivalents). Dopamine and L-dopa and catecholamines with antioxidant activity were identified	52
	The peel was cut and bleached at 95°C for 5 min and drying at 55°C and ground, then, 2.5 g was immersed in 50 mL of a solvent (methanol 50–water 48–formic acid 1.5, v/v) in homogenization for 2 min and an ultrasonic bath for 5 min. Subsequent centrifugation at 2500***g*** obtained extracts of banana peel flour	Total phenolic content: 29 mg/g, as GAE: FRAP, 14 μM/g; ABTS, 242 μM/g; ORAC, 436 μM/g (as Trolox equivalents)	53
	Evaluation of the impact of drying conditions on total phenolic compounds and antioxidant activity, as well as modeling of process variables using artificial neural networks. The samples, banana, were dried by warm air at 50 and 70°C and freeze-dried; each sample was subjected to multiple extractions: first with a methanol solution; three times with acetic acid (98:2), and then with an acetone–water solution (60:40), also three times. In each case the samples were placed in an ultrasonic bath at room temperature. Phenolic compounds and antioxidant activity were determined by spectrophotometric techniques. The experimental data were used to train a neural network in Matlab	The phenolic compounds present in all banana samples were preferentially recovered in the methanol extracts. The amount of total phenolic compounds in the dried samples ranged from 3.79 to 6.91 mg GAE/g dry matter. Convective drying resulted in all cases in a reduction of between 15 and 45% of the total phenolic compounds present, freeze-drying being a technique with a higher “preservative” effect. Neural network modeling showed that antioxidant activity and phenolic compound contents can be predicted with high accuracy from banana variety, drying state and extract type	54
	Evaluation of the relationship of peel lignin as an antioxidant and antimicrobial agent by controlling organosolvent process parameters. Ground banana peel was hydrolyzed using an aqueous solution of acetic acid (70–90% v/v) and 2.0% v/v HCl at 110°C for 1, 2 and 3 h	The proposed methodology was used to obtain banana peel lignin with peculiar physicochemical and structural characteristics, such as yield and purity, the relative proportion of monolignols and interunit bonds, total hydroxyl groups, molecular weight distribution and thermal stability, leading to antioxidant results that showed that 90% banana peel lignin followed by the 80 and 70% banana peel lignin, respectively. The results of antimicrobial activity against *Escherichia coli* showed that banana peel lignin was 70% and 80% inhibited	55
	Evaluation of the antihyperglycemic effect of the ethanolic extract of banana inner peels using a glucose tolerance test in normoglycemic rats and an *in vitro* antioxidant study. Banana pulp was removed and the fibrous inner part of the peel, called the “inner peel”, was dried at room temperature, pulverized and defatted. The extractions were then conducted in Soxhlet using ethanol as a solvent which was subsequently evaporated	Acute oral toxicity testing showed normal behavior of treated animals. No mortality was observed at high doses of 2000 and 5000 mg/kg, and there was a significant decrease in glucose level at 150 min compared with the control group. Antioxidant activity was found to vary between 25 and 250 μg/mL by DPPH and FRAP	56
	Banana peel extracts to be incorporated into a coating. Banana peel was frozen with liquid nitrogen and then pulverized. The powder was mixed with 80% ethanol in a 1:5 ratio and left to stir for 12 h at 25°C. The mixture was filtered and evaporated, and the extract was characterized	The results showed a total polyphenol content of 3.5 mg/mL, identifying three phenolic compounds: catechin, ferulic acid and kaempferol at concentrations of 148, 19 and 94 μg/mL, respectively. In addition, the average particle size obtained was 68 μm	57

Note: GAE, gallic acid equivalent; ABTS, 2,2-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt; Trolox, 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid; ORAC, oxygen radical absorbance capacity; FRAP, ferric reducing antioxidant power; DPPH, 2,2–diphenyl-1- picrylhydrazyl.

Fermentative processes

Production of ethanol

Ethanol is widely used in different applications. Such alcohol is frequently contained in fermented beverages for human consumption, but it is also used in nitrocellulose dissolution as a solvent. In addition, ethanol is involved in the oxidation process to produce acetic acid, while it is also used as a solvent in mixtures with gasoline in the hydrocarbon industry since ethanol is a renewable biofuel that improves the properties of the fossil fuel. Specifically, ethanol can be considered as an oxygenating agent, as it allows the substitution of the methyl tertiary butyl ether used in traditional processes, increasing the compressibility of fuel (octane index 70–75%) and improving the engine efficiency.[58] In this context, residual lignocellulosic biomass has gained marked importance owing to its energy potential. However, the design of the ethanol production process should consider the pretreatment that is frequently required to make it technically and environmentally efficient, depending on the substrate to be fermented.[59] The parallel generation of stillage and recalcitrant substances with high COD values should be also considered. Therefore, efficient approaches to wastewater management must be included.[60,61]

Processes such as hydrolysis of cellulose allow sugars to be obtained from fermentable plant material, with applicability to obtain biofuel (ethanol and methane).[62] Mena[63] used *Musa* spp. pseudostems and fruits to produce ethanol. The substrates were dried at 45°C to increase the concentration of sugars available and thus enhance the yield in obtaining ethanol. The particle size was reduced to approximately 2 mm and a subsequent pre-treatment through acid and alkaline hydrolysis was carried out (121°C, 7.5 kg/cm^2, 15 min). The pre-treatment allowed reduction of the crystallinity of cellulose and dissociation of the lignin–cellulose complex to release the fermentable sugars. The initial concentration of flour-reducing sugars contained in the liquor derived from the fruit reached a value of 67.2 ± 3.1 g/L, while the concentration from the pseudostem was found to be 49.1 ± 2.8 g/L, with glucose and mannose as predominant sugars. Both solutions were inoculated with 3×10^7 cell/mL of yeast, incubated at 30°C and stirred at 150 rpm for 3 days (all experiments were carried out in triplicate). Despite the pre-treatments, the microorganism only consumed 27% of the available reducing sugars, reaching a maximum percentage of 15.3% of ethanol (0.882 g/L). This result demonstrated the low efficiency of the process, with additional studies being necessary to improve the global process yield.[63]

