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REVIEW ARTICLE

Tropical agroindustrial biowaste revalorization through integrative biorefineries—review part II: pineapple, sugarcane and banana by-products in Costa Rica

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Abstract

Biorefineries are a model for greener production processes, based on the concept of bioeconomy. Instead of targeting first-generation biofuels—that compete with food supply—the focus relies on lignocellulosic material, considering many aspects, such as sustainable fuel production, as well as valorization of waste, as an alternative to the traditional petrochemical approach of goods production. Especially, in tropical countries agricultural activities lead to tremendous amounts of biomass, resulting in waste that has to be dealt with. In the case of Costa Rica, the five major crops cultivated for export are coffee, oil palm, pineapple, sugarcane, and banana. Traditional ways of waste treatment cannot cope with the increasing amount of biomass produced and therefore, bear various challenges often related to increased pollution. This review aims to bring up the recent state of waste treatment but even more, stress potential opportunities of adding value to not used residues; thus, improve sustainability in the agro industrial sector.

Part I of the review already highlighted the potential of producing promising bioactive chemical compounds by novel biorefinery concepts from agricultural waste originating from coffee and oil palm cultivation.

This second part focuses on the lignocellulose-rich biowaste from pineapple, sugarcane, and banana, showing biorefinery concepts, where fuel and energy production, as well as establishment of novel products and new applications, play an important role.

Keywords Waste biorefinery · Bioeconomy · Banana · Sugarcane · Pineapple · Value-added products

1 Introduction

Today, one of the most severe problems for humanity and other life forms is facing environmental pollution [1]. Factors influencing the challenge include population growth, technological advancement, and urbanization that are pushing the use of natural resources to their limits [1]. In order to establish a sustainable future, as expressed in the sustainable development goals (SDG) coined by the United Nations (UN) [2], advancement must meet the three pillars of sustainable development: economic growth, environmental stewardship, and social inclusion [1]. In the following sections, the challenges and opportunities of pollution and waste management are discussed on the example of Costa Rican agriculture to contribute to the SDG and at the same time demonstrating a beneficial biorefinery approach for three of the five most cultivated crops. Traditional forms of

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agroindustrial waste management are garbage, composting, or energy generation in a combustion process [3]. However, especially disposal in landfills entitles environmental damage, since tons of waste accumulates rapidly. Additionally, some agricultural waste can lead to the toxification of the soil, if not treated before dumping [4, 5]. In consequence, the impact of contamination does not solely affect land quality, but also water quality, when wastes are released into water. Alternatively, combustion [1], which is one way to produce energy [6], significantly reduces air quality.

In contrast, sustainable waste management implies a system where waste is further treated and handled as a resource that can lead to new processes, recycled, recovered, or treated further [7]. Increased sustainability is connected with the model of bioeconomy [8]. This new economic movement became popular in the 2000s, which is demonstrated in the bibliometric analysis of D'Amato et al., referring to the term "bioeconomy" to use biomass resources instead of fossil sources in any form of consumption and production [8, 9]. However, Pfau et al. pronounces various controversies in science and politics to stress whether a transition to a bioeconomy comes together with a more sustainable future, as the food vs. fuel dilemma is issued more frequently [8]. In 2020, the Costa Rican government launched the "National Strategy of Bioeconomy for Costa Rica, 2019–2030." The main idea behind this strategy is to promote sustainable development through the utilization of biodiversity and biomass in a circular economy approach [10]. This proposal contemplates five strategic areas: bioeconomy for rural development, biodiversity, development, biomass biorefinery and urban as well as green cities bioeconomy.

Biorefinery is defined as a facility that processes agricultural waste to produce energy, alternative fuels, and fine chemicals. The first-generation biorefineries focused on renewable materials, such as sugar and vegetable oil, to produce biofuel competitively to petroleum-based fuel [10]. The three main types of biofuel used vegetable oil to generate biodiesel, sugar or starch were converted to bioethanol and liquid manure to produce biogas by anaerobic digestion [10]. One of the main problems this first attempt faced in establishing a biorefinery was the competition with food supplies. In a second-generation biorefinery lignocellulosic materials, such as agricultural waste, forestry waste, and others, are used as a substrate for the biofuel production [10]. The degradation of woody and lignocellulose-rich biomass is more challenging due to the mixture of cellulose, hemicellulose and lignin, which has to be broken down to sugars or starch; therefore, specific treatments resembling in a multitude of additional unit operations are needed [6, 11]. Besides biofuels, biorefinery concepts also aim for bio-based chemicals, heat, and power production in the same manner [11]. Successful biorefinery concepts invariably couple energy production with the extraction of fine chemicals, thus contributing to the circular economy approach, a concept that aims to close material loops in order to preserve products and achieve their maximum utility [12]. According to the brochure 2020 of the National Institute of Electricity of Costa Rica (*span.:* Instituto Costarricense de Electricidad (ICE)), more than 98% of Costa Rica´s electricity was produced by renewable energy in the previous five years [13]. Nevertheless, this value only accounts for electricity usage. The electricity in Costa Rica comes from hydropower facilities, geothermal plants, wind turbines, and solar panels [13]. This gives rise to Costa Rica's great chance of further improvement in the biorefinery area, especially, when it comes to meeting the demand of gas and fuel in a sustainable manner coupled to the generation of valuable chemicals.

As mentioned earlier, the biorefinery approach is demonstrated for three of the five most cultivated crops in Costa Rica. In 1993–1994 banana, coffee, milk and beef industries accounted for a large part of Costa Rican export income [14]. On the other hand, up to 1.41 MT (million tons) of solid wastes from crops were disposed in the environment [14]. The majority of solid residues, dumped as waste, were generated by coffee, banana, sugarcane, and the oil palm industry, with each contributing up to 421,000 MT produced per year [14]. In 2014 the most extensively cultured crops still were coffee and banana, but also oil palm, sugarcane and pineapple, occupying around 295,000 hectares [15]. According to Vladimir González, there has been an increase in pineapple cultivation in Costa Rica of about 400%. In 2000 there were 13,304 hectares of land cultivated with pineapple; this number increased to 66,670 hectares in 2017 [16]. As in 2002, the total residues represented around 1,730,000 MT for sugarcane, 521,000 MT for banana, 488,000 MT for coffee and 221,000 MT for oil palm [14] and have further increased up until today. Residue utilization varies from animal feeding to fertilization and other uses, such as energy sources, human feeding or poultry bedding [14]. More recently, some coffee industries have innovated with natural health supplements derived from agrowaste, ranging from coffee mucilage concentrate (Natucafé, Colombia) [17], to coffee mucilage beverages (Naox, Colombia) [18]. Nevertheless, there are still more profitable uses, as some of the lignocellulosic residues also contain a large number of bioactive compounds of high interest in the pharmaceutical and cosmetics industry, such as enzymes, antioxidants, among others [19–21]. The aim of this review (part I [22] and II) is to evaluate five relevant tropical crops by presenting information about their features, biomass, and by-products, and to consider biorefinery perspectives for the sustainable production of value-added products.

2 Pineapple biowaste revalorization

Pineapple is a perennial plant with a height of 75–150 cm and a spread of 90–120 cm, which was initially found in South America [23]. According to the crop database of the Food and Agriculture Organization (FAO) of the UN, Costa Rica was the leading pineapple producer in 2019 cultivating more than 3 MT of fresh fruit [24]. Nowadays, pineapple plantations have increased in size by more than seven times since 1995, which implicates a tremendous environmental impact [25]. This product generates a venue of 941.5 million US$ per year and leads to 5.6 million tons of wet pineapple plant residue [26].

The plantations are predominantly located in the northern part of the country, covering an area of 24,653 hectares (56% of the cultivated area), the remaining plantations are located in the Caribbean area (11,188 ha, 25%) and Pacific area (8,659 ha, 19%) and gives work to about 250 producers, and employment to 32,000 workers [27].

In 2019, pineapple plantations in Costa Rica covered 40,000 harvested hectares [28], where nearly 59.36% of the total harvest accumulates to lignocellulosic waste, such as pineapple peel and core [25]. Plantations produce, on average, 200 tons of crop residue per hectare and harvest, resulting in an total amount of 4.5 MT of pineapple crop residue annually in Costa Rica [29].

2.1 Waste characterization

Pineapple field residues consist mainly of leaves as well as stems and correspond to 80–150 tons of crop residues per hectare and harvest. Sustainably, these residues are mostly used to return nutrients to the soil. Either after composting, or after burning, whereas composting is the preferred way of handling, as there is no such loss in plant nutrients. Additionally, composted pineapple residue returns lead to an increased availability of nutrients in the soil, as well as an increased abundance of microorganisms, stimulating the growth of next-cropped pineapple plants [30]. According to van Tran [31], pineapple is mainly consumed as canned fruit. Nevertheless, also juices, concentrates and jams are popular products made from pineapple. These, usually industrialized, production processes lead to additional by-products, such as residual pulp and peel [4]. Overall, about 50% of the total pineapple weight account for waste, whereas the main components are pineapple peel (29–40%) and core (9–10%), among others [25, 32].

Each part of the plant has a different nutritional composition, as summarized in Table 1. The incidence and concentration of these compounds are influenced by environmental factors, such as location, season, plant maturity period, and soil [37]. Because of the different climate zones where pineapple is produced, the final concentration of the constituents in pineapple waste varies.

In addition to the differences in structural components of pineapple waste, significant amounts of secondary metabolites are reported, ranging from organic acids such as citric acid, lactic acid, malic acid, oxalic acid to phenolic compounds such as myricetin, salicylic acid, tannic acid, *trans*-cinnamic acid, and *p*-coumaric acid [4, 38, 39]. Furthermore, primary polyphenols in pineapple peel, such as gallic acid, catechin, epicatechin and ferulic acid were reported [40, 41].

Table 1 Tabular overview of the cellulose, hemicellulose and lignin content of main pineapple components (in w/w %).

Plant part	Cellulose	Composition Hemicellulose	Lignin	Reference
Crown	43.5	21.9	13.9	[33]
	29.6	23.2	-	[34]
	59.0	17.5	3.3	[35]
Leaf	66.2	19.5	4.28	[35]
	40.6	28.7	10.0	[33]
	43.53	21.88	13.88	[36]
Shell	14.0	20.2	-	[34]
	10.1	5.8	7.8	[35]
	40.55	28.69	10.01	[36]
Stem	-	-	5.3	[35]
Stubble	25.8	17.3	3.4	[35]

3 Biorefinery approach

Biorefinery is the biomass conversion process, leading to production of fuel, and value-added chemicals, via biotechnological routes. The establishment of proper and alternative biorefinery processes to valorize pineapple waste will contribute to the development of a circular economy in this productive sector and to meet the Sustainable Development Goals (SDG) of the United Nations (UN). As shown by Nennie and De Boer [29] in the “Sustainable Pineapple Costa Rica, Market Study,” there are several revalorization strategies for the waste generated from pineapple production. These and others are exemplarily illustrated in Fig. 1. In the following sections, the highlighted applications and corresponding research regarding the by-product valorization from pineapple waste, will be explored.

4 Animal feedstock

Sruamsiri reported the use of pineapple waste in Thailand as an alternative feed for dairy cows [42]. According to Sruamsiri, pineapple waste is chosen due to its palatability, based on the high moisture and soluble carbohydrate content [42]. Nevertheless, due to the acidic pH, cattle prefer fermented pineapple waste over the fresh one. Between 25 and 50% of roughage in cattle feed can be replaced by ensiled pineapple waste [42–44]. Kyawt et al. state a significantly higher uptake of dry matter, crude protein, non-fiber carbohydrate, as well as energy, compared to a control group of cattle [44]. Besides, Buliah and coworkers developed a strategy of pellet production from pineapple leaf waste to feed cows [45]. The leaf waste has a high fiber content (48.7%), making it highly digestive for animals. Additionally, feeding trials proofed an increasing milk production of dairy cattle after a 90 day fed with silage from pineapple fruit residues in comparison to hybrid napier green fodder [46]. Raseel et al. analyzed the impact of incorporation of pineapple waste in milk production in dairy cow. Overall, an isonitrogenous and isocaloric mix, where maize was substituted by pineapple waste, increased the milk production to 12.94 kg, compared to a control group of cows fed with a conventional mix (11.94 kg) [47].

Complementary, a meta-analysis of the pineapple plant (*Ananas comosus*) as ruminant feed in Costa Rica was carried out by López-Herrera et al. [35], to determine the potential use of pineapple waste in their diet. As part of the study, silage products were characterized, and the analyzed materials were determined to be beneficial as part of the total regular portion in livestock feeding, without decreasing the productive yield.

Despite the high number of publications proving the great potential of pineapple waste as feed supplement, to our knowledge, there is no industrial application of pineapple waste as animal feeding, so far.

5 Fine chemicals

Another important procedure of valorizing pineapple waste is the production of fine chemicals, defined as single pure chemical compounds that play an essential role in the chemical industry, even though they are produced in limited quantities, but achieving high prices. Fine chemicals are divided into building blocks, i.e., compounds that are used as starting materials for the synthesis of certain chemicals or are used in pharmaceuticals as active ingredients or intermediates [48]. Traditionally, chemicals are produced by the petrochemical industry through organic synthesis. Nowadays, biorefinery has become a key technology to improve sustainability and decrease the environmental impact through biological synthesis.

Already in 1995, conditions for obtaining vanillin by oxidation of Kraft lignin (*Eucaliptus grandis*) with $Ca(OH)_2$ were determined. This method was applied to different types of agroindustrial wastes, such as pineapple peel, coffee husk, and bagasse, among others. Coffee husk, pineapple peel, and African palm tree were most promising, obtaining 1.8%, 1.5% and 0.6% (w/w) of vanillin, based on the lignocellulosic raw material [49].

Recently, Ong and co-workers reported a biotechnological approach to achieve the production of vanillin and vanillic acid from pineapple cannery waste (peel and core) [50]. Optimal conditions for the biotransformation of ferulic acid to vanillic acid in the presence of *Aspergillus niger* I-1472 and subsequent transformation to vanillin using *Pycnoporus cinnabarinus* MUCL 39,533 were studied by application of a central composite rotatable design. Factors such as inoculum size, yeast extract concentration, diammonium tartrate

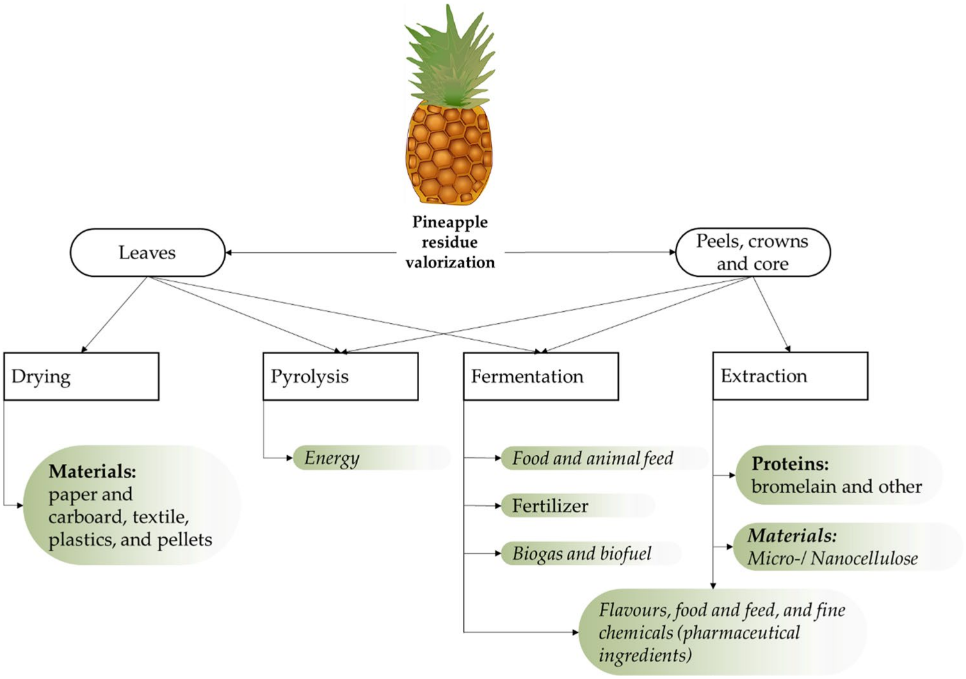


Fig. 1 Pineapple crop residue valorization options adapted from Nennie and De Boer. [29] Curved white rectangles: biowaste. Rectangles: processes. Green rectangles: value-added products. In italics: Discussed in this review

concentration, as well as the initial medium pH were considered. Finally, 163 mg/L vanillic acid were obtained from 20 g/L pineapple cannery waste in an optimized maltose containing medium, which led to a vanillin production of 141 mg/L. Additionally, the ferulic acid content was determined to be 3.25 mg/g pineapple cannery waste.

Alternatively, pineapple peels were also used to obtain citric acid. Kareem et al. demonstrated an efficient biotransformation by solid-state fermentation with *Aspergillus niger* KS-7 the efficient biotransformation [51]. Varying medium compositions were tested, for one, pineapple peel as the only carbon source, for another, supplementation of 5%, 10% and 15% glucose and sucrose were tested. With pineapple peel as the only carbon source, 17.2 g/kg citric acid were produced after 5 days of fermentation. An increasing concentration of added sugar, also enhanced the citric acid secretion, with a productivity of 36.6 g/kg citric acid, when using pineapple peel and 15% (w/v) sucrose. Pineapple waste supplemented with sucrose and ammonium nitrate showed the maximum yield of 60.6 g/kg citric acid in the presence of methanol.

Besides fermentations, polyphenolic compounds, such as gallic acid, hydroxyl benzoic acid, chlorogenic acid, epicatechin, coumaric acid, and caffeic acid were already extracted from pineapple waste [41]. The extraction process was improved using as mathematical optimization the Box-Behnken design, considering influence factors such as temperature, solid–liquid ratio and reaction time.

In an early study carried out by Larrauri and others, pineapple shells were applied as a promising source of dietary fiber with high antioxidant activity [39]. High amounts of arabinose, xylose, mannose, galactose, and glucose were determined from grinded pineapple peels, proving a high amount of total dietary fiber compounds. In addition, the antioxidant content of 86.7% in pineapple peel is superior compared to commercially available dietary fibers, such as apple and citrus. Those phytochemicals are associated with health benefits, making an optimization of (pre-)treatment and extraction economically valuable.

In 2018, Banerjee and coworkers reported the valorization of pineapple waste as a potential source of therapeutics [52]. Besides dietary supplements, the high content of carbohydrates (55%) in pineapple waste makes it a suitable substrate for fermentation processes, to produce xylitol, xylooligosaccharides, lactic acid and other high-value chemicals. In addition, an extraction process for bromelain from pineapple waste is a promising approach, due to its high market value of 2400 US$/kg and its importance in therapeutics and food industry [32, 52].

Vastrad et al. took advantage of the high carbohydrate content applying different fungi in a solid fermentation process, yielding tetracycline antibiotics. The influence of components such as carbon, inorganic and organic nitrogen sources, and inorganic salts on the tetracycline production by various strains of *Streptomyces* (*S. aureofaciens* NCIM (2417, 2614, 2615), *S. rimosus* NCIM 2213, among others) was reported [53]. Especially, supplemented nitrogen sources, such as peanut meal, beef extract and soybean meal, significantly increased the tetracycline production compared to the control, whereas, additional carbon sources, such as glucose and sucrose showed a negative trend in tetracycline secretion. Additionally, initial moisture content, incubation temperature, initial pH, substrate particle size, and inoculum size were parameters evaluated. The maximum secretion of 12.94 mg tetracycline per g pineapple peel was obtained after 7 days of fermentation on basal solid medium containing 100 g of pineapple peel at 5% moisture content [53].

Besides active pharmaceutical ingredients, also biosurfactants are yielded by pineapple peel juice fermentation with *Pantoea* spec. as reported by de Almeida et al. [54]. Biosurfactants are applicable in a variety of different fields, such as environmental, food industry, or biopharmaceutical technology areas due to their interfacial, emulsifying and antimicrobial activity, among others. The biosurfactant production was improved using different fermentation media compositions. Besides vegetable fat and corn steep liquor, also pineapple peel juice was investigated and optimized parameters for biosurfactant production determined. Vega et al. demonstrated the use of residual juice of pineapple waste for the production of high molecular weight dextran by inoculation with *Leuconostoc mesenteroides*, var. *mesenteroides* (ATCC 10,830) [55]. The fermentation was carried out in a bioreactor where the pineapple juice, obtained by pressing processing waste of pineapple, was used as substrate. After centrifugation, precipitation and purification with ethanol, the product was characterized in terms of viscosity, molecular weight, and functional groups. Finally, the produced dextran was used for further synthesis of an iron dextran complex. In comparison, Feng et al. published an alternative approach to obtain highly branched dextran using *Leuconostoc citreum* B-2, isolated from a fermentation product of pineapple waste, whereas the carbon source of fermentation was no agricultural waste but sucrose [56].

Furthermore, pineapple peel biomass is used as raw material for nanocellulose extraction and to produce silica nanoparticles [57]. Nanocrystalline cellulose possesses great potential as stabilizers for oil–water suspensions, drug delivery excipient, enzyme immobilization scaffold or tissue engineering, among others [57]. Camacho et al. optimized parameters such as solution concentration, temperature and time for deriving nanocrystalline cellulose from pineapple peels, envisioning an industrial process [57]. Also Corrales-Ureña et al. focused their research on silica in bracts and shell of pineapple [58], as silica is one of the stiffest cell wall components, which provides mechanical strength and rigidity [59].

Figure 2 illustrates microparticles in the range of 5 to 10 µm consisting of even smaller micro- and nanoparticles, extracted from the bracts and peel of pineapple. Due to the high surface-area-to-volume ratio, the application for heavy metal adsorption, among others, should be considered. Nevertheless, the extraction methods applied are still not environmentally friendly, as strong acids, such as NaClO, HCl or H_2SO_4, are frequently in use. Hence, the production of a valuable by-product, such as silica microparticles from pineapple biomass, should encourage efforts to improve extraction methods dealing with biomass removal in a more environmentally friendly manner [58].

6 Energy

Besides the previously mentioned material-based applications for pineapple by-products, waste-to-energy is another important issue, as the sustainable generation of energy is a global concern. A general review from Kothari et al. tackles the waste-to-energy routes, focusing not solely on agricultural waste types, but also municipal waste, among others [60]. Many countries like Poland, Greece and Malaysia obtain electricity from garbage [61]. It has been estimated that in 2010 Malaysia produced a total of 2.20×10^9 kWh of electricity, representing 219.5 million US$ [61]. In comparison, the Costa Rican government made a voluntary commitment in 2007 of becoming a carbon–neutral country by 2021. To achieve this objective, in 2012 the country developed the first national carbon neutrality program, which was officially announced in 2018 as the carbon neutrality national plan 2.0 (PPCN). This plan includes several lines of action, ranging from transportation, energy, and construction to waste management, and agriculture. Biorefinery becomes a key aspect in the achievement of the governmental goals [62]. Besides the exploration of renewable energy sources, also alternatives for agricultural waste management are of utmost importance [63, 64]. The PPCN established an action plan toward reaching 1.19 metric tons of emission by 2050. Furthermore, between 2012 and April 2019, the participating organizations saved 224,000 tons of CO_2 emissions, improving the savings until 2030 by 170,500 tons per year [62, 64]. Therefore, lignocellulosic agricultural waste could be an attractive option as an alternative for a greener source of energy. The use of agricultural waste in the production of energy has the advantage of not competing with food source, thus, it helps mitigating the environmental impact of large scale agriculture. Most of the agricultural activity is carried out by rural communities, which represents another option for local development, in addition to reducing greenhouse gases by substituting fossil fuels. In order to allow an appropriate use of these residues, an energetic characterization must be conducted.

This characterization of biomass allows an evaluation of the materials as alternative sources of energy, throughout different processes as: pyrolysis, combustion, gasification, and fermentation. In 2015, a research group from Brazil displayed that pineapple crowns have better energetic properties than elephant grass, rice husk, and sugarcane bagasse. The results also indicated a better suitability for thermodynamic processes, such as pyrolysis, combustion, or gasification due to its elevated volatile matter (84.93%), high heating value (18.9 MJ/kg), bulk density (420.8 kg/m^3), and a low fixed carbon and ash content [65].

Several studies, worldwide, report the use of pineapple biomass as an alternative for energy production, either via production of bioethanol, hydrogen, or biogas. A study conducted by Mund and coworkers reported the use of pineapple leaf waste as carbon source to produce biofuels. The study proved up to 43% glucose by digestion with cellulases on non-pretreated substrate. Including different pretreatment methods the glucose concentration increased up to 84% after 72 h incubation, leading to a theoretical ethanol yield of 212 L from 1 ton of dry leaf biomass, when assuming 100% conversion of glucose to ethanol [66].

Bioethanol can also be produced by sonication of pineapple peel as proven from Casabar et al. When applying *Trichoderma harzanium* a final ethanol concentration of 25% (v/v) was determined [67].

Varying the microorganism, fermentation medium and time can lead to the achievement of different products. As demonstrated by Choonut et al., *Saccharomyces cerevisiae* is a promising candidate for ethanol production with a yield of 9.69 g/L, when fermented on pineapple peel [68]. In comparison, *Enterobacter aerogenes* was applied for ethanol and hydrogen production, where hydrogen is applicable as an alternative fuel. Productivities of the just mentioned process

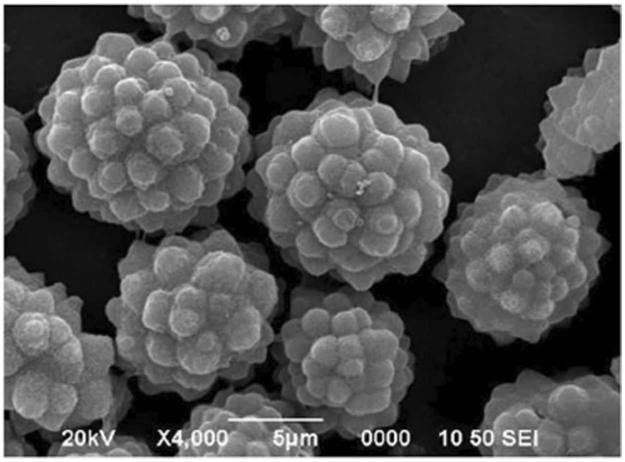


Fig. 2 SEM image from silica particles obtained from pineapple peel [58]. Unmodified from published work by Corrales-Ureña Y.R., Villalobos-Bermúdez C., Pereira R., Camacho M., Estrada E., Argüello-Miranda O. and Vega-Baudrit J. CC BY 4.0

were 1.38 g/L ethanol and 1.416 mL/L hydrogen after 72 and 12 h of cultivation, respectively [68].

Besides ethanol and hydrogen production, countries like Thailand have explored the production of biogas from several agricultural products, among them also pineapple peels. According to the study carried out by Paepatung and coworkers, a maximum specific methane production rate of 36.77 mL/d was achieved, when the inoculum, which was taken from an anaerobic digester of a pig farm, was mixed with pineapple peel as substrate. The biodigestibility was tested over a period of 90 days. The estimated fuel oil that could be replaced by this alternative energy source corresponds to 17 million liters per year [69].

Costa Rica is the leading producer of fresh pineapples worldwide, as a consequence, several research projects have been conducted to find alternative applications of pineapple residues [70]. In 2014, the National Institute of Electricity of Costa Rica (ICE; from its acronym in Spanish), worked on a project in which pineapple residues were transformed into biogas to determine savings for co-generated production plants. The most promising approach was the fermentation of chopped pineapple stubble, which lead to 25.7 m^3 of biogas per ton of substrate, with 52% (v/v) methane composition. In comparison with other substrates for biogas production, pineapple stubble is more difficult to process and contains less energy. Nevertheless, the produced biogas can be further used to feed an electric co-generator, which results in annual savings of more than 200.000 US$ in power production for a pineapple processing plant, without mentioning the positive environmental impact that this initiative would have [71]. Unfortunately, this project is currently on standby.

A recent paper published by Chen et al. demonstrates a holistic valorization of pineapple plant residues, resulting in the production of value-added protein, renewable energy, and fibrous material. The pineapple plant residue is treated mechanically with an extruder to generate juice and fiber. Fibrous pulp can be applied elsewhere, whereas the juice is further fermented using *Kluyveromyces marxianus* ATCC 12,424, to produce ethanol and spent yeast proteins. Overall the energy balance is mentioned to achieve a positive net energy output of 216 GJ per hectare including 112 GJ biofuel [26]. This demonstrates the applicability of a beneficial biorefinery concept proving promising opportunities for valorization of agroindustrial residues.

7 Conclusion of pineapple biorefinery concepts

Pineapple production brings up a considerable amount of waste that needs to be treated. Various studies are already published showing the great potential of valorizing waste residues by biorefinery processes. However, based on the varying chemical composition of the pineapple waste, due to the environmental impact, valorization processes are challenging to design.

For competition with conventional production processes, the utilization of agro-residues, such as pineapple by-products, still must overcome some limitations. A techno-economic feasibility study of Banerjee et al. proves the feasibility of pineapple processing waste biorefinery under specific circumstances [72]. To further improve the viability of biorefineries, the development of progressing technologies for more efficient pretreatment processes, as well as improved enzymatic hydrolysis processes, is of utmost importance. Furthermore, optimal fermentation conditions and a better utilization of pentoses and hexoses (hydrolyzed hemicellulose) must be achieved. Moreover, so far, all processes have to be tailor-made for each residue [73].

Despite this, the application of processed biowaste is extensive, especially as processing of several target products could be combined, such as fine chemicals and energy production [72], aiming for a circular economy approach. Previous studies have already shown the potential of combining industrial-scale production of dried pineapple slices with reusability of processed waste for fertilizing applications, leading to a reduced consumption of fossil fuels, when utilizing digestion heat for product drying [74]. Moreover an integrated biorefinery approach using fresh pineapple processing waste was studied by Banerjee et al. leading to a promising approach for complete utilization of by-products resulting from pineapple processing [75]. Nevertheless, techno-economic studies still have to be performed. These combined approaches leading to full utilization of agricultural waste and newly generated by-products are highly interesting, to support SDG goals in terms of responsible consumption and production, as well as affordable and clean energy.

Further valorization possibilities that should be studied in terms of techno-economic feasibility as a circular economy approach range from animal feedstock, where even an improved milk production for cows was observed, over fine chemicals, such as vanillin, tetracycline antibiotics and silica nanoparticles, toward energy production in the form of bioethanol, hydrogen, and biogas. Further applications of pineapple waste were excellently summarized by Vieira et al. [76] and Banerjee et al. [52].

Still, more research is needed to find economic alternatives for further treatment of the generated biowaste and replace burning and dumping of residuals as a standard method for dealing with waste materials. When expanding the valorization of pineapple waste toward food or feed supplements, studies about enrichment of agricultural fertilizer and its impact on human and animal organisms must be key aspects to examine.

Despite the available research, only few industries have been developed using pineapple waste. Two examples can be mentioned: Biomé enzyme technology, located in Liberia, Guanacaste (Costa Rica) extracts bromelain out of pineapple waste [77].

Another German-based company, Eco:fibre, extracts pulp out of pineapple waste for further processing in the paper industry [78].

In general, biomass represents a vital economic resource in Costa Rica; the diversity and the volume of agricultural biomass produced in the country opens up a diversity of opportunities for developing new and sustainable industries.

8 Sugarcane biowaste revalorization

According to FAOSTAT [24], in 2019, the annual world production of sugarcane was nearly 1950 MT with a yield of 73 t/ha. The same year, Costa Rica produced 4,421,210 tons of sugarcane from 62,630 ha, which is equivalent to 0.23% of the world's production for that year. When comparing harvest areas of various crops in Costa Rica, sugarcane belongs to the five most cultivated crops of the country in 2014 [15].

Sugarcane is a perennial plant growing in tropical and subtropical regions. One plant can be harvested for several years, but with decreasing yields [79]. Bagasse is the solid residue remaining after the extraction of the sugarcane juice from the sugarcane plant. Another main residue of the sugarcane crop are the leaves, named straw, which are left to dry out and, generally, are burnt in the fields.

Each ton of sugarcane generates 280 kg of humid bagasse (about 140 kg of dry bagasse) and 250 kg of dry leaves [23]. Therefore, the amount of dry bagasse produced in 2019 in Costa Rica was approximately 620,000 tons and the amount of dry post-harvest leaves and trash left in the fields was near 1.1 MT.