On the other hand, Monsalve *et al.*[58] studied the alcoholic fermentation of banana peel and cassava starch. The starch, cellulose and hemicellulose present in banana peel represented more than 80%, which potentializes such residual biomass as a carbonaceous source. It was also possible to obtain ethanol at a concentration of 7.92 ± 0.31%. These results are similar to those reported by Afanador,[64] who encouraged the installation of fuel alcohol plants in the sites with the highest production of banana, although the optimization of the fermentation efficiency is still required. Alonso-Gómez *et al.*[6] have recently performed a techno-economic analysis of the bioethanol and plantain flour production using unripe plantain as a raw material (using the whole plantain flour with peel and after separating peel and pulp).[6] The starch content of peel (39.4%) and pulp (84.2%) in the unripe plantain fruits allows such substrates to be proposed to produce flour and bioethanol. Moreover, the calorific value of the peel and pulp flours (15.32 and 15.12 MJ/kg, respectively) allows elucidation of their high potential to be upgraded in biotechnological processes. However, starch should be extracted, hydrolyzed and then fermented. This process is also necessary when using the pseudostem, as well as with the shell, because their composition is characterized by a high content of polysaccharides that in a hydrolysis process, either chemical or biological in nature, allows high concentrations of reducing sugars to be obtained that can be fermented by microorganisms (*i.e.* yeast). Another alternative might be carrying out the fermentative process in two phases: the first one using microorganisms that generate hydrolytic enzymes, and a second phase in which yeast or bacteria carry out the fermentation process itself.[65]

Furthermore, Uchôa *et al.*[66] evaluated three residues to produce bioethanol: pulp, peel and pseudostem. They compared the use of *S. cerevisiae* monoculture as a fermentation inoculum with a combination of *S. cerevisiae* and *Pachysolen tannophilus*. From the experimental results they estimated the energy consumption of the production stages (from pre-treatment of the residue to distillation to obtain bioethanol), with an economic analysis of its possible implementation in Brazil. The study found that the two microorganisms evaluated for fermentation had a positive effect on the process, with a pulp–peel–pseudostem ratio of 1:2:10 leading to the highest ethanol yield. In the simulation, they found a maximum productivity of 45 080 m^3/year for the region of Catarina, but from the economic point of view they indicate the need for the cogeneration of energy (ethanol–methane) to improve the feasibility of the valorization process.[66]

Bio-methane

In the context of fermentation processes, it is known that waste from the food industry as well as the agro-industrial and domestic sector, among others, can be exploited through anaerobic digestion. In biogas production it is important to consider the biodegradability of organic matter to determine the capacity of the microorganisms involved to transform the substrate into methane.[67] To do so, the biochemical potential for methane generation is usually established and, in this way, the ideal material for energy production processes can be selected.[68] In this context, biomethanization becomes an alternative to mitigate the environmental impact caused by overexploitation of natural resources to obtain fossil fuels and the impact of greenhouse gases.[69] However, as reported by Adelt *et al*.,[70] to evaluate the feasibility of the whole biomethanization processes from the environmental point of view, the parallel greenhouse gas emissions associated with biomethane production must be also taken into account, covering the emission of carbon dioxide derived from the entire production chain, that is, substrate production, collection and transport, uncontrolled fermentative processes (in raw materials, products, waste, *etc*.), biogas up-grading and energy supply for the biogas plant, among others. Additionally, the global energy balance must be evaluated, considering that the biogas yield should compensate for, at least, the energy requirement of the full process. This fact, together with the complexity of the biochemical steps taking place and the wide range of factors that might inhibit them, might hinder the feasibility of such promising biotechnological processes.[70,71]

The cultivation and processing of *Musa* spp. generate wastes and by-products (pulp, peel, leaves, *etc*.) that could be valorized through biomethanization. Table 3 shows the main results and methodology reported so far in the scientific literature for obtaining methane from *Musa* spp. residual substrates. Those investigations confirm the biomethanization capacity of by-products derived from such important agro-industrial sectors worldwide. In fact, the generation of biogas is an interesting alternative in the food industry and other sectors, since it could decrease the dependence on fossil fuels that currently generate a high degree of environmental contamination, with the consequent economic and environmental benefits.

In parallel, biomethanization processes generate a secondary stream called "digestate", that is characterized by containing nutrients and non-degraded organic substrates that might be suitable for use as organic amendments in agricultural soils.[90] Specifically, Chanakya & Sreesha[81] carried out the anaerobic digestion of banana leaves and areca husk.[81] They reported mass recovery levels for banana leaf fiber of 20%, 70% biogas (400 mL/g TS (total solids)) and 10% digestate, while for areca husk recoveries were found to be 50%, 45% (250 mL/g TS) and 5%, respectively. Taking advantage of the digestate in the *Musa* spp. cultivation soils would allow the recycling of essential nutrients and promotion of the circular economy in this important sector.

Composting

Composting is an aerobic fermentation process of organic substrates that, under controlled conditions, allows organic amendment with agronomic application to be obtained. Nowadays, the transition to the use of fertilizers of biological origin has increased, owing to the low concentration of metals and residual chemical substances that remain in some fruits and vegetables in post-harvest terms.[81] Additionally, the need to incorporate alternatives to conventional chemical fertilizers, which in some cases have caused deterioration and soil contamination, has arisen recently. Consequently, sustainable fertilizing products that are friendly to the environment and to the health of consumers, such as those derived from some biological residues, are required as their implementation and incorporation in activities of agronomic origin would allow the mitigation of negative impacts associated with excessive use of agrochemicals. However, composting in uncovered piles generates significant environmental impacts, especially in terms of the emitssion of markedly unpleasant odors that usually lead to social rejection in nearby populations. Volatile organic compounds (VOC), ammonia and volatile organic sulfur compounds (VOSC) rank among the most common gaseous compounds emitted in the process. Specifically, mercaptans, aldehydes and nitrogen-containing compounds are some of the chemical compound families that contribute significantly to composting odors, whose minimization is highly desirable.[91,92] In addition, the generation of contaminated leachate is frequent throughout the process and its proper management must be considered in depth.[93]

Musa spp. peels have been used with agricultural purposes after being subjected to biotechnological processes. Kalemelawa *et al*.[90] evaluated the composting process of banana peels using different inocula for soil nutrient replenishment.[90] For this purpose, they evaluated the changes in the chemical composition of different compost formulations: plain banana peel (B), a banana–bovine feces mixture (BC) and a banana–poultry litter mixture (BP), for 12 weeks. The peels were dried to 60% moisture under natural conditions for approximately 4 weeks. In each composting box, 5 kg of substrate containing 0.5 kg of inoculum were

Table 3. Biomethanization of residual substrates derived from *Musa* spp. processing.