Bagasse has a 46–52% moisture content [80] and its composition in dry format is very variable: 30–52% cellulose, 25–35% hemicellulose, 10–26% lignin and 2.5–23% ash [23, 81–83]. The low ash content, as compared to rice straw (17.5%) or wheat straw (11%) is an advantage for using it among bioconversion processes [23, 81]. The dry leaves tend to have about 8% less cellulose and 10% more lignin [23].

9 Sugarcane agroindustrial waste handling

Sugarcane is mainly left on the fields to dry out and burn, nevertheless, also studies about sugarcane leaves and straw as a source of bioenergy were recently published [84]. In comparison, bagasse has a broad spectrum of uses. Most commonly, bagasse is burnt for generation of heat, steam, or electricity. Furthermore, utilization of fiber to produce pulp, paper, and composite material, as well as application in the field of bioconversion are typical forms of exploitation as shown exemplarily in Fig. 3.

10 Energy generation from sugarcane harvest residues

Bagasse amounts to one-third of the cane ground. Due to its high combustibility, it is mainly used as captive fuel in sugar factories [85], where almost 50% of the total bagasse are utilized as potential energy source [81]. As a result, many sugar mills are linked to ethanol distilleries, or upgraded with cogeneration facilities to re-utilize leftover residues [86].

In 2013, Dantas et al. published a study about the cost of energy generation from bagasse in Brazil [87]. The equivalent annual cost per unit energy of the most used alternatives were compared: Rankine cycle engine, biomass integrated gasification (gas turbine combined cycle), and biochemical route for ethanol production. The rankine cycle engine connects the burning of fuel, in this case sugarcane bagasse, to finally produce energy via steam generation; with this technique sugarcane processing mills can cover their own energy requirements [88]. According to Dantas et al. the equivalent annual cost per unit energy of the routes via biomass integrated gasification (37.74 US$/GJ) and fermentative route for ethanol production (34.70 US$/GJ) nearly double the price of Rankine cycle engine (19.72 US$/GJ). Also, in a projected scenario for 2030, including a cost reduction of 20 – 30% for biochemical and biomass integrated routes due to emerging technologies, still the Rankine cycle engine was greatly favored [87].

Go and Conag studied the potential of sugarcane waste leaves and bagasse to produce energy assuming total combustion and use of the heat to produce electricity via turbine [84]. The amount of heat produced from leaves and straw only (17.48 ± 0.82 MJ/kg) adds up to 59.9 ± 1.3 PJ of energy per year, amounting to approximately 5.9 TW/h, at 36% plant efficiency.

In 2016, Santos et al. compared the main technological routes to make electricity and chemicals from bagasse in Brazil [89]. They studied four thermochemical routes (biomass integrated gasification combined cycles for electricity, biomass to liquid for obtaining dimethyl ether as a fuel for electricity burning, biomass to liquid for obtaining Fischer–Tropsch liquids for electricity or blending with gasoline or diesel, and biomass to liquid for obtaining ethanol and higher alcohols for electricity, blending fuels or other uses) and two biochemical routes (hydrolysis and fermentation to ethanol, and production of bio-platform molecule succinic acid as an alternative route instead of the petrochemical pathway), to prove sugarcane bagasse competitive beyond the electricity and thermal generation. Solely the synthesis of succinic acid led to a minimum selling price (0.57 US$/kg) lower than for comparable reference prices (2.03 US$/kg). For the biochemical route to produce ethanol the minimum selling price (0.41 US$/L) was slightly higher than the comparable reference price (0.36 US$/L). Hence, simultaneous biochemical production of electricity and ethanol, or electricity and succinic acid is prospective, as long as technologies improve further [89].

Arshad and Ahmed revised the bagasse cogeneration, referring to the production of electricity and heat energy simultaneously, in Pakistan. Currently, this approach is already established in Brazil and India and could be implemented elsewhere. Nevertheless, an accurate forecast of electricity prices is required to evaluate the potential savings from cogeneration [90], which is also mentioned as one of the major hurdles to the adoption of circular economy in the Brazilian sugarcane ethanol sector [91].

Gasification is another alternative to combustion due to its high efficiency, nevertheless, for any type of gasifier, an adequate bagasse pretreatment must be selected. In South Africa, Anukam et al. investigated several pretreatments of sugarcane bagasse for gasification in a downdraft biomass gasifier [92]. Contemplated methods were size reduction, drying, pelletizing, briquetting and torrefaction finding the last, the most efficient method. It was recommended to reproduce this study for other gasification technologies [92].

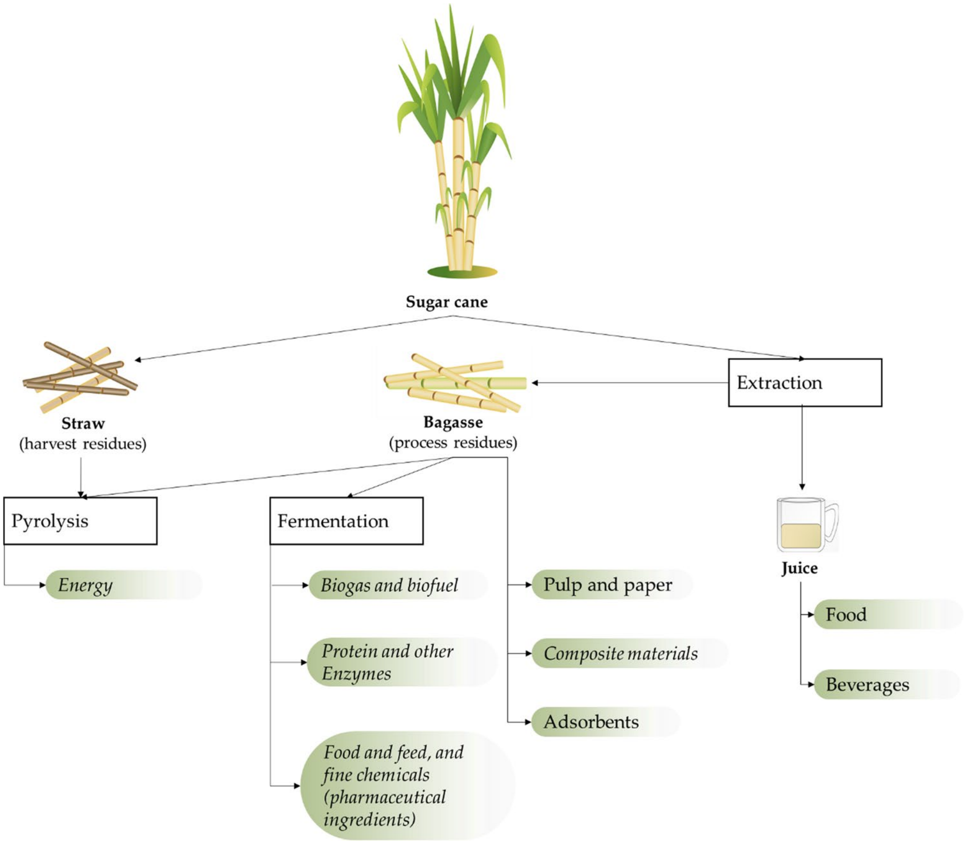
In summary, burning of residues is an efficient way to cover energy and heat consumption of the factory, nevertheless the key aspect of saving potential through electricity generation is based on the forecast of electrical prices over the next several years [90].

11 Utilization of fibers

Due to its fibrous nature, one of the highest revenue earners in the global sugarcane industry is pulp and paper industry, where 2–5% of bagasse are used for global production of pulp and paper products [93]. Bagasse is used to produce four major types of paper with both chemical and mechanical pulping processes. However, one of the main drawbacks of its use is the pith content, since it blocks the pores of the paper mat and reduces its final quality. Chemical bagasse pulp, as compared to hardwood pulps, tends to have poorer draining capacity due to the pith and lower burst, tear and tensile strength [93].

Other promising applications of sugarcane fibers are the composition of sugarcane fiber cellulose, tapioca starch and glycerol for production of disposable food packaging. It is suggested to improve the necessary properties, such as hydrophobicity, for the desired application, in upcoming studies [94]. A similar approach to replace petroleum-based polymers was followed by Jumaidin et al., where starch-based polymers were used as the basis to produce biodegradable polymers. Those biopolymers tend to have poor mechanical properties, where sugarcane fiber can be used for reinforcement to produce bio-based composite material. The application of sugarcane fiber led to a reduced water uptake and

Fig. 3 Sugarcane bagasse valorization possibilities. White rectangles: biowaste. Rectangles: processes. Green curved rectangles: value-added products. Italics: Discussed in this review



decreased swelling. Additionally, the water solubility of the produced composite decreased, leading to a stable green packaging material [95]. In addition, nanocellulose-based foams in packaging applications [96], as an alternative to polystyrene-based foams are prospective. Different composite materials were also produced out of sugarcane bagasse and straw ashes, that were used as cement replacement and pozzolanic additive [97]. Furthermore, the major inorganic component of the ash is SiO_2, which can be further utilized as building material for several other applications, such as silicate compositions or components in glass ceramic products [98]. Possible applications in bio-nanocomposites for replacement of glass-fiber-reinforced polymer composites are proposed. A more detailed overview about bagasse composites is given in the review by Wei Xiong [99].

Besides, fibers of sugarcane bagasse bare great potential as low-cost biosorbent for the removal of hazardous materials or wastewater treatment. Due to the multiplicity of components available in sugarcane bagasse, there are several functional groups, such as hydroxy-, carboxy-, carbonyl or amine groups, enabling to attract and bind different polluting or hazardous substances [100]. An important improvement of adsorptive capacity can be achieved using bagasse cellulose nanocrystals due to their high increase in dispersibility and augmented chemical and physical interaction with the adsorbates [101]. A mild pretreatment process for production of nanocellulose particles from sugarcane bagasse was published by Ramesh et al. while combining chemical and biochemical routes at a final yield of approximately 34% and an average particle size of 401 nm [102].

For more details, Sarker et al. published an excellent review about sugarcane bagasse as low-cost biosorbent in 2017 [100].

Apart from fiber re-valorization, there are even more promising processes in development, as demonstrated in the subsequent biorefinery possibilities for sugarcane bagasse.

12 Biorefinery approach

The bioconversion of bagasse shows an ample variety of applications such as single-cell protein production for enriched animal feed, fermentation for production of mainstream chemicals (e.g., alcohol, lactate) or fine and specialty chemicals (e.g., alkaloids) and enzymes (e.g., cellulases, laccases, xylanase) [81, 103–105]. According to Pandey et al. [81] differences in the bioprocess technique have to be made, as there are two groups: liquid fermentation, also called submerged fermentation, and solid-state fermentation. Furthermore, liquid fermentation can be divided into two groups. One using whole bagasse as the substrate, the other applying hydrolyzed bagasse as substrate, where the latter is a lot more frequently applied. Solid-state fermentation is further divided into using bagasse as a carbon source and applying bagasse as inert solid support. All the just mentioned techniques are revised in the following sections, while different pretreatment procedures have a massive impact on the final fermentation yields. A quick overview is given in the following, for more detailed literature about pretreatment methods for lignocellulosic material, reviews from Sun et al. [106], Hassan et al. [107] and Yin et al. [108], among others, are recommended.

13 Bagasse pretreatment

To improve bagasse digestibility, a pretreatment is required to favor the fractionation of its components and open the cellulose structure [81, 103]. A pretreatment method should have low cost, avoid the need for particle size reduction, preserve hemicelluloses, and restrict the formation of degradation products and fermentation inhibitors [82, 103]. Studies with *Aspergillus clavatus* proved, that depending on the type of pretreatment, the composition of bagasse is varying significantly. This change has a large impact on the expressed enzymes (e.g., holocellulases and pectinases) in a subsequent fermentation process, to enable bioconversion [109].

Generally, acid hydrolysis of lignocellulosic substrates degrades the hemicellulose fraction into a variety of sugar monomers, in comparison, alkaline pretreatment and bio-delignification methods remove lignin, leaving cellulose and hemicellulose [23]. Delignification and break down of the lignocellulose structure constitute the main aim of bagasse pretreatments; however, extraction and recovery of lignin from sugarcane bagasse is important to enhance economic recovery and environmental friendliness.

Although, alkaline delignification has been used with different approaches, a simple sequential process involving (a) grinding, (b) hot water pretreatment for two hours at 70–80 °C with a ratio of 1:10 solid/liquid; (c) pulping with 15% NaOH (w/v) with a ratio of 1:10 (solid:liquid) for 1.5–4 h at 90–98 °C followed by (d) lignin precipitation by acidification have rendered the best extraction of lignin (up to 13% by weight, rendering an 86% lignin yield) at relatively low cost and high yield [110].

On the other hand, Nath et al. reported the pretreatment of sugarcane bagasse with 1% (w/v) NaOH at 50 °C for 2 h followed by phosphoric acid-acetone, delignification reaches 83% and the cellulose recovery is of 66%, aiming additionally high enzymatic digestibility of cellulose [111]. Alkaline sulfite pretreatment at 140 °C for 30 min has been shown quite efficient to remove more than 70% of the total lignin content and render a delignified material that responds to enzymatic hydrolysis of cellulose and xylan as to reach up to 90% conversion [112]. In comparison, high-boiling solvents can achieve delignification of more than 60% in 90 min at 190 °C [113], whereas Lima et al. focused on ozone treatment of sugarcane bagasse with subsequent alkaline extraction, aiming 72% lignin removal after 120 min of pretreatment [114].

Besides alkaline pretreatment, Pin et al. compared eleven different ionic liquids, finding acetate ions most efficient due to its alkaline character [115]. Bagasse pretreated with the ionic liquid $[Me(NH_2)(CH_2)_2OH][OAc]$ showed the best performance in enzymatic hydrolysis, yielding 72% glucose after 3 h at 160 °C [115]. Liang et al. additionally reported a high efficiency recovery of the ionic liquids, specifically, 1-ethyl-3-methylimidazolium hydrogen sulfate, while achieving up to 64% of delignification. Recycling of the ionic liquids is performed by ultrafiltration and bipolar membrane electrodialysis with a recovery ratio of 94% which promotes the green solvent strategies [116].

Besides physical and chemical pretreatment methods, also ligninolytic enzymes are exploited as an alternative method. Lignin is typically mentioned as one major inhibitor of enzymatic hydrolysis and usually accumulates throughout the process, as it is not broken down by cellulases [117]. The major lignin degrading enzymes are lignin peroxidase, manganese-dependent peroxidase, versatile peroxidase and laccase; however, lignin biodegradation is enhanced by the presence of other enzymes such as glyoxal oxidase, aryl alcohol oxidase, pyranose 2-oxidase, cellobiose/quinone oxidoreductase and cellobiose dehydrogenase [118]. According to Wong, in nature, only basidiomyceteous white-rot fungi are able to degrade lignin efficiently [118]. Matei and coworkers performed bagasse delignification for 48 h at 28 °C, using laccases from different basidiomycetes species (*Trametes villosa* among others). Subsequently a standardized saccharification was carried out, proving enzymatic delignification as a promising and eco-friendly pretreatment method [119].

Overall, in a pretreatment process of sugarcane bagasse, lignin must be removed, but this stream does not have to be wasted. As the removal of lignin has significant influence on the further application possibilities, several different methods should be considered. Technical lignin, for example, is commonly produced at industrial scale as residue of the pulp and paper industry, where typical applications of lignin are bricks, reinforcement fibers, or combustion to steam, heat or power [120].

Although there is great interest in applying lignin in functional food products, cosmetics and pharmaceuticals, there are challenges arising in regard of safe use, as e.g., differing biorefinery processes lead to different forms of purity of the final lignin product. A review tackling potential applications of lignin in food and pharmaceutical was published by Gil-Chávez et al. [120]. Nonetheless, novel and harmless pretreatment methods have to be developed, one way to go might be the biological bagasse pretreatment.

14 Bagasse hydrolysis

As mentioned earlier, hydrolysis of lignocellulosic substrates degrades the hemicellulose fraction into a variety of sugar monomers, which is crucial for subsequent fermentation processes. Nevertheless, not just acid hydrolysis is possible, but many other types of hydrolysis will be contemplated in the following.

Organic acid pretreatments have been successfully used in recent studies, Dai et al. used 3% furoic acid in a pretreatment method to degrade the lignocellulosic structure in sugarcane bagasse, with the advantage that the furoic acid can be easily recycled by cooling and crystallization [121]. The final yield was 120 g of xylooligosaccharides and 335 g glucose from 1000 g sugarcane bagasse. Using a pretreatment with 0.1 M maleic acid, Liu et al. reached a final recovery of 199 g xylose and 310 g glucose with only 3.7 g of furfural generated per 1000 g of wheat straw [122]; a promising pretreatment to be tested with sugarcane bagasse, as well. Also, use of formic acid and choline chloride in the presence of Tween 80 for the pretreatment of bagasse at relatively low temperature (110 °C for 120 min) resulted in almost complete extraction of hemicellulose (about 95.6%) and a large amount of lignin (about 72.6%) rendering a pretreated residue more susceptible to enzymatic hydrolysis [123].

Adsul et al. applied steam explosion on delignified bagasse with subsequent bleaching. The substrate was further treated with cellulases for a final hydrolytic efficiency (HE) of 94.6% [124]. Similar enzymatic hydrolytic efficiencies have been achieved on bagasse pretreated with *N*-methylmorpholine *N*-oxide to dissolve the cellulose (95% HE) [125], NaOH and peracetic acid (92% HE) [126], or SO_2 catalyzed steam pretreatment (92% HE) [127]. In regard of dry pretreatments, the applied chemicals are listed in decreasing order of efficiency: NaOH, $Ca(OH)_2$, NH_4OH and H_2O_2 [128].

Sharma et al. developed a combinatorial pretreatment based on ultrasonic irradiation and application of deep eutectic solvent by evaluation of reducing sugar yields. The comparison of seven different deep eutectic solvents, with the favorite being choline chloride/glycerol, was finalized by determination of optimal parameters such as biomass loading (5.72% w/w), sonication amplitude (60%) and time (7.79 min), yielding 1.12-fold enhanced sugar yield (312 mg/g) by DoE-based optimization [129].

In comparison Visser et al. studied enzymatic hydrolysis on partially delignified sugarcane bagasse, focussing on an enzyme blend containing FPase, endoglucanase, xylanase and β-glucosidase in batch and fed-batch processes. Recycling of insoluble fractions enabled a reutilization of a significant amount of enzymes, however, through recycling of the solid fraction, the lignin content increased, which in this case had no negative effect on enzymatic hydrolysis [130]. Enzymatic cocktails from varied microbial sources have been studied for the saccharification of pretreated bagasse. Mixtures containing basic cellulase complex enzymes as well as auxiliary xylanases and other hemicellulase, and pectinase were evaluated at varied individual ratios depending on the bagasse pretreatment [131]. In addition to the regularly used enzyme cocktails of lytic polysaccharide monooxygenases, that promote lignin oxidation, boosted the saccharification of recalcitrant cellulose [132].

More examples for enzymatic hydrolysis are demonstrated with subsequent fermentation in the following chapters.

15 Liquid fermentation of bagasse

The main raw material for ethanol production from sugar mills is black strap molasses, but sugarcane bagasse may be an alternate source. Using lignocelluloses requires high energy input for pretreatment [133]. So far, bagasse itself is not easily saccharifiable and fermentable, however, its hydrolysates were already studied as sources of fermentable sugars. Bagasse hydrolysates mainly consist of xylose, glucose, mannose, arabinose and galactose. Nonetheless, also inhibitory by-products might be present that should be removed by treatment of the hydrolysate [81].

A study comparing cellulase and biomass production by *Trichoderma reesei* QM-9414 on pretreated bagasse and on Avicel (microcrystalline cellulose) was performed by Aiello et al. and showed highest biomass yield (0.78 g/g cellulose) with alkali-treated bagasse at room temperature, followed by Avicel (0.67 g/g), untreated bagasse (0.57 g/g) and alkali-treated bagasse at 100 °C (0.50 g/g). However, enzyme activity was highest in the Avicel culture (0.163 IU/mL), followed by alkali-treated bagasse at room temperature (0.090 IU/mL) and untreated bagasse (0.087 IU/mL). There was no evidence of cellulase activity for alkali-treated bagasse at 100 °C [134].

Another promising technology for bagasse fermentation is presented by Paz-Cedeno et al. [135], using alkali pretreated sugarcane bagasse for further hydrolysis by covalently immobilized commercial cellulase and xylanase on magnetic graphene oxide particles. Finally, 72% of conversion of cellulose to glucose during the first cycle (24 h) was achieved. Reusability studies showed only 27% conversion after 6 cycles, for hydrolysis of cellulose, whereas the hydrolysis of xylan was 96% in the first cycle, decreasing to 78% after the third cycle.

Lima et al. report that alkaline treatment of bagasse (0.4% NaOH, 70 ºC, 3 h) followed by an acid pretreatment with sulfuric acid (0.5% (v/v), 140 ºC, 15 min) improves the ethanol production using *S. passalidarum* due to the deacetylation of hemicellulose [136].

In comparison, Yu et al. extracted hemicelluloses from sugarcane bagasse by autoclaving 5% bagasse in water at 4 MPa, at 180 °C for 20 min. The extracted volume was reduced and saccharified in 4% sulfuric acid at 121 °C for 1 h, or by using 54 U/mL of xylanase at 50 °C for 24 h. Afterwards, it was detoxified with anionic exchange resins. The hydrolysate was fermented with *Pichia stipitis* to produce ethanol. The xylanase treated hydrolysate showed a high ethanol productivity of 0.066 g/L/h [137]. Le Khuong et al. studied the effect of chemical factors on fungal fermentation of sugarcane bagasse by *Phlebia* sp. MG-60 resulting in a strong influence of initial moisture [138]. Highest ethanol yield achieved was 44%, with further optimization by additives being prospective. Whereas Ong and coworkers applied a *Yarrowia lipolytica* strain for co-fermentation of glucose and xylose yielding 0.35 g/g glucose and 0.15 g/g xylose with a final conversion to succinic acid instead of ethanol [139].

Naturally occurring microorganisms prefer converting glucose first, in some cases also xylose after glucose depletion. Nonetheless, genetically modified organisms or mixed cultures are a great tool to convert both sugars [133]. Martín et al. published the application of a genetically engineered xylose-utilizing strain of *Saccharomyces cerevisiae*, adapted to sugarcane bagasse hydrolysis. The cultivation during 353 h with increasing concentration of inhibitors led to an improved performance in regard of ethanol production. Xylose was reduced from 11 g/L to 5.2 g/L, while the ethanol yield after 24 h of fermentation increased to 0.38 g/g and the specific ethanol productivity was reported as 2.55 g ethanol per g of initial biomass per h [140].

Another engineered strain was applied by Amoah et al., using an engineered xylose assimilating *Saccharomyces cerevisiae* strain for co-fermentation of xylose and glucose in ionic liquid to ethanol resulting in the highest saccharification efficiency of 0.7 g/L xylose and 2.3 g/L glucose in presence of ionic liquids. Additionally, the final ethanol yield increased to 84% [141]. Also, natural sugarcane bagasse was used as inoculum for anaerobic thermophilic dark fermentation of sugarcane bagasse. After 60 days, the fermentation reached a constant production of hydrogen at varying production yields of up to 1.2 mol H_2/g substrate. Changing yields were attributed to varying metabolite composition and the effect of substrate pretreatment. The consortium responsible for degradation was a mixture of microorganisms of the phyla *Firmicutes*, *Bacteroidetes* and *Actinobacteria*, with cellulolytic organisms of the genera *Clostridium* and *Tepidimicrobium* being predominant [142].

Generally, it is difficult to compare the efficiency and productivity of the different fermentation studies of bagasse hydrolysates, as the hydrolysate composition shows a large variation in pentose and glucose contents, maybe as the result of the variation of the bagasse composition as well as the differences in the hydrolytic processes. There is also high variation in the microorganisms used, and the amount applied, as well as the fermentation technique used. Finally, ethanol production is reported using different criteria and units, while some report a final concentration (g ethanol/L), others report a direct yield (g ethanol/g carbohydrate) or a productivity (g ethanol/g biomass).

In a review published by Bezerra and Ragauskas an overview of various bagasse pretreatments with subsequent division in separate hydrolysis and fermentation (SHF) vs. simultaneous saccharification and fermentation (SSF) was given, where final ethanol yields range from 40.8–46.6 g/L in SHF and 31.6–37.2 g/L in SSF [143]. When comparing to our previously referenced publications, mostly SHF is applied [111, 114, 117, 129], whereas SSF [125] finds lower interest, so far. In the SHF process, temperatures for hydrolysis and fermentation are optimized independently, resulting in lower enzyme amounts needed, compared to the SSF approach. Nevertheless, the SSF approach finds significant advantages, as well, as the saccharification and fermentation is carried out in just one fermenter, without any purification processes in between, hence the capital cost is lower [144].

Besides ethanol, there are many more products yielding from sugarcane bagasse. Some of the before mentioned references also not solely target increased ethanol yields, but different routes of re-valorization, such as hydrogen [142], cellulase [134], laccase [119], or succinic acid [139] production. Further possibilities are lactic acid [145], mosquito pathogenic [146], biochar [147], xylitol [148] production, among many others.

16 Solid fermentation of bagasse

Bagasse is also used, to produce animal feed by solid state fermentation, employing *Basidiomycetes*. An inoculum of *Polyporus* sp. grown in salt medium on bagasse powders, applied at a high ratio of inoculum/substrate (1.0/1.5 (v/w)) at pH 5.5 rendered a product enriched in protein and reduced lignin content, presenting a good source of animal feed [149]. Besides the production of animal feed, also enzymes can be produced by solid fermentation processes from bagasse [150]. For instance, Buenrostro-Figueroa et al. produced ellagitannase, a novel enzyme responsible for biodegradation of ellagitannins and ellagic acid, by *Aspergillus niger*, using sugarcane bagasse as a matrix support [151]. Laccase production over sugarcane bagasse by *Pleurotus ostreatus* has been optimized by Karp et al. Those studies determined major influences of the substrate composition on the production of laccases resulting in large affects by nitrogen, copper sulfate and ferulic acid content [152]. They developed a statistical model that predicted the highest laccase activity (161.3 U/g of sugarcane bagasse); however, experimentally, the maximum activity was 151.6 U/g under the optimized conditions the model suggested. In comparison, a process for cellulase production via *Trichoderma koningii, Rhizomucor* sp. and *Penicillum* sp. was developed by Salomão et al., comparing different pretreatment methods for natural sugarcane bagasse. Highest cellulase production was reported for *T. koningii* on non-pretreated sugarcane bagasse, resulting in 8.2 U/g of substrate [153]. Additionally, cellulase production has been broadly studied using *Trichoderma* sp., *Penicillium* sp., *Cellulomonas* sp. and *Candida* sp. as well as mixed cultures [103, 154]. Loureiro dos Reis et al. optimized a solid-state fermentation using bagasse as carbon source [155]. The bagasse was inoculated with *Metarhizium anisopliae* to produce chitinase and determine the effect of temperature, moisture and chitin mass in the chitinase production.

Soares et al. even used fermented solids from sugarcane bagasse, which was obtained by application of *Burkholderia cepacia,* for esterification of fatty acids with ethanol in a subsequent closed-loop batch reactor. This hydroesterification reaction is a promising technology for the production of biodiesel from agroindustrial residues [156]. Fine chemical production by solid-state fermentation on sugarcane bagasse is published by Yadegary et al. producing 75.45 g citric acid per kg of untreated sugarcane bagasse, or 97.81 g/kg and 87.32 g/kg on sodium hydroxide and acid pretreated sugarcane bagasse [157].

17 Bagasse as an inert substrate

Solid-state fermentation with sugarcane bagasse as support for production of L-asparaginase by *Aspergillus terreus* was reported by Muso Cachumba et al. A horizontal column reactor filled with a mixture of dry bagasse and Czapek-Dox medium containing a nitrogen source (0.44% w/v of asparagine and 1.14% w/v of glutamine) and 0.54% w/v of starch as carbon source was applied [158]. The resulting activity of extracellular L-asparaginase was 105.3 U/L, making it a promising model for large scale production. Nevertheless, typical drawbacks of solid-state fermentation, such as difficulty in controlling the amount of oxygen, microorganism concentration and the compaction degree of the support are still unsolved.

Another scope of utilizing sugarcane bagasse is its application as immobilization support. This was successfully demonstrated by Liu et al. for immobilization of *Bacillus pumilus* HZ-2 for production of the bioremediation product mesotrione [159].

John et al. produced L-lactic acid from hydrolyzed cassava bagasse, using sugarcane bagasse as inert solid support in solid-state fermentation. A maximum of 249 mg L-lactic acid per gram of dry fermented matter was obtained after 5 days fermentation with *Lactobacillus delbrueckii* [160].

Overall, this type of application for sugarcane bagasse is rather scarce, nevertheless, to complete the whole biorefinery approach, it is not neglectable.

18 Conclusion of sugarcane biorefinery concepts

Traditionally, bagasse has been used in the industry as fuel for boilers, what means that there are no remnants for the sector. In some countries, it is used for the generation of electricity. So far, the most sustainable type of sugar mills is a combination of a sugar mill and biorefinery, producing both sugar and ethanol [161], while utilizing steam and power generation from bagasse [162]. Nevertheless the reuse of side streams, such as bagasse, that has a biotechnological potential as carbon source for fermentation processes, or the production of even higher-value added products, compared to ethanol, are still pending and bear great potential [89, 163, 164].

However, the biggest challenge is the lack of an effective method to hydrolyze the polysaccharides present in the bagasse. To make bagasse more suitable as a substrate for biotechnological processes, researchers need to find better cost-effective procedures hydrolyze cellulose, hemicellulose and lignin, in order to achieve an enhanced accessibility of sugars or transform it into high-valued chemical compounds to cover the costs of the hydrolysis of the polysaccharides. A potential market for lignin already exists, as few companies, such as LignoPure (Hamburg, Germany), deal with applicability of lignin in everyday life. Taking advantage of such industries, hence, enabling a holistic approach for sugarcane residue revalorization, should also push research to enable the technology development needed.

To close the cycle of agroindustrial waste from sugarcane, also harvesting residues, left over in the fields, have to be considered, nevertheless, these parts are mostly considered as fertilizer [164]. In summary, sugarcane bagasse is not an available residue but a by-product, mostly being used as an energy source, at least until the efficient processes, allowing to exploit the saccharides in the fibers, are reached.

19 Banana biowaste revalorization

Bananas, consumed all over the world, belong to the most popular fruits worldwide and are harvested in countries with a subtropical and tropical climate. The FAO estimates a harvested area of 5.2 million hectares and a production of 117 MT of bananas worldwide in 2019 [28]. Bananas are the fourth most harvested crop in Costa Rica by area after coffee, oil palm, and sugarcane [165]. Compared to large countries like India, Costa Rica seems to be a small producer of bananas in terms of harvested area and production (43 169 ha and 2.4 MT in 2019 for dessert bananas, and further 10 367 ha and 111 470 t for plantains) [28]. When focusing on Gross Domestic Product and agricultural export value, Costa Rica belongs to the top 5 banana industries [166].

The genus *Musa* includes more than 1000 varieties of bananas; however, the most commercially available bananas are of the Cavendish type, which is *Musa* AAA, a triploid cross of *Musa acuminata* (A), and is best suited for global trade and transport. Dessert bananas are consumed raw or baked, and display a sweet taste when ripe, while cooking bananas, also called plantains, are consumed cooked, and taste less sweet than dessert types. The plantain is *Musa* AAB, a triploid cross of *Musa acuminata* (A) and *Musa balbisiana* (B).

Consumption and processing of bananas lead to the generation of extensive amounts of peel and fruit waste already in the countries of origin. Each banana plant gives fruit only once in its plant life, after harvest of the fruits the whole plant leaves, stem and rhizome is left in the field for natural degradation [167]. Banana fruits comprise about 18–33% peel [168], where the amount depends on cultivar and ripening conditions. The FAO estimates that about 30–40% of the total banana production mass is wasted due to export rejection, damage in the field, and household throwaway [169].

20 Banana pseudo-stem and further plant wastes

Banana plants grow up to a height of 10 m and do not possess an actual trunk, where the hard parts of the leaves form a stem-like structure which is called pseudo-stem. Since most banana cultivars are monocarpic plants, this pseudo-stem is wasted after a single harvest [168].

The main component of the banana is its pseudo-stem, which constitutes of the following components, shown in Table 2, based on the characterization by Cordeiro et al. [170].

Dried banana pseudo-stem is usually reported to contain approximately 20–24% of lignin [167]. A higher value of 28% lignin was reported for the pseudo-stem of *Musa paradisiaca L* grown in India [171]. Additionally, the extraction of pectin from banana pseudo stem was reported by Neravathu et al. with its applicability as gelling agent for food materials [172].