Substrate	Conditions	Main result	Reference
Pulp	They used vinasse derived from previous processes of alcoholic fermentation of banana pulp (2.7% TS). Digestion trials were conducted without inoculum and with 10% swine manure or rumen excrements in relation to the total solids in the stillage	The highest yield was obtained with rumen: 2.24 L_{CH4}/L and 0.93 mL/h. Swine manure produced 2.09 L_{CH4}/L and 0.87 mL/h, while 0.92 L_{CH4}/L and 0.77 mL/h were obtained without inoculum	72
	Inoculation of anaerobic reactors with 20% TS of banana pulp, at a temperature of 16–25°C. Excreta from various ruminants, wastewater and soil were used as inoculum. The hydraulic retention time (HRT) was fixed at 60 days	The methane yield was 0.218 L_{CH4}/L. In the organic acid profile, the highest concentrations of acetic, butyric and propionic acids were found to be 7.36, 5.29 and 3.78 g/L, respectively	73
Peel	They performed loads of 2.5, 5.0, 7.5 and 10.0% TS of fresh peel at 37°C for 192 h	Methane yield: 0.439 L/kg VS, with the best results obtained at 7.5% VS	74
	At laboratory scale, with 8% (v/v) of sewage sludge as inoculum. The biomass–residue ratio was 0.001 kg VS/L:2 g COD (peel). HRT, 63 days and temperature, 35°C	Reported values of methane production as high as 64 L CH_4/kg COD	68
	Two-phase digestion of peel at 55° and 35°C, with loads of 1.0, 1.5 and 2.0% TS, at 20 days HRT	Methane yield: 17 L_{CH4}/kg VS. The concentration of volatile fatty acids increased with the 2.0% load, which led to a decrease in pH, making the process unfeasible at higher loads under the operational conditions evaluated	75
	Evaluation of the effect of biodigester shape: cylindrical, cubic and conical (15 m^3) in biogas production by co-digesting banana peels with animal waste. Modeling and optimization with NeuralPower software	Average biogas production of 0.58, 0.46 and 0.36 dm^3/d for cylindrical, cubic and conical shape, respectively. The genetic algorithm model yielded an optimal biogas production of 13.65 dm^3 with a substrate combination of 0.7 kg poultry droppings, 0.0004 kg cow dung, 0.6 kg piggery waste and 0.2 kg banana peels	76
	Evaluation of the effect of mixing ratio (1.0, 1.5, 2.0 and 2.5) and warm air oven pretreatment on the anaerobic co-digestion of water hyacinth and banana peels. Cow dung was added as inoculum for anaerobic batch tests	Pretreatment for anaerobic co-digestion of water hyacinth and banana peels showed a better production of 0.296 L/gVS compared with the results with no pretreatment: 0.253 L/gVS	77
	Evaluation of biogas production using peels with cow manure at laboratory scale. Sludge from a wastewater treatment plant was used as inoculum. Loads of 10, 14, 18 and 22 g VS/L; cow manure mixed at 10, 20 and 30%	The yields with cow manure percentages (10, 20, 30%) and loadings of 18 and 22 g VS/L were 0.05, 0.04 and 0.06 L/g VS·day, and 0.04 0.03 and 0.05 L/g VS·day), respectively. No dependence of the loadings on the percentage of cow manure was identified	78
	Mesophilic biomethanization of banana peel at different volatile solids loadings (0.5,1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 g SV/L)	Methane yield: 182 L_{CH4}/kg VS. Biodegradability of banana peel was found to be 68%	79
	Production of methane from peels under mesophilic conditions at laboratory scale. Inoculum from a wastewater treatment plant. The substrate was loaded in ratios of 0.5–3.0 g VS/L	Methanogenic potential of 257 L/kg VS (7.5 kW/ton·day)	80

(Continues)

Table 3. (Continued)

Substrate	Conditions	Main result	Reference
Leaves	Fresh banana leaves for methane production at an HRT of 27 days, in a plug flow digester	Production coefficient of 400 L/kg TS	81
	Dried banana leaves to produce biogas. Different sample amounts (0.05, 0.1 and 0.15 kg/L) were incubated at 35°C for 55 days	Volumetric concentration of methane in the biogas of 65% was obtained from 0.1 kg/L	82
	Anaerobic mesophilic co-digestion of cow manure and banana peel at laboratory scale. Different mixture ratios (in VS): 100:0, 80:20, 60:40, 50:50, 40:60, 20:80 and 0:100	Maximum methane yield of 229 mL/g VS at a ratio of 40:60. Biodegradability was found to be 86% for an organic loading rate in the range of 1.49–3.57 kg/m^3·day	83
	Digestion of semi-dried plantain leaves at laboratory scale, using sewage as inoculum (50 g leaves/L). Evaluation of the effect of additives such as $FeCl_3$ and urea (15 mg/L)	Maximal biogas production was obtained with the addition of $FeCl_3$+ urea (0.09 L CH_4/L·day)	84
	They evaluated the biogas production potential using banana peel and sewage sludge: 0:100, 20:80; 40:60, 60:40; 80:20 and 100:0, and the effect of hydrolysis with NaOH at different concentrations: 0.50, 0.75, 1.00, 1.25, 1.50, 1.75 Mol/L. HRT, 24 h	An increase in the percentage of Banana Peel Waste (BPW) increases the methane yield; however the production limit was 60% (producing 732 mL). With hydrolysis, the highest biomethane was achieved with the second dose (621 mL/day)	85
Pseudostem	Alkaline pre-treatment (NaOH) of banana stem for biogas production. Subsequently, solid-state fermentation in combination with pig excreta was evaluated (20% w/v at a ratio of 1:4 for pseudostem/excreta, respectively). The process was conducted at 35°C for 40 days	The best condition was found to be 6% (by weight) of NaOH, based on the total solids of the evaluated sample: 232 L CH_4/kg TS	3
	Evaluation of size reduction, enzyme addition and co-digestion of plantain stems with cow dung. Wastewater treatment sludge was used as inoculum. Pre-treatments at particle sizes of 5, 10 and 20 mm. Cellulase and co-digestion with cow dung were used for the enzymatic treatment. All tests were carried out under mesophilic conditions	Methane yields of 287, 340 and 347 mL/g VS, with particle sizes of 5, 10 and 20 mm, respectively. The addition of enzyme and co-digestion improved the hydrolysis rate, although there was no improvement in methane production	86
	Different banana fractions (pseudostem, peel and pulp), as well as whole unpeeled bananas, were individually studied in a laboratory-scale biochemical methane potential tests (at 37°C, in 2 L reactors)	Specific yields of 0.25, 0.32, 0.37 and 0.35 m^3/kg VS were obtained for stem, peel, pulp and unpeeled banana, respectively	87
	Evaluation of batch methane production from cattle rumen and banana stalk residues. Temperature range, 24–27°C; incubation time, 80 days	Biogas generation from pseudostem of 167 L/kg dry basis (d.b.), with an energy potential of 264 000 m^3 biogas/year, equivalent to 330 MWh of electricity	88
Banana waste mixtures	Digestion was conducted using banana leaf, banana stem and banana stalk as substrates; the inoculum was digested sludge in a laboratory-scale reactor under mesophilic conditions	Methane yield (m^3 CH_4/kg TS): 0.125 from stem, 0.132 from peduncle, 0.062 from leaf, 0.367 from waste fruit and 0.322 from peels. Their mixture produced 0.201 m^3/kg TS	89