Furthermore, several enzymes are present in the banana pseudo-stem, leaves, and roots, including starch phosphorylase, γ-amylase, phospho-hexo-isomerase, acid and alkaline invertase, sucrose synthase, sucrose phosphate synthase and acid and alkaline phosphatase, among others [173]. Polyphenol oxidases (EC 1.14.18.1) have been successfully extracted from banana peel, indicating the presence of at least two isoenzymes with different thermal stability [174].

The peel amounts to approximately 18–33% of the total fruit mass [168, 175]. In Table 3 a general overview of the

Table 2 Tabular overview of banana pseudo-stem components (in w/w %) [170]

Component	Sub-Component	Content
Lignin		12%
Holocellulose (consisting of 1:2 ratio hemicellulose:cellulose)		60%
	Glucose	74%
	Xylose	13%
	Galactose	3%
	Arabinose	9%
	Mannose	1%
Ashes		14%
	Potassium	33%
	Calcium	8%
	Magnesium	4%
	Silicium	3%
	Phosphor	2%
Extractives		14%

peels components is demonstrated, the exact content varies depending on climate, cultivar, ripening stage, and extraction method [176].

Reports about the detailed composition of the peel are available by different authors, see Agama-Acevedo et al. [175] for fibers and Khamsucharit et al. for pectin content [179], in addition, Anhwange summarized trace elements [178].

Besides, banana peel provides various polyphenols and flavonoids. Banana peel contains carotenoids in a concentration of up to 1.86 µg/g of banana peel [176]; lutein, β-carotene, α-carotene, violaxanthin, auroxanthin, neoxanthin, isolutein, β-cryptoxanthin and α-cryptoxanthin were identified [180]. Further compounds present in banana peels are saponins (24 mg/g) [178], sterols and triterpenes (β-sitosterol, stigmasterol, campesterol, cycloeucalenol, cycloartenol, 24-methylene cycloartanol) [181].

In contrast to the other major crops grown in Costa Rica, bananas are often traded unprocessed. Nevertheless, the composition of the pulp will be considered in this review as well. The banana pulp has a high content of moisture (about 75%), low content of protein (1–2%) and ash (1%) [182, 183]. The carbohydrate composition of banana pulp strongly depends on the degree of ripening. Hence, reported values do not only vary with variety and origin, but also with the ripening stage. Green banana pulp contains high amounts of starch (18–21%) and low amounts of total sugars (0.8–1.3%) [182–184]. Furthermore, small amounts of hemicellulose (2%) and pectin (1%) can be present [184]. During ripening, a variety of carbohydrate hydrolases are responsible for carbohydrate hydrolysis. The hydrolases include pectinase, cellulase, hemicellulase, amylase, xylanase, α-mannosidase, laminarinase, and β-galactosidase. The xylanase activity in bananas has been reported to be higher than in other fruits like mango, papaya and capsicum [184]. In the pulp of ripe bananas, between 4% [182] and less than 1% [183] of starch are reported. Consequently, the total sugar content has increased to 14–17% [182, 183]. For Cavendish bananas in the fully ripe state, the main sugars are sucrose (8.8%), glucose (4.2%) and fructose (3.2%) [183]. Banana pulp contains various further compounds in lower concentrations, which include neurotransmitters (i.e., dopamine 2.5–10 mg/100 g [185], serotonin [186]), amino acids (i.e., tryptophan, tyrosine [186]), and phenolics [187, 188].

21 Biomass applications

Based on the chemical composition of different parts from the banana plant, also the biomass applications vary, as illustrated in Fig. 4.

Table 3 Tabular overview of the banana peel composition

Musa paradisiaca	Content	Author	Literature
Carbohydrates	68 g/100 g dry weight	Aboul-enein et al	[177]
Proteins	13 g/100 g dry weight	Aboul-enein et al	[177]
Crude fat	8 g /100 g dry weight	Aboul-enein et al	[177]
Musa sapientum	Content	Author	Literature
Carbohydrates	59%	Anhwange et al	[178]
Proteins	2%	Anhwange et al	[178]
Crude fat	1%	Anhwange et al	[178]
Plantains	Content	Author	Literature
Cellulose	132 g /kg	Agama-Acevedo et al	[175]
Hemicellulose	46 g/kg	Agama-Acevedo et al	[175]
Lignin	17 g/kg	Agama-Acevedo et al	[175]

22 Pseudo-stem

Currently, Costa Rican banana pseudo-stem biowaste is mostly left on the fields to rot [189]. An aerobic solid state fermentation with a ligninase-rich culture of *Volvariella* sp. can turn this waste into a plant growth stimulating soil conditioner and significantly reduce the need for chemical fertilizers [190]. Given the promising quality of the material, for example the low lignin content that simplifies saccharification, this potential resource can be utilized in many other applications. Yet, to enable the extensive use of this raw material, economic processes are necessary. In literature, a variety of banana pseudo-stem applications are reported ranging from bioethanol and pulp production to functional food products and composite materials; nevertheless, the focus will lay on biorefinery applications.

Considering the high carbohydrate content of the banana pseudo-stem, the most straightforward use is to access the cellulose. For the paper industry in the 1880s, the Kraft pulping process was established [191], where lignin containing biomass is treated with hot water and alkali among other mechanical and chemical steps yielding a pulp that contains mainly cellulose. Banana pseudo-stem, as well as leaves and peduncles are considered a material worth pulping [167].

Afterwards, the high carbohydrate content is exploited to gain sugars and subsequently, for conversion to bioethanol. The production of bioethanol from readily available waste material is a more sustainable option than cultivating plants for this purpose. In literature, several authors compare different kinds of pretreatments to access the sugars for fermentation to bioethanol [192–194]. Additionally, Putra et al. demonstrated a decomposition of banana pseudo stem into various gas products, such as hydrogen, by using radio frequency in-liquid plasma, with the highest hydrogen production rate of 25.93 mmol/s from banana pseudo stem at an initial concentration of 3% (w/w) [195].

Besides biofuels, also higher value products can be gained from banana pseudo-stem wastes.

For example, the sugars released from the banana pseudo-stem can be fermented to yield lactic acid [196].

The banana pseudo-stem contains significant amounts of polyphenols and flavonoids, which can be extracted with organic solvents [197]. Ferulic acid is a hydrocinnamic acid and natural antioxidant abundant in plants and hence a higher-value product than sugars that can be obtained from banana pseudo-stem, as shown by Samad and Zainol, as well as by Sharif et al. [198, 199]. Even though, the extracted amount of ferulic acid is significantly lower than from corn fibers (18,400 mg/kg), the advantage of this process is its sustainability since no alkali pretreatment of the biomass or solvent extraction is applied [200]. Subsequently, it can be converted into vanillin by *Streptomyces setonii* ATCC39116 [200].

Due to its content of bioactive compounds, the banana pseudo-stem is also a potential raw material for the creation of functional food products. In most of the reported studies, the bioactive compounds are not isolated as pure components from the biomass. Instead, added-value products are made, and their contents analyzed. Sharma et al. created a functional prebiotic juice with glucooligosaccharides

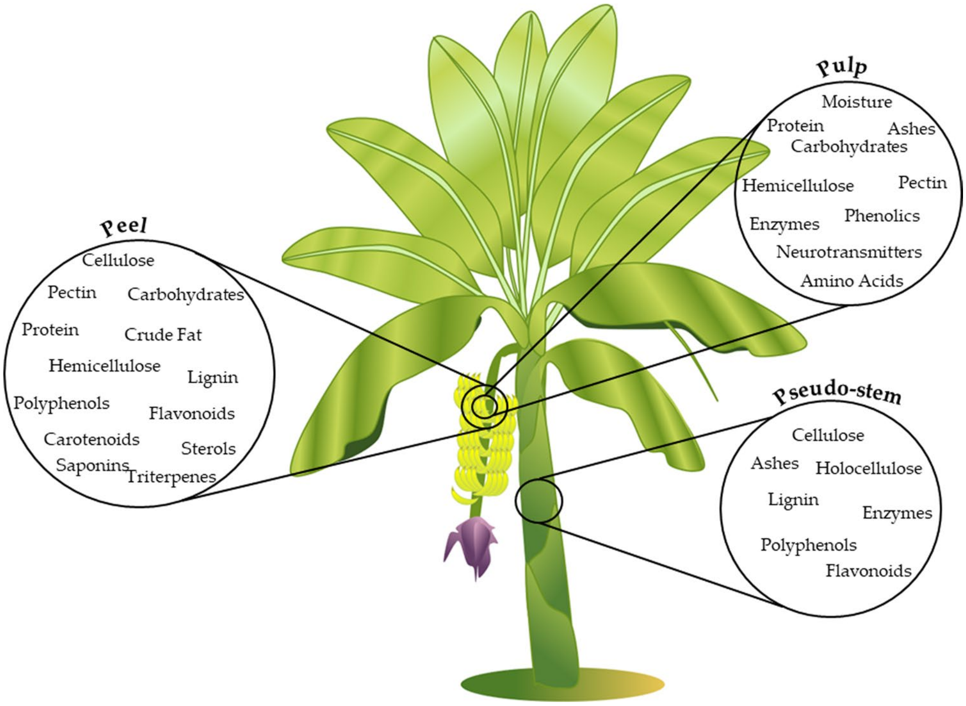


Fig. 4 Chemical composition of the banana plant

(5 g/L) and D-allulose (7 g/L), where glucooligosaccharides have a positive growth effect on the probiotic bacterial strains *L. acidophilus* and *L. fermentum*, while the rare sugar D-allulose is nearly calorie free. Hence, the authors propose potential health benefits of the prebiotic juice [201]. Further potential health benefits have been indicated for banana pseudo-stem extracts. Ramu et al. investigated the antihyperglycemic activity of an ethanol extract from banana pseudo-stem on normal and diabetic rats [202]. In vivo, the extract significantly reduced maltose-induced postprandial glucose elevation in non-diabetic and diabetic rats [202].

In addition to the production of bulk and fine chemicals, agroindustrial banana waste has a huge potential in the fabrication of functional materials. The fibers can be functionalized to produce sorbents for different pollutants. Additionally, their potential as additives in the composite material can be taken advantage of.

Sheng et al. evaluated the adsorption capacities of a modified banana pseudo-stem sorbent for heavy metal ions in water [203]. The material reduced between 37 and 99% of Pb^{2+} and Cd^{2+} from solutions containing between 1000 and 10 mg/L of the heavy metals.

The use of residual plant waste in composite materials is ecologically advantageous, especially the use of natural fibers. Vishnu Vardhini et al. characterized the reinforcement of thermoplastic composites by banana fibers obtained from waste pseudo-stem, yielding an increased hardness of up to 21% [204]. Faradilla and coworkers reported on the properties of biodegradable nanocellulose plastic produced from banana pseudo-stem [205]. The properties of the produced nanocellulose films can be engineered via type and concentrations of additives. Ramesh and coworkers produced banana fiber reinforced epoxy composites that have the potential to be used as alternative materials for conventional fiber reinforced polymer composites [206]. A composition containing 50% banana fiber and 50% epoxy resin was able to withstand higher loads compared to other combinations and comprised a maximum tensile strength of 112 MPa. Mumthas and coworkers evaluated several extraction methods and their influence on the physical properties of the resulting fibers. Given the increase in fiber strength, an application, e.g., in the textile industry is conceivable, although further studies have to be performed to investigate biological extraction methods [207]. Velumani et al. studied the implementation of fine bast fibers obtained from banana pseudo-stem into textile processes, criticizing its great stiffness, less cohesiveness and higher irregularity of natural fibers. Therefore, they adapted a lignin removing process after fiber extraction to yield a banana/cotton knitted fabric with increasing abrasion resistance by increasing banana fiber content [208].

23 Peel and pulp

The peel comprises 18–33% of the total fruit mass, and usually discarded by consumers, food service or banana processing industries, encloses the pulp of dessert and cooking bananas. Nonetheless, the peel contains valuable bioactive components, like polyphenols and flavonoids, and has a high potential in the production of bulk and fine chemicals, as well as application in advanced materials.

Predominant components of the peels of *Musa sapientum* are 59% carbohydrates and 32% crude fiber [178]. Similar to the pseudo-stem, the carbohydrates can be saccharified by different methods [209, 210]. In these studies, only the peels have been considered. If the biomass also contains pulp, the carbohydrate composition will be different. Green banana pulp will increase the starch content in the biomass, which can also be saccharified to yield sugars. Gebregergs et al. studied an industrial process to valorize banana peel from a banana juice company to yield ethanol [209].

The plant biomass is also a viable substrate for enzyme production. Banana peels and agrowaste were used as a substrate to produce, e.g., cellulases [211] and α–amylases [212], applying *Penicillinum oxalicum* and *Bacillus subtilis*. Also, fungal species of *Aspergillus fumigates* were studied on the banana peels for production of pectinase and xylanase [213].

Nonetheless, similar to the pseudo-stem, from banana peels a variety of higher value products can be obtained.

The carbohydrates within the banana peel can be utilized beyond saccharification. Pectin is a gelling agent and widely used in food and bioprocess industries as an emulsifier, texturizer, thickener, and stabilizer [214]. In banana peels, a pectin content of 4.54% was found [215], respectively, with a comparable degree of esterification to conventional pectin sources from citrus or apple pomace [179].

Several authors investigate the isolation of pectins [179, 214, 215]. The pectin extracted from banana peels can be further employed either as stabilizer in fruit juice, jam and marmalade, or other composite materials. Oliveira and coworkers combined the pectin extraction with citric acid and with acid hydrolysis to access cellulose nanoparticles, and prepared bionanocomposite films based on these two materials [216]. The cellulose nanoparticles acted as reinforcing phase, while citric acid was added as a crosslinker and glycerol as plasticizer.

In addition to pectin isolation, the gelling capacity due to the high pectin content can be utilized to create functional food products with dietary fiber and antioxidant activities. Functional jellies created from different amounts of banana peels, sugar, and citric acid provided 4 – 12% total dietary fiber, total phenolic contents of 100–300 mg gallic acid equivalents (GAE)/100 g dry weight, and total flavonoid contents of 50–180 mg catechin equivalents (CE)/100 mg dry weight. The phenolic and flavonoid contents are even higher than expected from the employed amounts of banana peel, which suggests an increased extractability due to the conditions during the production [217].

The flour from banana peels is another product that can add value to foods. The extracts of banana (*Musa* AAA) peel flour show high total phenolic contents (29 mg GAE/g), and important amounts of flavonoid phenolics: highly polymerized prodelphinidins (3953 mg/kg), flavonol glucosides (3-rutinosides and quercetin-based structures, 129 mg/kg), B-type procyanidin dimers, and monomeric flavan-3-ols (126 mg/kg) [218]. The flour can be used as a partial replacement for wheat flour in bread. This leads to increased mineral (potassium, sodium, calcium, iron, and magnesium), protein and fiber contents compared to pure wheat bread [219]. Since a better bread pliability was reported, banana peel flour is a valuable material to improve microstructural activity and add bioactive constituents to food [220].

The presence of banana pulp is not expected to impede bakery applications of banana peel flour. The flour of green bananas has been used in layer and sponge cakes. In the former, only minor declines in sensory perception were reported in comparison to the control. In the latter, a lower specific volume and worse sensory attributes were criticized. The addition of banana flour increased the content of resistant starch and dietary fiber, and enhanced the antioxidant activity due to the presence of polyphenols in the cakes [221].

The great variety of bioactive compounds in banana peels can be isolated by different extraction methods. The most common solvents for extraction are water, methanol, ethanol, acetone, and their mixtures. Extractions with mixtures of acetone and water are effective to extract catecholamines, phenolic and anthocyanin compounds [222]. The extracts from banana peels comprise antioxidant activity and a variety of polyphenols and flavonoids. While most studies determine total polyphenols (mg GAE/100 g), total flavonoids (mg CE/100 g), and antioxidant activities with DPPH (2,2-diphenyl-1-picrylhydrazyl, in mg Trolox/100 g) and FRAP (*ferric ion reducing power*, mM Fe^{2+}/100 g) methods, some extractable components of banana peels have been quantified as well. Compared to extracts from apple pomace and orange peels, extracts from banana peels comprise the highest total flavonoid contents (752 mg CE/100 g dry weight), and highest antioxidant capacity in terms of FRAP (24.6 mM Fe^{2+}/100 g dry weight) [223]. Banana peel extracts do not contain vitamin C, the total phenolic content (490 mg GAE/100 g dry weight) is lower than for orange peel extract (729 mg GAE/100 g dry weight), and antioxidant activity in terms of DPPH (999 mg Trolox/100 g dry weight) is slightly lower than for apple pomace extract (1029 mg Trolox/100 g dry weight) [223]. A comparison of total phenolic content was published by Passo Tsamo et al., considering dessert banana and plantains with different genomic constitutions (AAA, AB, AA, ABB, AAB and ABB). The total phenolic compounds in the peel are between 131.4 and 587.6 mg/100 g fresh weight. In comparison, the pulp contains between 39.5 and 319.5 mg phenolic compounds per 100 g fresh weight [224]. Flavonoid contents vary between 2.18 mg CE/100 g in banana pulp [225] and 21.04 mg/g in banana peel extracts [177]. The variations in the literature data are mostly ascribable to extraction methods, while differences between different cultivars seem to be of minor extent.

Dopamine is also present in banana pulp in concentrations of 25 – 100 mg/kg [185], and has been isolated from the pulp in analytical scales with imprinted polymers [226].

The extracts from banana peels have been employed in different applications. The addition of 5 mg methanolic banana peel extract per mL of orange juice increases the free radical scavenging and antioxidant capacity without negative influence on taste and product quality [227]. In raw poultry meat, aqueous banana peel extract and sapodilla peel extract show an antioxidant effect that is comparable to butylated hydroxytoluene in view of decreasing thiobarbituric acid reactive substances [228]. Banana peel extracts have antimicrobial activity against several bacteria including *Bacillus* sp., *Escherichia coli, Pseudomonas* sp., *Klebsiella pneumoniae, Staphylococcus aureus,* and *Streptococcus* sp. [229]. The injection of banana peel extract in the giant freshwater prawn *Macrobrachium rosenbergii* increased survival percentages at six days after treatment significantly, which is attributed to its activity against *Lactococcus garvieae* and other strains. Hence, banana peel extract has potential as bacteriostat, immunostimulant and physiological regulator for prawn [230]. Furthermore, antidiabetic effects of banana peel extracts (*Musa cavendish* and *Musa acuminata*) have been demonstrated in vitro in rats [231], and antiangiogenic effects have been investigated for *Musa sapientum* peel extracts [232].

In addition to saccharification, pectin extraction, and the utilization of bioactive compounds, banana peels have potential in the production of advanced materials. Their extracts have been utilized as reducing and stabilizing agent in the green synthesis of silver [233, 234] and gold nanoparticles [235]. The silver nanoparticles are strong DPPH radicals and ABTS (2,2′-Azinobis-(3-Ethylbenzothiazoline-6-Sulfonic Acid)) scavengers [234]. The gold nanoparticles synthesized with banana peel extract show biofilm inhibition activity against multiple antibiotic resistant gram-positive *Enterococcus faecalis*, inhibition of viability of human A549 lung cancer cells, and no mortality for the freshwater micro crustacean *Ceriodaphnia cornuta* at 250 mg/mL [235]. Nanomaterials can be obtained from banana peels as well. Pelissari and coworkers developed nanocomposites based on banana starch that was reinforced with cellulose nanofibers from banana peels [236]. The cellulose nanofibers improved the features of the starch-based materials and are potentially applicable as reinforcing elements in polymer composites.

The structure of the banana peel is furthermore interesting for material science. After carbonization, banana peel can be applied as hierarchically porous activated carbon scaffolds for energy storage applications; either as high-performance activated banana peel/$NiCo_2O_4$ electrode materials for supercapacitor applications, or as activated banana peel/Ni/graphene composite for Li/S batteries [237]. Similar to the pseudo-stem, this porous structure can be used as a sorbent. Various applications of banana peel sorbents for various materials have been published, ranging from heavy metals, such as chromium and copper, over radioactive material to organic substances, such as phenolic compounds [238–240]. Besides also fluoride and pesticides can be removed from wastewaters by banana peel sorbents [241].

24 Biorefinery approaches

There is a variety of potential applications for banana pseudo-stem and peel wastes, which are depicted in Fig. 5.

Both materials are applicable for saccharification and ethanol production with different methods, and allow ethanol yields comparable to other fruit wastes. Apart from saccharification and ethanol production, higher-value compounds can be accessed. Banana pseudo-stems can be subjected to extraction processes to access phenolic compounds, or their flour can be used in foods. They have further potential to produce sorbents and nanocellulose for functional and composite materials. Banana peel wastes have potential in pectin extraction since pectin contents are similar to the traditionally used pectin sources apple pomace and citrus peels. Since extraction conditions strongly influence the properties of the pectin, the procedure can be adjusted to fit the favored product. Further potential uses are extracts of bioactive compounds, and sorbents for various pollutants. Even combinations of these uses are possible, for example extraction and sorbent preparation. The potential of flour or extracts from banana peels as food additives is huge. Nonetheless, if an application as food ingredient is aspired or positive health effects should be advertised, probably further studies are necessary to investigate the carryover of agrochemicals to these products, for example pesticides. Further agrochemicals are used to improve flowering and fruit development. Peels have been shown to contain more than ten-fold the amount of pesticide residues compared to pulp [242], and the techniques presented in the studies shown here did not evaluate pesticide removal by washing procedures, nor carryover to the products. The same applies to the pseudo-stems used in food or health related products.

The application possibilities presented in this review are promising. Many processes have been developed for the production of bulk chemicals like ethanol from banana waste biomass. In many of these applications, high transport costs are expected due to the water content of the biomaterial. Nonetheless, a variety of value-added products can be achieved from banana wastes, especially when biorefineries are planned close to the production site. Consequently, further studies are necessary for establishing feasible processes to gain these high value materials.

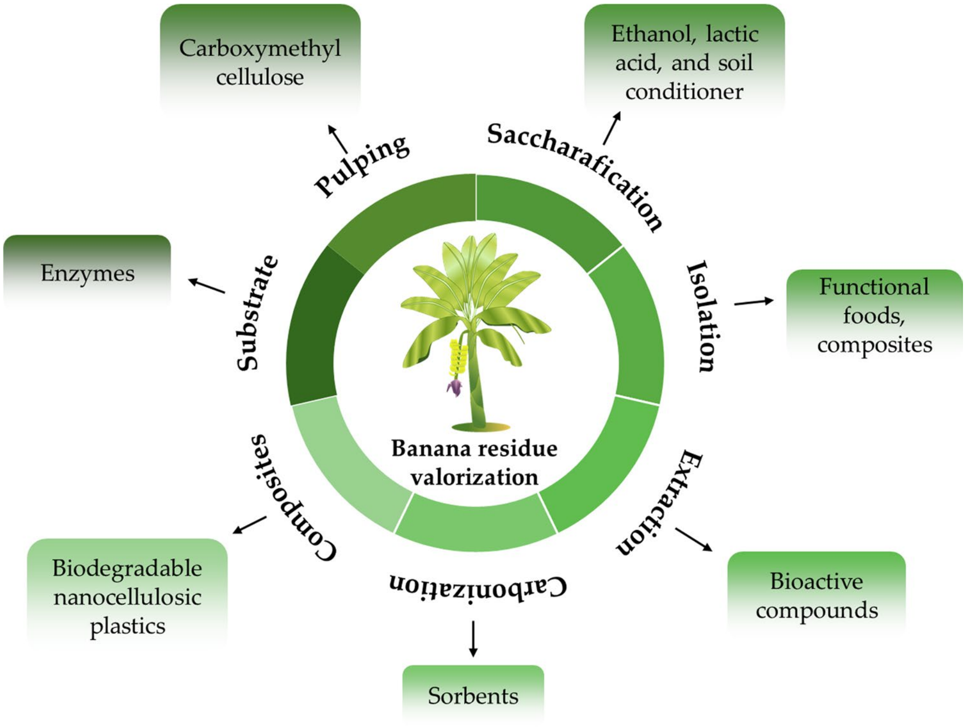


Fig. 5 Application and production process of value-added products from banana residues

25 Conclusion of banana biorefinery concepts

Most of the biomass residues resulting from banana cultivation in Costa Rica are currently not utilized. These agricultural wastes include plant wastes, especially the pseudostem, peels, and rejected fruits. Value-added products, such as bulk chemicals like ethanol, bioactive compounds, food additives or nanocellulose materials, can be obtained from these residues. Many studies focused on bulk chemical production from leftovers of banana cultivation. In addition, techno-economic feasibility studies were performed proving promising valorization processes to produce biogas or co-generate other higher value products, such as ethanol, xylitol, syngas and electricity [243]. A promising alternative application of banana agriculture by-products is the processing towards bioplastics and biodegradable packaging, therefore, closing the production cycle and reducing the accumulation of waste from banana industries [244]. Additionally, exploitation of high value compounds as plant extracts or comparable products are excellent target chemicals. For some of these products, positive health effects are expected. Nevertheless, due to the high water content of this biomass, resulting transportation costs can be the limiting factor in the decision if a biorefinery process is economically justified. Therefore, it is suggested to carry out case studies, determining the most economically feasible combination of value-added products, combining several recycling techniques to fully convert agro-industrial banana residues into valuable products.

26 Overall conclusion

Costa Rican climate and its rich soil are advantageous for the cultivation of tropical crops, which are mainly produced for export reasons. Therefore, the increasing crop cultivation also leads to an enormous amount of solid residues with high potential for value-added products, such as bio-based chemicals, fuel, and energy.

Possibilities for the valorization of by-products range from ethanol and fuel to plant extracts and comparable value-added products, when talking about banana biomass.

Sugarcane and bagasse traditionally found their way to industry as fuel for boilers or generation of electricity. However, to improve its value, the applicability in biotechnological processes depends on more suitable and especially feasible pretreatments for the hydrolysis of polysaccharides, which have to be found.

Waste valorization of pineapple is partly already done on an industrial scale, but solely in terms of bromelain extraction. In general, the lignocellulosic waste can be used for energy supply. Additionally, pineapple waste offers the opportunity to generate antibiotics, biosurfactants, as well as silica nanoparticles, among others.

Eventually, the possibilities of upgrading solid waste from various agricultural industries, are promising, especially, as closing the cycle of production in terms of circular economy, will help to extract the maximum utility out of those renewable resources. Additionally, economic growth, as well as environmental stewardship, that are inevitable according to the SDG-UN pillars for sustainable growth, are fulfilled.

In addition, in 2016, the United Nations (UN) published 17 Sustainable Development Goals (SDG). The introduction of biorefineries in Costa Rica, and elsewhere, will help produce value-added products from agro-industrial waste, making great strides in achieving “affordable and clean energy” as agro-industrial waste is increasingly used for energy production. Focusing on sustainable biotechnology processes with better energy and resource efficiency will contribute to “industry, innovation and infrastructure”, as well as “responsible consumption and production.” Positive side effects will also be visible in terms of “clean water and sanitation” and “zero hunger,” as waste dumping and soil and water toxification will no longer be a major concern, and food will no longer be used to produce energy.

Nevertheless, improvements are needed, as most production processes are not on an industrial scale yet and might even face challenges to economically compete with the so far petroleum-based way of production. However, when striving for more sustainable production processes, these challenges must be addressed, without neglecting social responsibilities, such as employment and food security. Therefore, further investigations are inevitable to find a holistic approach for the most suitable combination of by-product valorization in concert with green and sustainable technologies, as well as logistic issues.

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Data availability Not applicable.

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Declarations

Conflicts of interests/Competing interests Not applicable

References

1. Krishna IVM Manickam V (2017) Environmental management: Science and engineering for industry. Butterworth-Heinemann is an imprint of Elsevier, Kidlington, Oxford, United Kingdom
2. United Nations (2021) Take Action for the Sustainable Development Goals. https://www.un.org/sustainabledevelopment/sustainable-development-goals/. Accessed 18 Oct 2021
3. Ruslan NA Aris NFM Othman N et al. (2017) A Preliminary Study on Sustainable Management of Pineapple Waste: Perspective of Smallholders. IJARBSS 7. https://doi.org/10.6007/IJARBSS/v7-i6/2937
4. Upadhyay A, Lama JP, Tawata S (2013) Utilization of Pineapple Waste: A Review. J Food Sci Technol Nepal 6:10–18. https://doi.org/10.3126/jfstn.v6i0.8255
5. Janissen B, Huynh T (2018) Chemical composition and value-adding applications of coffee industry by-products: A review. Resour Conserv Recycl 128:110–117. https://doi.org/10.1016/j.resconrec.2017.10.001
6. Kaltschmitt M Hartmann H Hofbauer H (2009) Energie aus Biomasse, Springer B, Berlin, Heidelberg
7. Seadon JK (2010) Sustainable waste management systems. J Clean Prod 18:1639–1651. https://doi.org/10.1016/j.jclepro.2010.07.009
8. Pfau S, Hagens J, Dankbaar B et al (2014) Visions of Sustainability in Bioeconomy Research. Sustainability 6:1222–1249. https://doi.org/10.3390/su6031222
9. D'Amato D, Droste N, Allen B et al (2017) Green, circular, bio economy: A comparative analysis of sustainability avenues. J Clean Prod 168:716–734. https://doi.org/10.1016/j.jclepro.2017.09.053
10. MICITT (2020) Estrategía Nacional de Bioeconomía. Cost Rica 2020–2030, San José, Costa Rica
11. Fatih Demirbas M (2009) Biorefineries for biofuel upgrading: A critical review. Appl Energy 86:S151–S161. https://doi.org/10.1016/j.apenergy.2009.04.043
12. Zink T, Geyer R (2017) Circular Economy Rebound. J Ind Ecol 21:593–602. https://doi.org/10.1111/jiec.12545
13. Grupo ICE (2020) We Are Renewable and Solidary Energy. https://www.grupoice.com/wps/wcm/connect/579dfc1f-5156-41e0-807d-d6808f65d718/Fasciculo_Electricidad_2020_inglés_compressed.pdf?MOD=AJPERES&CVID=m.pGzcp. Accessed 18 Oct 2021
14. Ulloa JB, van Weerd JH, Huisman EA et al (2004) Tropical agricultural residues and their potential uses in fish feeds: the Costa Rican situation. Waste Manage 24:87–97. https://doi.org/10.1016/j.wasman.2003.09.003
15. Instituto Nacional de Estadística y Censos (2015) VI Censo Nacional Agropecuario. http://www.mag.go.cr/bibliotecavirtual/U40-10581.pdf. Accessed 01 Sep 2020
16. González Gamboa V (2019) Informe Estado de la Nación en Desarrollo Humano Sostenible 2019: La piña en Costa Rica: ubicando conflictos ambientales en Áreas Silvestre Protegidas y Ecosistemas de Humedal. https://estadonacion.or.cr/wp-content/uploads/2019/12/Gonzalez-V.-2019.-Piña.pdf. Accessed 18 Oct 2021
17. Natucafé S.A.S Coffee mucilage concentrate. http://natucafe.co/coffee-mucilage-concentrate.php. Accessed 17 Jan 2022
18. Naox Colombia. https://www.naoxcolombia.com/home. Accessed 17 Jan 2022
19. Scully D, Jaiswal A, Abu-Ghannam N (2016) An Investigation into Spent Coffee Waste as a Renewable Source of Bioactive Compounds and Industrially Important Sugars. Bioengineering 3:33. https://doi.org/10.3390/bioengineering3040033
20. Ruesgas-Ramón M, Figueroa-Espinoza MC, Durand E (2017) Application of Deep Eutectic Solvents (DES) for Phenolic Compounds Extraction: Overview, Challenges, and Opportunities. J Agric Food Chem 65:3591–3601. https://doi.org/10.1021/acs.jafc.7b01054
21. Torres-Valenzuela LS, Ballesteros-Gómez A, Rubio S (2020) Green Solvents for the Extraction of High Added-Value Compounds from Agri-food Waste. Food Eng Rev 12:83–100. https://doi.org/10.1007/s12393-019-09206-y
22. Mora-Villalobos J-A Aguilar F Carballo-Arce A-F et al. (2021) Tropical agroindustrial biowaste revalorization through integrative biorefineries—review part I: coffee and palm oil by-products. Biomass Conv Bioref. https://doi.org/10.1007/s13399-021-01442-9
23. Chandel AK, da Silva SS, Carvalho W et al (2012) Sugarcane bagasse and leaves: foreseeable biomass of biofuel and bio-products. J Chem Technol Biotechnol 87:11–20. https://doi.org/10.1002/jctb.2742
24. Food and Agriculture Organization of the United Nations (2019) FAOSTAT. http://www.fao.org/faostat/en/#data/QC/visualize. Accessed 20 March 2020
25. Sukruansuwan V, Napathorn SC (2018) Use of agro-industrial residue from the canned pineapple industry for polyhydroxybutyrate production by Cupriavidus necator strain A-04. Biotechnol Biofuels 11:202. https://doi.org/10.1186/s13068-018-1207-8
26. Chen A, Guan YJ, Bustamante M et al (2020) Production of renewable fuel and value-added bioproducts using pineapple leaves in Costa Rica. Biomass Bioenerg 141:105675. https://doi.org/10.1016/j.biombioe.2020.105675
27. CANAPEP. https://canapep.com/. Accessed 01 Jul 2020
28. Food and Agriculture Organization of the United Nations FAOSTAT: Statistic Division. http://www.fao.org/faostat/en/#home. Accessed 03/20/2020
29. Nennie I De Boer H (2018) Sustainable Pineapple Costa Rica Market Study. https://www.rvo.nl/sites/default/files/2018/06/sustainable-pineapple-costa-rica-market-study.pdf. Accessed 01 Jul 2020
30. Liu CH Liu Y Fan C et al. (2013) The effects of composted pineapple residue return on soil properties and the growth and yield of pineapple. Journal of soil science and plant nutrition:0. https://doi.org/10.4067/S0718-95162013005000034
31. van Tran A (2006) Chemical analysis and pulping study of pineapple crown leaves. Ind Crops Prod 24:66–74. https://doi.org/10.1016/j.indcrop.2006.03.003