Note: COD, chemical oxygen demand; TS, total solids; VS, volatile solids; STP, standard temperature and pressure conditions (0°C, 1 atm).

placed at a temperature of 40°C, with weekly manual turning. High concentrations of nitrogen and potassium mineral nutrients were detected in the final compost formulations. In the case of other nutrients such as phosphorous (<0.39%), calcium (<0.46%) and magnesium (<0.39%), their concentration was low, while the pH value was markedly alkaline (pH > 9). It is worth noting that the decomposition of banana peel was also faster with the poultry litter under aerobic conditions, where there was a higher content of potassium and nitrogen. Therefore, *Musa* spp. wastes and by-products are promising sources of potassium and nitrogen, while their use as neutralizing agents in acid soils might be advisable.

An additional study carried out by Khatua *et al.*[94] focused on producing vermicompost from pseudostem combined with cow dung at different proportions (1:2, 2:1 and 2:1, respectively). Earthworms (*Eisenia fetida*) were added as an adjuvant. The results of the chemical composition of the substrate after 60 days showed that the ratio 1:2 led to the highest values of potassium, iron and magnesium, while the proportion 2:1 allowed complete mineralization of the mixture and reduction of polypeptides, polysaccharides and aromatic structures. The vermicompost obtained was rich in nutrients and might be used as compost to improve the productivity of crops. Furthermore, Mago *et al.*[95] have recently evaluated vermicomposting of banana leaf and cow dung using the same earthworms. After 105 days, earthworm activity reduced the pH, the concentration of total organic carbon (40–64%) and the C:N (8.9–24.3) and C:P ratios, while the macronutrients and micronutrients increased throughout the valorization process. The results indicated that the growth and fecundity of the earthworms were the best in the vermireactors containing 20–40% leaf.[95]

Isibika *et al.*[96] evaluated the feasibility of applying microbial, chemical and/or thermal pretreatments to banana peel, combined with the subsequent inoculation of black soldier fly larvae (*Hermetia illucens* (L.)). The biological pretreatment was carried out with *Trichoderma reseii*, *Rhizopus oligosporus* and bacteria extracted from the gut of the larvae (7–21 days). The chemical treatment took place with 0.8 and 1.0% ammonia (7–14 days), while the thermal treatment was developed at 120°C for 1 h. The microbial pretreatment with *R. oligosporus* (14 days) and the combination of ammonia + *Rhizopus* led to the highest final larval weight (229 mg larva^{-1} compared with the control 33 mg larva^{-1}). Furthermore, tannins and phenolic compounds were identified as inhibitors after applying the thermal pretreatment. Isibika *et al.*[97] also evaluated the co-composting of banana, orange and fish wastes, at different mixing ratios. All mixtures were tested on the composting efficiency of black soldier fly larvae, considering biomass conversion, waste reduction and larval survival. The mixtures of orange and banana peels resulted in the lowest biomass conversion efficiency (4.5 ± 1.3%). Furthermore, a recent study characterized the odoriferous impact derived from the aerobic decomposition of banana peel carried out in a laboratory-scale bioreactor (25 days).[98] The emissions of volatile organic compounds (VOC) were continuously measured by using advanced analytical techniques, membrane inlet single photon ionization time-of-flight mass spectrometer (MI-SPI-ToF-MS) and 18 VOCs belonging to 10 functional groups were detected in the air samples. The highest emission was identified during the first 14 days, with an average emission rate of total VOC of 44.3×10^{-3} mg/kg of dry banana peel. More than half of the VOCs belonged to malodorous substances such as styrene, dimethyl sulfide and diethyl sulfide, which might hinder the applicability of such valorization processes.

Consequently, the composting of residual streams from *Musa* spp. might be a viable alternative in the production of environmentally friendly fertilizers, in which additional biotechnological applications could be incorporated to increase the process yield, efficiency and beneficial characteristics of the final product obtained from different applications. In general, the demand for bio-fertilizers has increased from small to medium-sized producers who are interested in producing cleaner and more environmentally responsible food. So, composting could be a booming market with a view to becoming part of large-scale industries devoted to coffee production. However, it is still necessary to carry out complementary research studies to delve deeper into the topic to obtain maximum profitability and sustainability of the process, especially in terms of reducing the associated impacts (generation of lixiviate and unpleasant odors) and evaluating the productivity of soils amended with compost derived from *Musa* spp. wastes and by-products.