32. Ketnawa S, Chaiwut P, Rawdkuen S (2012) Pineapple wastes: A potential source for bromelain extraction. Food Bioprod Process 90:385–391. https://doi.org/10.1016/j.fbp.2011.12.006
33. Sánchez Pardo ME, Ramos Cassellis ME, Mora Escobedo R et al (2014) Chemical Characterisation of the Industrial Residues of the Pineapple (Ananas comosus). Jacen 03:53–56. https://doi.org/10.4236/jacen.2014.32b009
34. Ban-Koffi L, Han YW (1990) Alcohol production from pineapple waste. World J Microbiol Biotechnol 6:281–284. https://doi.org/10.1007/BF01201297
35. López-Herrera M WingChing-Jones R Rojas-Baurrillón A (2014) Meta-análisis de los subproductos de piña (Ananas comosus) para la alimentación animal. Agron Mesoam:383–392. https://doi.org/10.15517/am.v25i2.15453
36. Pardo MES, Cassellis MER, Escobedo RM et al (2014) Chemical Characterisation of the Industrial Residues of the Pineapple (Ananas comosus). Jacen 03:53–56. https://doi.org/10.4236/jacen.2014.32B009
37. Baidhe E, Kigozi J, Mukisa I et al (2021) Unearthing the potential of solid waste generated along the pineapple drying process line in Uganda: A review. Environ Challenges 2:100012. https://doi.org/10.1016/j.envc.2020.100012
38. Roda A, de Faveri DM, Dordoni R et al (2017) Pineapple Wines Obtained from Saccharification of Its Waste with Three Strains of Saccharomyces cerevisiae. J Food Process Preserv 41:e13111–e13111. https://doi.org/10.1111/jfpp.13111
39. Larrauri JA, Rupérez P, Calixto FS (1997) Pineapple Shell as a Source of Dietary Fiber with Associated Polyphenols. J Agric Food Chem 45:4028–4031. https://doi.org/10.1021/jf970450j
40. Li T, Shen P, Liu W et al (2014) Major Polyphenolics in Pineapple Peels and their Antioxidant Interactions. Int J Food Prop 17:1805–1817. https://doi.org/10.1080/10942912.2012.732168
41. Sepúlveda L, Romaní A, Aguilar CN et al (2018) Valorization of pineapple waste for the extraction of bioactive compounds and glycosides using autohydrolysis. Innov Food Sci Emerg Technol 47:38–45. https://doi.org/10.1016/j.ifset.2018.01.012
42. Sruamsiri S (2007) Agricultural wastes as dairy feed in Chiang Mai. Animal Sci J 78:335–341. https://doi.org/10.1111/j.1740-0929.2007.00445.x
43. Suksathit S Wachirapakorn C Opatpatanakit Y (2010) Effects of levels of ensiled pineapple waste and Pangola hay fed as roughage sources on feed intake, nutrient digestibility and ruminal fermentation of Southern Thai native cattle. Songklanakarin Journal of Science and Technology 33
44. Kyawt Y, Win K, Mu K et al (2020) Feeding pineapple waste silage as roughage source improved the nutrient intakes, energy status and growth performances of growing Myanmar local cattle. J Adv Vet Anim Res 7:436. https://doi.org/10.5455/javar.2020.g439
45. Buliah N Jamek S Ajit A et al. (2019) Production of dairy cow pellets from pineapple leaf waste. In: 6TH INTERNATIONAL CONFERENCE ON ENVIRONMENT (ICENV2018): Empowering Environment and Sustainable Engineering Nexus Through Green Technology. AIP Publishing, p 20048
46. Gowda NKS, Vallesha NC, Awachat VB et al (2015) Study on evaluation of silage from pineapple (Ananas comosus) fruit residue as livestock feed. Trop Anim Health Prod 47:557–561. https://doi.org/10.1007/s11250-015-0762-2
47. Raseel K, Chacko B, Shyama K et al (2020) Evaluation of Pineapple Waste Based TMR on Performance of Crossbred Dairy Cows in Early Lactation. Anim Nutr Feed Technol 20:155. https://doi.org/10.5958/0974-181X.2020.00015.3
48. Pollak P (2011) Fine Chemicals. John Wiley & Sons Inc, Hoboken, NJ, USA
49. Vega-Baudrit J MOYA M Sibaja M et al. (1995) Obtención de Vainillina de Desechos Agroindustriales. INDOTECNIA 7
50. Ong KL, Tan BW, Liew SL (2014) Pineapple cannery waste as a potential substrate for microbial biotransformation to produce vanillic acid and vanillin. Int Food Res J 21:953–958
51. Kareem SO Akpan I Alebiowu OO (2010) Production of citric acid by Aspergillus niger using pineapple waste. MJM. https://doi.org/10.21161/mjm.19009
52. Banerjee S, Ranganathan V, Patti A et al (2018) Valorisation of pineapple wastes for food and therapeutic applications. Trends Food Sci Technol 82:60–70. https://doi.org/10.1016/j.tifs.2018.09.024
53. Vastrad BM Neelagund SE (2011) Production and Optimisation of Tetracycline by Various Strains of Streptomyces under Solid State Fermentation using Pineapple Peel as a Novel Substrate. RRST 3
54. Almeida FCGd Silva TAdLe Garrard I et al. (2015) Optimization and Evaluation of Biosurfactant Produced by Pantoea sp. Using Pineapple Peel Residue, Vegetable Fat and Corn Steep Liquor. JCCE 9. https://doi.org/10.17265/1934-7375/2015.04.005
55. Vega-Baudrit JR, Ballestero S, del Rosario M et al (2012) Biosíntesis de dextranos de alto peso molecular mediante la inoculación con Leuconostoc mesenteroides, var. mesenteroides (ATCC 10830) de jugos residuales de la agroindustria de la piña: síntesis y caracterización de hierro-dextranos. Revista del laboratorio tecnológico del Uruguay 7:55–58
56. Feng F, Zhou Q, Yang Y et al (2018) Characterization of highly branched dextran produced by Leuconostoc citreum B-2 from pineapple fermented product. Int J Biol Macromol 113:45–50. https://doi.org/10.1016/j.ijbiomac.2018.02.119
57 Camacho M, Ureña YRC, Lopretti M et al (2017) Synthesis and Characterization of Nanocrystalline Cellulose Derived from Pineapple Peel Residues. J Renew Mater 5:271–279. https://doi.org/10.7569/JRM.2017.634117
58. Corrales-Ureña YR, Villalobos-Bermúdez C, Pereira R et al (2018) Biogenic silica-based microparticles obtained as a sub-product of the nanocellulose extraction process from pineapple peels. Sci Rep 8:10417. https://doi.org/10.1038/s41598-018-28444-4
59. Perry CC, Fraser MA (1991) Silica deposition and ultrastructure in the cell wall of Equisetum arvense : the importance of cell wall structures and flow control in biosilicification? Phil Trans R Soc Lond B 334:149–157. https://doi.org/10.1098/rstb.1991.0104
60. Kothari R, Tyagi VV, Pathak A (2010) Waste-to-energy: A way from renewable energy sources to sustainable development. Renew Sustain Energy Rev 14:3164–3170. https://doi.org/10.1016/j.rser.2010.05.005
61. Kalyani KA, Pandey KK (2014) Waste to energy status in India: A short review. Renew Sustain Energy Rev 31:113–120. https://doi.org/10.1016/j.rser.2013.11.020
62. Gobierno de Costa Rica (2018–2022) Plan Nacional De Descarbonización. https://unfccc.int/sites/default/files/resource/Plan%20Nacional%20de%20Descarbonizaci%C3%B3n%20-%20Espa%C3%B1ol.pdf. Accessed 18 Oct 2021
63. Barz M, Delivand MK, Dinkler K (2018) Agricultural Wastes – A Promising Source for Biogas Production in Developing Countries of the Tropical and Subtropical Regions. RFMK 16:2–12. https://doi.org/10.18845/rfmk.v16i38.3991
64. Rona N Ronald Arce AMM Costa Rica: Programa País de Carbono Neutralidad 2.0 - Categoría Organizacional - Estudio de caso. https://ledslac.org/wp-content/uploads/2020/05/EdC-Carbono-Neutralidad-Costa-Rica-ene20_mod.pdf. Accessed 18 Oct 2021
65. Braga RM, Queiroga TS, Calixto GQ et al (2015) The energetic characterization of pineapple crown leaves. Environ Sci Pollut Res Int 22:18987–18993. https://doi.org/10.1007/s11356-015-5082-6

66. Mund NK Dash D Mishra P et al. (2021) Cellulose solvent–based pretreatment and enzymatic hydrolysis of pineapple leaf waste biomass for efficient release of glucose towards biofuel production. Biomass Conv Bioref. https://doi.org/10.1007/s13399-020-01225-8
67. Casabar JT, Ramaraj R, Tipnee S et al (2020) Enhancement of hydrolysis with Trichoderma harzianum for bioethanol production of sonicated pineapple fruit peel. Fuel 279:118437. https://doi.org/10.1016/j.fuel.2020.118437
68. Choonut A, Saejong M, Sangkharak K (2014) The Production of Ethanol and Hydrogen from Pineapple Peel by Saccharomyces Cerevisiae and Enterobacter Aerogenes. Energy Procedia 52:242–249. https://doi.org/10.1016/j.egypro.2014.07.075
69. Paepatung N, Nopharatana A, Songkasiri W (2009) Bio-methane potential of biological solid materials and agricultural wastes. Asian J Energy Environ 10:19–27
70. Guevara A Arce R Guevara P (2017) Impacto Económico, Social y Ambiental de la Piña en Costa Rica. https://canapep.com/download/impacto-economico-social-ambiental-la-pina-costa-rica/. Accessed 01 Jul 2020
71. Arce A Hernández C Amador R (2015) Determinación de la cantidad y composición de biogás a partir de rastrojo de la piña (Ananas comosis) por medio de un sistema continuo a escala laboratorio. https://www.grupoice.com/wps/wcm/connect/bd310837-a437-491a-8b74-b98053902d2c/20150309EnsayorastrojodepinNa.pdf?MOD=AJPERES&CVID=l0.sz0M. Accessed 01 Jul 2020
72. Banerjee S Munagala M Shastri Y et al. (2022) Process Design and Techno-Economic Feasibility Analysis of an Integrated Pineapple Processing Waste Biorefinery. ACS Eng Au. https://doi.org/10.1021/acsengineeringau.1c00028&ref=pdf
73. Gupta A, Verma JP (2015) Sustainable bio-ethanol production from agro-residues: A review. Renew Sustain Energy Rev 41:550–567. https://doi.org/10.1016/j.rser.2014.08.032
74. Azouma YO, Drigalski L, Jegla Z et al (2019) Indirect Convective Solar Drying Process of Pineapples as Part of Circular Economy Strategy. Energies 12:2841. https://doi.org/10.3390/en12152841
75. Banerjee S, Vijayaraghavan R, Patti AF et al (2022) Integrated Biorefinery Strategy for Valorization of Pineapple Processing Waste into High-Value Products. Waste Biomass Valor 13:631–643. https://doi.org/10.1007/s12649-021-01542-7
76. Vieira IMM Santos BLP Santos CVM et al. (2021) Valorization of Pineapple Waste: a Review on How the Fruit's Potential Can Reduce Residue Generation. Bioenerg Res. https://doi.org/10.1007/s12155-021-10318-9
77. Bromé (2021) Bromé enzyme tehcnology. https://www.bromenzyme.com/. Accessed 20 Jan 2022
78. Eco:fiber (2021) Eco:fibr. https://www.ecofibr.de/. Accessed 20 Jan 2022
79. OECD/FAO OECD-FAO Agricultural Outlook 2019–2028. https://doi.org/10.1787/agr_outlook-2019-en. Accessed 03/20/2020
80. Manickavasagam M, Elango T, Siddharth S et al (2018) Methods for determining moisture content in bagasse of sugarcane using microwave oven. International Journal of Advanced Research in Management, Architecture. Technol Eng IJARMATE 4:149–152
81. Pandey A, Soccol CR, Nigam P et al (2000) Biotechnological potential of agro-industrial residues. I: sugarcane bagasse. Biores Technol 74:69–80. https://doi.org/10.1016/S0960-8524(99)00142-X
82. Karp SG, Woiciechowski AL, Soccol VT et al (2013) Pretreatment strategies for delignification of sugarcane bagasse: a review. J Agric Food Chem 56:679–689. https://doi.org/10.1590/S1516-89132013000400019
83. Dias MOS, Junqueira TL, Cavalett O et al (2013) Biorefineries for the production of first and second generation ethanol and electricity from sugarcane. Appl Energy 109:72–78. https://doi.org/10.1016/j.apenergy.2013.03.081
84. Go AW, Conag AT (2019) Utilizing sugarcane leaves/straws as source of bioenergy in the Philippines: A case in the Visayas Region. Renew Energy 132:1230–1237. https://doi.org/10.1016/j.renene.2018.09.029
85. Yadav RL, Solomon S (2006) Potential of Developing Sugarcane By-product Based Industries in India. Sugar Tech 8:104–111
86. Meghana M, Shastri Y (2020) Sustainable valorization of sugar industry waste: Status, opportunities, and challenges. Biores Technol 303:122929. https://doi.org/10.1016/j.biortech.2020.122929
87. Dantas GA, Legey LFL, Mazzone A (2013) Energy from sugarcane bagasse in Brazil: An assessment of the productivity and cost of different technological routes. Renew Sustain Energy Rev 21:356–364. https://doi.org/10.1016/j.rser.2012.11.080
88. Seabra JEA, Macedo IC (2011) Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil. Energy Policy 39:421–428. https://doi.org/10.1016/j.enpol.2010.10.019
89. Santos VEN, Ely RN, Szklo AS et al (2016) Chemicals, electricity and fuels from biorefineries processing Brazil's sugarcane bagasse: Production recipes and minimum selling prices. Renew Sustain Energy Rev 53:1443–1458. https://doi.org/10.1016/j.rser.2015.09.069
90. Arshad M, Ahmed S (2016) Cogeneration through bagasse: A renewable strategy to meet the future energy needs. Renew Sustain Energy Rev 54:732–737. https://doi.org/10.1016/j.rser.2015.10.145
91. Jesus GMK Jugend D Paes LAB et al. (2021) Barriers to the adoption of the circular economy in the Brazilian sugarcane ethanol sector. Clean Techn Environ Policy. https://doi.org/10.1007/s10098-021-02129-5
92. Anukam A, Mamphweli S, Reddy P et al (2016) Pre-processing of sugarcane bagasse for gasification in a downdraft biomass gasifier system: A comprehensive review. Renew Sustain Energy Rev 66:775–801. https://doi.org/10.1016/j.rser.2016.08.046
93. Rainey TJ, Covey G (2016) Pulp and paper production from sugarcane bagasse. In: O'Hara IM, Mundree SG (eds) Sugarcane-Based Biofuels and Bioproducts, vol 75. John Wiley & Sons Inc. Hoboken, NJ, USA, pp 259–280
94. Jeefferie AR, Nurul Fariha O, Mohd Warikh AR et al (2011) Preliminary Study on the Physical and Mechanical Properties of Tapioca Starch / Sugarcane Fiber Cellulose Composite. Asian Res Publ Netw 6:7–15
95. Jumaidin R, Adam NW, Ilyas RA et al (2019) Water Transport and Physical Properties of Sugarcane Bagasse Fibre Reinforced Thermoplastic Potato Starch Biocomposite. J Adv Res Fluid Mech Therm Sci 61:273–281
96. Phaodee P, Tangjaroensirirat N, Sakdaronnarong C (2015) Biobased Polystyrene Foam-like Material from Crosslinked Cassava Starch and Nanocellulose from Sugarcane Bagasse. BioResources 10:348–368
97. Bahurudeen A, Kanraj D, Gokul Dev V et al (2015) Performance evaluation of sugarcane bagasse ash blended cement in concrete. Cement Concr Compos 59:77–88. https://doi.org/10.1016/j.cemconcomp.2015.03.004
98. Teixeira SR, Arenales A, de Souza AE et al (2015) Sugarcane Bagasse: Applications for Energy Production and Ceramic Materials. J Solid Waste Technol Manag 41:315–324
99. Xiong W (2018) Bagasse composites. J Thermoplast Compos Mater 31:1112–1146. https://doi.org/10.1177/0892705717734596