Alternative fermentative processes

The high content of polysaccharides in the different waste and by-products derived from processing banana and plantain makes them an interesting source of carbon for microbial applications. Yeng *et al.*[99] evaluated the feasibility of using juice extract obtained from banana residues for lipase production using *Escherichia coli*. The juice contained a concentration of glucose of 16.6 g/L, that is, 55% of the total fermentable sugars. In that medium, lipase production was found to be 200.0 U/mL, while in the blank medium (basal medium with glucose) it was found to be 206.3 U/mL. In the case of the banana pseudostem, previous hydrolysis was performed owing to its high starch content, increasing the concentration of glucose to 36% (10.4 g/L) (the initial sugar concentration of 7.78 g/L was observed in the juice derived from direct pressing). From the above, it can be concluded that banana residue juice could be successfully used as an alternative fermentable carbon source or to produce lipase by recombinant *E. coli*. In the same line, Granda *et al*.[100] evaluated the potential of plantain residues as solid fermentation substrates to produce secondary metabolites (enzyme lignin peroxidase and manganese peroxidase) with the fungus *Lentinus crinitus*. The production of metabolites was carried out for a period of 21 days, incubating seven combinations of substrates at 23°C: stems–fruits, leaves–fruits, leaves–stems, leaves, stems, fruits and leaves–fruits–stems. Biomass was previously cut and dried at 80°C for 24 h. As a result, it was determined that the treatment of leaves and stem is the most suitable to produce enzymes lignin peroxidase and manganese peroxidase under the experimental conditions tested. Concerning aromatic compounds, they were found at low concentrations, but after the 16th day of fermentation, concentrations as high as 0.6, 0.4, 0.6 and 254 ppm were obtained for ferulic acid, vanillin, vanillic acid and eugenol, respectively.

The fermentation by autochthonous microbial biomass for hydrogen production from banana waste and the identification of enzymatic routes were evaluated by Mazareli *et al*.[65] They reported optimal pH (5.09–7.91) and temperature (27.1–46.9°C) for carrying out the fermentative process. Fructose and glucose are the primary alternative carbon sources in banana waste-fed batch reactors. The high concentration of lactic acid and H_2 production was associated with *Lactobacillus* sp. and *Clostridium* sp. (14–35%), while the organic acid related to hydrogen production was butyric acid, rather than acetic acid. The pH affected carbohydrate fermentation and organic acid production. The predominance of the bacterial genus was identified through metagenomic analysis. The metabolic pathways related to the metabolism of galactose, sucrose, fructose, arabinose and xylose were also mapped using bioinformatics tools. The authors also described the metagenomics results with their expression through enzymes and the metabolic response to the conditions studied for hydrogen production. In the same line, the productivity (P) (mL H_2) and hydrogen production rate (R_m) ranged from 6.06 to 62.43 mL H_2 and from 1.13 to 12.56 mL H_2/h, respectively. A temperature of 37°C and a pH of 7.0 were the optimal conditions for P (70.19 mL H_2) and R_m (12.43 mL H_2/h). They found a high concentration of lactic acid and H_2 production was associated with *Lactobacillus* sp. (52–81%) and *Clostridium* sp. (14–35%). Additionally, they found butyric acid to be an indicator of H_2 production.[65]

Therefore, fermentative processes are interesting alternatives to valorize *Musa* spp. residual streams. Nevertheless, it is still necessary to deepen research into this type of procedure to establish the optimal process conditions using *Musa* spp. waste of different natures and thus scale up the processes to obtain valuable compounds at high production yields, contributing to mitigation of the environmental impact caused by their inappropriate use and exploitation. In addition, to obtain biotechnological products, upstream operations involving significant energy and water consumption are usually required. Moreover, different by-products may be generated in the process, involving further downstream operations that might require the use of chemicals and generate secondary environmental impacts.[101–103] Therefore, in the process design it is essential to consider the entire biotechnological life cycle, from raw material selection to waste management, and the wide range of environmental impacts and economic indicators.[101,104]

Biomaterials

Plastic products are considered as one of the main sources of the generation of solid pollutants, since their degradation is markedly slow and toxic substances are released into the environment, altering soils and water biota and microbiota. Such types of pollution affect not only the environment, but also human health. This fact is a consequence of their manufacturing process, since plastic materials are generally made from fossil fractions derived from petroleum. As an alternative, the need to evaluate different arrays to obtain biomaterials such as biopolymers that are environmentally friendly and meet the characteristics demanded by industry has arisen recently. In this context, waste derived from *Musa* spp. processing could be suitable to produce bioplastics, owing to its high cellulose and starch content. In turn, that bioplastic could provide nutrients during the final degradation process (composting) that do not alter biodiversity.[13]

Various studies have been carried out to obtain bioplastic from *Musa* spp. biomass. López *et al.*[13] evaluated the obtention of biopolymers from banana peels. They used 70 g of banana peel mixed in 400 mL of distilled water and 2.0 g of sodium metabisulfite. The mixture was boiled, and HCL and NaOH were added. Subsequently, the bioplastic obtained was dried at 103°C for 30 min, obtaining a maximal deformation of 0.0194 mm/mm and maximal tension of 3.206 MPa. However, despite the success of the process, the authors stated the necessity to improve the homogeneity of the product and the global yield of the process. Alternatively, Orsuwan & Sothornvit[105] developed and characterized banana nanocomposites and starch nanoparticles as biopolymeric material. The preparation of the banana nanoparticles was carried out by the reticulation method of water in oil mini-emulsion. These nanoparticles were mixed with 5% w/w montmorillonite; they found that the mixture of banana flour and montmorillonite was sufficient to reinforce biopolymer films as packaging materials for food and pharmaceutical applications.

Furthermore, Arquelau *et al.*[106] produced edible flour coatings from ripe banana peels with different heating times and corn starch concentrations (33.3–66.6 g starch/100 g flour). The peels were immersed in 0.5% (w/v) citric acid solution for 30 min, ground and dehydrated at 60°C for 24 h. The results show a yield of 5.6% on a dry basis. They also found that the thickness was influenced by increasing corn starch concentration, while the chroma remained uniform with different corn starch concentrations and heating time. In terms of barrier properties, water vapor permeability of the films was influenced by the corn starch concentration. The mechanical behavior showed low tensile strength values and the elastic modulus had a direct relationship with corn starch concentration and heating time. Consequently, banana peel flour film is an alternative biopolymeric material and an interesting reinforcing agent, although its mechanical properties and water vapor permeability still need to be improved. In this sense, Dias *et al.*[107] developed edible films based on banana peel flour, starch and loquat leaf extract, evaluating their physical, mechanical, barrier and antioxidant properties. They made films with 35% (g starch/100 g flour) maize starch and added 50% ethanolic extract of *Eriobotrya japonica* Lindl. The addition of the extract reduced the tensile strength, elastic modulus and water vapor permeability. All films were biodegradable. The morphological structure of the banana peel films was continuous and compact, showing roughness.

On the other hand, Raturi *et al.*[108] evaluated the use of banana peel to form an ionic polymer membrane using polyvinylidene fluoride (PVDF), polyvinylpyrrolidone (PVP) and banana peel. Dimethylformamide was used as a solvent. The peels were cut and immersed in water for 5 days, then crushed to form a solution, and filtered. The liquid was used to form the ionic membranes with PVDF and PVP 1:10, agitated at 110°C until complete homogenization occurred. The results showed that the composition of PVDF/PVP/BP (4 mL BP) is suitable in terms of conductivity. Increasing the banana peel concentration increased the conductivity and reduced the dielectric loss as this contains conductive elements such as Cd^{2+}, Cu^{2+}, Ni^{2+}, Pb^{2+} and Zn^{2+}.[108]

Other types of biomaterials that can be produced from *Musa* spp. include particleboard. Nadhari *et al.*[109] reported that banana pseudostem waste has potential to be used as raw materials for the manufacture of binderless particleboard. The mechanical strength and dimensional stability of steam pre-treated pseudostem and waste binderless particleboards were demonstrated. The pretreatment of pseudostem was carried out for 15 min at 111–131°C with stems. The density of the particle board was fixed at 0.7 g/cm,[3] while the steamed banana particles were hot pressed at 180°C for 40 min. The obtained particleboard was tested for standard mechanical and physicochemical properties. The results indicated that after steam treatment at 121°C the resulting particleboard had an optimal modulus of rupture (4.57 MPa) and modulus of elasticity (662.33 MPa). In fact, the physical and mechanical properties were found to be comparable with the standard particleboard properties issued by the Japanese Industrial Standards A 5908:2003.[110]

Manufacturing biomaterials from *Musa* spp. waste might lead to significant positive impacts by contributing to the mitigation associated with the excessive use of hardly biodegradable plastic materials.[33] Banana flour nanocomposite film can be used to obtain environmentally friendly packaging that also prolongs the shelf life of the packaged food and can even incorporate substances such as antioxidants. Nevertheless, obtaining biomaterial requires extensive studies to make the process competitive in the market and comply with the requirements of the industry. Yet such materials are an alternative of marked value in terms of social and environmental aspects that might deserve to be evaluated in depth. However, as mentioned above, it should be considered that the inclusion of pretreatments with alkaline/acidic compounds can generate large volumes of hazardous effluents to the environment, while thermal processes might hinder the applicability of the whole process and increase the indirect emission of greenhouse gases derived from electricity generation.

Other uses

Energy valorization

Another possible use of residual fractions derived from *Musa* spp. is the direct obtention of thermal energy by burning. In this line, by-products derived from banana cultivation, such as peels, pseudostems and leaves have been described as feasible substrates to be used as renewable fuels for heat production. Ahmad *et al.*[69] elaborated briquettes and evaluated the effects of the mixing proportion of peels, pseudostem and leaves (120 g, at proportions of 1:1:0, 1:1:1, 1:2:1 and 1:2:2, respectively). Specifically, the authors studied the thermal combustion and mechanical capacity of the different waste mixtures. Briquettes with a mixture of leaves and pseudostems were considered the most suitable ones since their characterization complied with the standard values for use as fuel. On the other hand, the thermogravimetric analysis showed that the samples with the highest proportion of banana leaves (1:2:2) had a calorific value within the range 12–22 MJ/kg, which indicates the good combustibility of briquettes. In terms of chemical characterization, the ash content in the mixtures was found to vary within 13–29%, while the concentrations of volatile matter and moisture were 71–86% and 12–19%, respectively. All briquettes had a compressive strength of approximately 13 MPa, which is an acceptable value for the specific case of being used for domestic heating. It is noteworthy that the combustion of biomass substrates does not lead to a net increase in the concentration of global warming gases in the atmosphere owing to the carbon dioxide derived from renewable biomass being subsequently assimilated by plants, in the short to medium term, through photosynthesis. Nevertheless, the emission of nitrogen oxides, dioxins and furans should be considered, together with the initial degree of humidity of renewable combustible materials, which might limit their use in combustion processes and contribute significantly to undesirable environmental impacts.

Bio-adsorbents and other carbonaceous materials

Among other alternative uses of *Musa* spp. residues, organic lignocellulosic residues from banana have been reported to be useful as filtering materials in the treatment of wastewater and even as nutritional sources for bacterial growth in the bioremediation of contaminated environments.[111] Adsorption is a viable option for capturing heavy metals contained in polluted aqueous effluents, since it is easy to apply, entails low treatment cost and, above all, has a good capacity to remove pollutants at low concentrations.[112] Among the materials used for the removal of metals, activated carbon stands out owing to its high specific surface, chemical stability and durability.[113] Tejeda *et al.*[113] studied the chemical and physical modification of residual biomass from orange and banana peels and evaluated unmodified biomass, biomass transformed to coal and biomass modified with chitosan. For the coal, they performed a wash pre-treatment with water and ethanol to remove polymers and residual particles, followed by drying at 90°C for 24 h, pre-incineration at 400°C for 1 h and the addition of 1 mL of 85% phosphoric acid per gram of coal. The substrate was then re-incinerated at 600°C for 1 h. For the biomass with chitosan, they were immersed in chitosan 1:5, agitated for 12 h at 150 rpm, washed and dried; this was repeated three times. For assays of adsorption, a solution containing 100 ppm of chromium (at pH values within the range 3–5) was treated at different adsorbent concentrations (2, 4, and 6 g/L). The results showed Cr^{6+} removal of 93 ppm using treated peels and 95 ppm using orange and banana coal, respectively. In addition, Ahmad & Danish[114] carried out a wider review related to the production of absorbents from banana waste (peel, trunks, pseudostems and leaves) with applicability for heavy metals, pesticide dyes and other pollutants. The authors reported that the investigations to date have shown markedly ambiguous results. However, the use of adsorbents derived from banana residues in wastewater treatment has significant advantages, as it has low cost and good availability owing to the abundance of waste and contributes to the protection of the environment by recycling waste.[114] Hashem *et al.*[115] used waste banana peels as an environmentally friendly adsorbent for methylene blue, and performed a mechanical pre-treatment and bio-organic activation using *Rhizopus* sp. microspores, where the adsorption rate reached approximately 96.5% (991 mg/g). The adsorption parameters indicated that the Langmuir model better describes the adsorption of dye with excellent maximal adsorption capacity (991 mg/g). In conclusion, biologically activated banana peel waste is very efficient for dye adsorption.[115] Furthermore, Lapo's[116] recent study aims to valorize banana wastes – rachis, pseudostem and peel as sustainable adsorbent materials for the recovery of the rare earth elements Nd^{3+}, Eu^{3+}, Y^{3+}, Dy^{3+} and Tb^{3+}. The adsorbent materials were characterized using Fourier transform infrared spectroscopy, X-ray photoelectron spectroscopy, zeta potential and scanning electron microscopy with an energy dispersive X-ray probe. The results show good adsorption capacities for the three materials, highlighting rachis that presented ~100 mg/g for most of the cations evaluated. The adsorption process (100 mg cations/L) reached 60% uptake in 8 min and equilibrium occurred within 50 min. The adsorption is spontaneous and exothermic ($\Delta H° < 40$ kJ/mol). Consequently, the authors have found a new and promising renewable bioresource to recover cations with high adsorption capacity and moderate processing cost.

Within the context of wastewater treatment, the denitrification process contributes to the control of nitrate pollution. Wang *et al.*[117] evaluated the coupling mechanism of banana peel, organic matter and microorganisms in the denitrification process systematically through a 17-cycle experiment. The results showed that a significant $N\text{-}NO_3^-$ removal load and rate could be obtained (164.42 mg/g and 4.69 mg/L·h, respectively). Organic matter analysis and 16 S rRNA sequencing showed that the evolution of organic matter was dominated by *Anaerolineaceae* sp. (fermenting bacteria).[117]

On the other hand, it is worth noting that nanoscience and the structuring of materials is a current and highly demanded trend in materials development. Atchudan *et al.*[118] have recently reported the sustainable synthesis of carbon quantum dots from banana peel waste. They applied hydrothermal method with ground material in an autoclave and then used a hot air oven heated at 200°C for 24 h. The material carbon quantum dots had a particle size of 5 nm and emitted intense blue fluorescence under the excitation of UV-light (365 nm) with a good quantum yield of 20%. Moreover, they were soluble in water, had high photostability and could serve as an efficient probe for multicolor cell imaging in nematode bioimages. An additional study carried out by Hussain *et al.*[119] performed the synthesis of carbon nanostructures from banana peels at low hydrothermal temperatures. They developed a one-step hydrothermal method, and the desired product was obtained at 220°C using two dispersing solvents: distilled water and ethanol. Scanning electron microscopy analysis showed a morphology similar to that of graphite flakes using water as the solvent. A mixture of graphite flakes and the presence of carbon nanoparticles was observed using ethanol as solvent. The energy dispersive X-ray analysis reported two primary elements: carbon (C) and oxygen (O).[119] Furthermore, Serna-Jiménez *et al.*[79] obtained biochar from *Musa* spp. peels using a method of chemical activation with zinc chloride, phosphoric acid and sodium hydroxide. They performed a physical–chemical characterization of the carbonaceous material, including nitrogen content, thermogravimetric analysis, X-ray diffraction and surface analysis, finding that the properties of the carbons vary depending on the activation agent used. Specifically, the authors reported surface area values of 110, 342, 259 and 12 m^2/g and percentages of micropores of 61.7, 78.3, 75.6 and 10.8% for the control and using zinc chloride, orthophosphoric acid and potassium hydroxide, respectively. The carbon was subsequently tested as an anode electrode in lithium-ion batteries, and a remarkable reversible capacity of 225 mAh/g at 0.2 C was observed after 200 cycles. Therefore, *Musa* spp. waste and by-products have promising applications for the absorption of different environmental pollutants. In addition, residual banana biomass can be chemically transformed to develop efficient commodities according to industry requirements, since the modification of the functional groups of the chemical surface might enable multiple uses of the carbonaceous substrate within the industrial standards. In general, the pretreatment processes that are required and carried out with acidic and/or alkaline compounds are not considered as sustainable and environmentally friendly, owing to the potential discharge of harmful chemicals into the environment. Moreover, the energy demand to generate bio-adsorbents and other carbonaceous materials is usually high, while the saturated materials that cannot be subsequently regenerated are usually landfilled or treated as hazardous waste.[59,120]

Perspectives

Owing to the increasing world production and their composition, the residues and by-products derived from *Musa* spp. (specifically the pseudostem and peel) might be considered as alternative biomass resources to make the transition from waste to by-products. In this context, several crucial aspects should be considered. The first is the need to generate plans that allow the fulfillment of the Sustainable Development Objectives proposed by the United Nations; within them, those related to responsible consumption, water, soil, climate change and non-fossil energy generation take special importance and *Musa* spp. residual biomass might be an alternative to generate solutions that lead to their compliance.[121,122] The second is climate change – the global purpose at international level promotes agricultural production systems to form clusters with producers and processors at the local level to address strategies that mitigate the effect of greenhouse gases and the pollution of water bodies, among others. In this sense the generation of renewable energy is promoted, either through direct combustion or in the form of biofuels (ethanol or methane), organic amendments or bioplastics, which contribute to the life cycles of the processes.[123] Third, there is a need for progress in research systems as many of the resources explored are evidenced in technology readiness levels 1–4. Therefore, for technology transfer processes it is necessary to advance the scaling and prototyping of processes that impact the real environment.[124] Fourth, mitigation of non-communicable diseases is required. In this sense, the deep characterization of wastes and by-products in terms of the presence of biomolecules and functionality exhibits a promising possibility in the development of new foods, supplements, medicines or ingredients with a marked impact on the corresponding industries.[48]

Figure 2 shows a proposal for the use of wastes and by-products from *Musa* spp. The recycling of the abundant residual streams derived from the processing of the banana and plantain agri-food industry could play an important role in the framework of the circular economy, with consequent economic, social and environmental benefits, turning such waste biomass into a valuable resource; from the by-products obtained from *Musa* spp. production, the main characteristics are a high content of polysaccharides such as cellulose, lignin and starch, as well as compounds with biological activity such as tannins. Within the proposed valorization is the route of

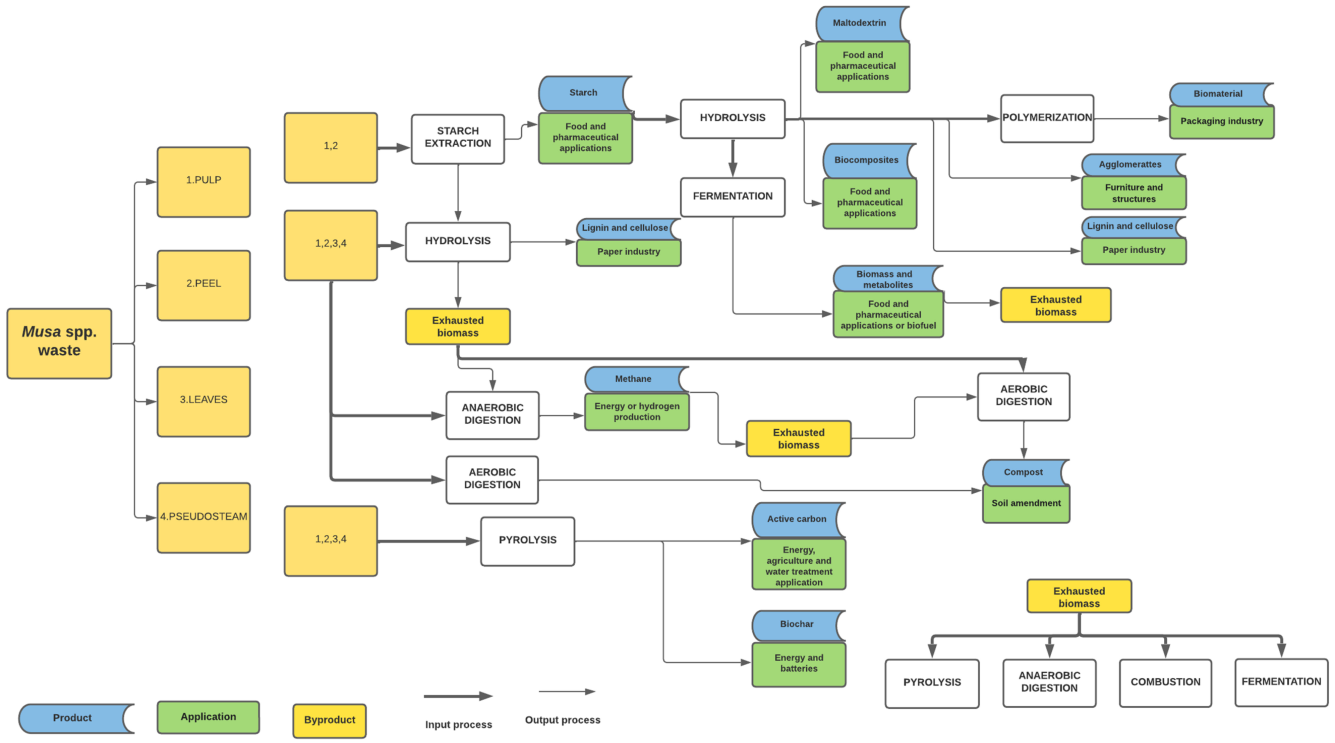

Figure 2. Schematic representation of the alternatives of use of *Musa* spp. waste and by-products.

energy generation, biomaterials and polysaccharides; these will depend on the interests in valorization and may have combinations or production systems in several stages that maximize the use and generation of alternative products with high added value.

In the context of the implementation of biorefinery systems and within the framework of waste utilization, authors such as Shah *et al.*[122] indicate some additional aspects to consider. First are technical aspects to achieve efficient production systems from the financial, ecological and environmental points of view. It is recommended to include technical and economic feasibility assessment, which helps organizations to define internal optimization objectives and achieve market sustainability, and to combine this with life cycle assessment to evaluate environmental sustainability.[43,51,101] Second are financial aspects related to everything involved in the transition from waste to raw material, including the logistics of collection, transformation and distribution. Third are social aspects – to increase the knowledge of producers and potential consumers to improve acceptability. Finally, different policies should be established at different levels (regions, countries and/or international organizations) to encourage and support circular production systems. In addition, it is essential to promote associativity among producers where different links of transformation are involved to ensure the profitability of the whole systems.[122]

Conclusions

The production of *Musa* spp. is increasing worldwide and the trend in production systems is shifting towards clean and sustainable production to minimize climate change and migrate to renewable energies, allowing the transition from what are called wastes to by-products. In this sense, it is possible to generate other products with an added value even more important than the products derived from the original production process. Research has shown that it is possible to use waste derived from *Musa* spp. processing in an integrated manner, generating alternative products with high added value that might generate additional income options for producers. However, it is still necessary: (1) to improve the processes of extraction and stabilization of biocomponents (*i.e.*, polyphenols) that can have a high potential in the pharmaceutical, cosmetic and food industries; (2) to deepen the knowledge on new microbial pretreatments that allow the reduction of some anti-nutrient compounds in animal or human food (*i.e.* tannins); (3) to improve the biotechnological processes of alcoholic fermentation, biomethanization and hydrogen generation, by pretreatment, co-digestion and/or obtaining or isolating more efficient microorganisms. (4) Furthermore, scaling-up the production of alternative biomaterials to plastic (given the worldwide restrictions on the production and commercialization of single-use plastics), biochar or nanocomposite systems for bioremediation or energy generation systems are essential. Such improvements would allow the promotion of an integrated implementation of the waste treatment stages, in which the waste obtained in one stage can be used as a raw material in the next, in accordance with the definition of a biorefinery approach and circular economy.

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Conflict of interest

All authors confirm that they have no conflict of interest.

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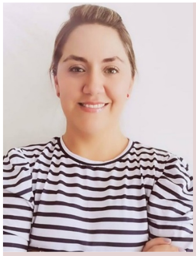

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