100. Sarker TC, Azam SMGG, El-Gawad AMA et al (2017) Sugarcane bagasse: a potential low-cost biosorbent for the removal of hazardous materials. Clean Techn Environ Policy 19:2343–2362. https://doi.org/10.1007/s10098-017-1429-7
101. Khoo RZ, Chow WS, Ismail H (2018) Sugarcane bagasse fiber and its cellulose nanocrystals for polymer reinforcement and heavy metal adsorbent: a review. Cellulose 25:4303–4330. https://doi.org/10.1007/s10570-018-1879-z
102. Ramesh S Doddipatla P Pamidipati S (2021) Optimization of parameters for biological pre-treatment route for the production of nanocellulose from sugarcane bagasse. Biomass Conv Bioref. https://doi.org/10.1007/s13399-021-01306-2
103. Konde KS, Nagarajan S, Kumar V et al (2021) Sugarcane bagasse based biorefineries in India: Potential and challenges. Sustain Energy Fuels 5:52–78. https://doi.org/10.1039/d0se01332c
104. da Cunha Abreu Xavier M, Franco TT (2021) Obtaining hemicellulosic hydrolysate from sugarcane bagasse for microbial oil production by Lipomyces starkeyi. Biotech Lett 43:967–979. https://doi.org/10.1007/s10529-021-03080-7
105. Lu J, Li J, Gao H et al (2021) Recent progress on bio-succinic acid production from lignocellulosic biomass. World J Microbiol Biotechnol 37:1–8. https://doi.org/10.1007/s11274-020-02979-z
106. Sun S, Sun S, Cao X et al (2016) The role of pretreatment in improving the enzymatic hydrolysis of lignocellulosic materials. Biores Technol 199:49–58. https://doi.org/10.1016/j.biortech.2015.08.061
107. Hassan SS, Williams GA, Jaiswal AK (2018) Emerging technologies for the pretreatment of lignocellulosic biomass. Biores Technol 262:310–318. https://doi.org/10.1016/j.biortech.2018.04.099
108. Yin X, Wei L, Pan X et al (2021) The Pretreatment of Lignocelluloses With Green Solvent as Biorefinery Preprocess: A Minor Review. Front Plant Sci 12:670061. https://doi.org/10.3389/fpls.2021.670061
109. de Lucas RC, de Oliveira TB, Lima MS et al (2021) The profile secretion of Aspergillus clavatus: Different pre-treatments of sugarcane bagasse distinctly induces holocellulases for the lignocellulosic biomass conversion into sugar. Renew Energy 165:748–757. https://doi.org/10.1016/j.renene.2020.11.072
110. Arni SA (2018) Extraction and isolation methods for lignin separation from sugarcane bagasse: A review. Ind Crops Prod 115:330–339. https://doi.org/10.1016/j.indcrop.2018.02.012
111. Nath P, Maibam PD, Singh S et al (2021) Sequential pretreatment of sugarcane bagasse by alkali and organosolv for improved delignification and cellulose saccharification by chimera and cellobiohydrolase for bioethanol production. World J Microbiol Biotechnol 11:1–16. https://doi.org/10.1007/s13205-020-02600-y
112. Paz-Cedeno FR, Henares LR, Solorzano-Chavez EG et al (2021) Evaluation of the effects of different chemical pretreatments in sugarcane bagasse on the response of enzymatic hydrolysis in batch systems subject to high mass loads. Renew Energy 165:1–13. https://doi.org/10.1016/j.renene.2020.10.092
113. Wang Q Chen K Liu S et al. (2011) Kinetics of bagasse delignification by using highboiling solvent. Bioresources 6. https://doi.org/10.15376/biores.6.3.2366-2374
114. Lima DRS, Oliveira Paranhos de AG, Adarme OFH et al (2021) Integrated production of second-generation ethanol and biogas from sugarcane bagasse pretreated with ozone. Biomass Conv Bioref. https://doi.org/10.1007/s13399-020-01234-7
115. Pin TC, Nakasu PYS, Mattedi S et al (2019) Screening of protic ionic liquids for sugarcane bagasse pretreatment. Fuel 235:1506–1514. https://doi.org/10.1016/j.fuel.2018.08.122
116. Liang X, Wang J, Guo Y et al (2021) High-efficiency recovery, regeneration and recycling of 1-ethyl-3-methylimidazolium hydrogen sulfate for levulinic acid production from sugarcane bagasse with membrane-based techniques. Biores Technol 330:124984. https://doi.org/10.1016/j.biortech.2021.124984
117. Zhao X, Dong L, Chen L et al (2013) Batch and multi-step fed-batch enzymatic saccharification of Formiline-pretreated sugarcane bagasse at high solid loadings for high sugar and ethanol titers. Biores Technol 135:350–356. https://doi.org/10.1016/j.biortech.2012.09.074
118. Wong DWS (2009) Structure and action mechanism of ligninolytic enzymes. Appl Biochem Biotechnol 157:174–209. https://doi.org/10.1007/s12010-008-8279-z
119. Matei JC, Soares M, Bonato ACH et al (2020) Enzymatic delignification of sugar cane bagasse and rice husks and its effect in saccharification. Renew Energy 157:987–997. https://doi.org/10.1016/j.renene.2020.05.028
120. Gil-Chávez J Gurikov P Hu X et al. (2019) Application of novel and technical lignins in food and pharmaceutical industries: structure-function relationship and current challenges. Biomass Conv Bioref. https://doi.org/10.1007/s13399-019-00458-6
121. Dai L, Huang T, Jiang K et al (2021) A novel recyclable furoic acid-assisted pretreatment for sugarcane bagasse biorefinery in co-production of xylooligosaccharides and glucose. Biotechnol Biofuels 14:1–8. https://doi.org/10.1186/s13068-021-01884-3
122. Liu Z, Shi E, Ma F et al (2021) An integrated biorefinery process for co-production of xylose and glucose using maleic acid as efficient catalyst. Biores Technol 325:124698. https://doi.org/10.1016/j.biortech.2021.124698
123. Ling R Wu W Yuan Y et al. (2021) Investigation of choline chloride-formic acid pretreatment and Tween 80 to enhance sugarcane bagasse enzymatic hydrolysis. Bioresource Technology 326. https://doi.org/10.1016/j.biortech.2021.124748
124. Adsul MG, Ghule JE, Shaikh H et al (2005) Enzymatic hydrolysis of delignified bagasse polysaccharides. Carbohyd Polym 62:6–10. https://doi.org/10.1016/j.carbpol.2005.07.010
125. Kuo C-H, Lee C-K (2009) Enhanced enzymatic hydrolysis of sugarcane bagasse by N-methylmorpholine-N-oxide pretreatment. Biores Technol 100:866–871. https://doi.org/10.1016/j.biortech.2008.07.001
126. Zhao X, Peng F, Cheng K et al (2009) Enhancement of the enzymatic digestibility of sugarcane bagasse by alkali–peracetic acid pretreatment. Enzyme Microb Technol 44:17–23. https://doi.org/10.1016/j.enzmictec.2008.07.011
127. Carrasco C, Baudel HM, Sendelius J et al (2010) SO2-catalyzed steam pretreatment and fermentation of enzymatically hydrolyzed sugarcane bagasse. Enzyme Microb Technol 46:64–73. https://doi.org/10.1016/j.enzmictec.2009.10.016
128. Rodríguez-Vázquez R, Díaz-Cervantes D (1994) Effect of Chemical Solutions Sprayed on Sugarcane Bagasse Pith to Produce Single Cell Protein: Physical and Chemical Analyses of Pith. Biores Technol 47:159–164
129. Sharma V, Nargotra P, Sharma S et al (2021) Efficacy and functional mechanisms of a novel combinatorial pretreatment approach based on deep eutectic solvent and ultrasonic waves for bioconversion of sugarcane bagasse. Renew Energy 163:1910–1922. https://doi.org/10.1016/j.renene.2020.10.101
130. Visser EM, Leal TF, de Almeida MN et al (2015) Increased enzymatic hydrolysis of sugarcane bagasse from enzyme recycling. Biotechnol Biofuels 8:5. https://doi.org/10.1186/s13068-014-0185-8
131. Karp SG, Rozhkova AM, Semenova VM et al (2021) Designing enzyme cocktails from Penicillium and Aspergillus species for the enhanced saccharification of agro-industrial wastes. Biores Technol 330:124888. https://doi.org/10.1016/j.biortech.2021.124888
132. Velasco J, de Oliveira Arnoldi Pellegrini V, Sepulchro AGV et al (2021) Comparative analysis of two recombinant LPMOs from Aspergillus fumigatus and their effects on sugarcane bagasse

saccharification. Enzyme Microb Technol 144:109746. https://doi.org/10.1016/j.enzmictec.2021.109746

133. Chaudhary N, Qazi JI (2011) Lignocellulose for ethanol production: A review of issues relating to bagasse as a source material. Afr J Biotech 10(8):1270–1274
134. Aiello C, Ferrer A, Ledesma A (1996) Effect of alkaline treatments at various temperatures on cellulase and biomass production using submerged sugarcane bagasse fermentation with Trichoderma reesei QM 9414. Biores Technol 57:13–18. https://doi.org/10.1016/0960-8524(96)00012-0
135. Paz-Cedeno FR, Carceller JM, Iborra S et al (2021) Magnetic graphene oxide as a platform for the immobilization of cellulases and xylanases: Ultrastructural characterization and assessment of lignocellulosic biomass hydrolysis. Renew Energy 164:491–501. https://doi.org/10.1016/j.renene.2020.09.059
136. Lima CS Neitzel T Oliveira Pereira I de et al. (2021) Effect of the Sugarcane Bagasse Deacetylation in the Pentoses Fermentation Process. Bioenergy Research. https://doi.org/10.1007/s12155-020-10243-3
137. Yu Q Xu C Zhuang X et al. (2014) Xylo-oligosaccharides and Ethanol Production from Liquid Hot Water Hydrolysate of Sugarcane Bagasse. BioResources; 10:1 (2015)
138. Le Khuong D, Kondo R, de Leon R et al (2014) Effect of chemical factors on integrated fungal fermentation of sugarcane bagasse for ethanol production by a white-rot fungus, Phlebia sp. MG-60. Biores Technol 167:33–40. https://doi.org/10.1016/j.biortech.2014.05.064
139. Ong KL, Li C, Li X et al (2019) Co-fermentation of glucose and xylose from sugarcane bagasse into succinic acid by Yarrowia lipolytica. Biochem Eng J 148:108–115. https://doi.org/10.1016/j.bej.2019.05.004
140. Martín C, Marcet M, Almazán O et al (2007) Adaptation of a recombinant xylose-utilizing Saccharomyces cerevisiae strain to a sugarcane bagasse hydrolysate with high content of fermentation inhibitors. Biores Technol 98:1767–1773. https://doi.org/10.1016/j.biortech.2006.07.021
141. Amoah J, Ogura K, Schmetz Q et al (2019) Co-fermentation of xylose and glucose from ionic liquid pretreated sugar cane bagasse for bioethanol production using engineered xylose assimilating yeast. Biomass Bioenerg 128:105283. https://doi.org/10.1016/j.biombioe.2019.105283
142. Ratti RP, Delforno TP, Sakamoto IK et al (2015) Thermophilic hydrogen production from sugarcane bagasse pretreated by steam explosion and alkaline delignification. Int J Hydrogen Energy 40:6296–6306. https://doi.org/10.1016/j.ijhydene.2015.03.067
143. Bezerra TL, Ragauskas AJ (2016) A review of sugarcane bagasse for second-generation bioethanol and biopower production. Biofuels Bioprod Bioref 10:634–647. https://doi.org/10.1002/bbb.1662
144. Ishizaki H Hasumi K (2014) Ethanol Production from Biomass. In: Research Approaches to Sustainable Biomass Systems. Elsevier, pp 243–258
145. Laopaiboon P, Thani A, Leelavatcharamas V et al (2010) Acid hydrolysis of sugarcane bagasse for lactic acid production. Biores Technol 101:1036–1043. https://doi.org/10.1016/j.biortech.2009.08.091
146. Poopathi S, Mani C, Rajeswari G (2013) Potential of sugarcane bagasse (agro-industrial waste) for the production of Bacillus thuringiensis israelensis. Trop Biomed 30:504–515
147. Inyang M, Gao B, Pullammanappallil P et al (2010) Biochar from anaerobically digested sugarcane bagasse. Biores Technol 101:8868–8872. https://doi.org/10.1016/j.biortech.2010.06.088
148. Vaz de Arruda P, dos Santos JC, de Cássia Lacerda Brambilla Rodrigues R et al (2017) Scale up of xylitol production from sugarcane bagasse hemicellulosic hydrolysate by Candida guilliermondii FTI 20037. J Ind Eng Chem 47:297–302. https://doi.org/10.1016/j.jiec.2016.11.046
149. Nigam P (1990) Investigation of some factors important for solid-state fermentation of sugar cane bagasse for animal feed production. Enzyme Microb Technol 12:808–811. https://doi.org/10.1016/0141-0229(90)90156-K
150. Cerda A, Artola A, Barrena R et al (2019) Innovative Production of Bioproducts From Organic Waste Through Solid-State Fermentation. Front Sustain Food Syst 3:1–6. https://doi.org/10.3389/fsufs.2019.00063
151. Buenrostro-Figueroa J, Ascacio-Valdés A, Sepúlveda L et al (2014) Potential use of different agroindustrial by-products as supports for fungal ellagitannase production under solid-state fermentation. Food Bioprod Process 92:376–382. https://doi.org/10.1016/j.fbp.2013.08.010
152. Karp SG Faraco V Amore A et al. (2015) Statistical optimization of laccase production and delignification of sugarcane bagasse by Pleurotus ostreatus in solid-state fermentation. BioMed Research International 2015. https://doi.org/10.1155/2015/181204
153. Salomão GSB, Agnezi JC, Paulino LB et al (2019) Production of cellulases by solid state fermentation using natural and pretreated sugarcane bagasse with different fungi. Biocatal Agric Biotechnol 17:1–6. https://doi.org/10.1016/j.bcab.2018.10.019
154. Jain L, Kurmi AK, Agrawal D (2021) Conclusive selection of optimal parameters for cellulase production by Talaromyces verruculosus IIPC 324 under SSF via saccharification of acid-pretreated sugarcane bagasse. Biofuels 12:61–69. https://doi.org/10.1080/17597269.2018.1449063
155. dos Reis L, Bianchi C, Masutti MA, Carús Guedes JV et al (2018) Production of Chitinase from Metarhizium anisopliae by Solid-State Fermentation Using Sugarcane Bagasse as Substrate. Ind Biotechnol 14:230–234. https://doi.org/10.1089/ind.2017.0031
156. Soares D, Serres JDdS, Corazza ML et al (2015) Analysis of multiphasic behavior during the ethyl esterification of fatty acids catalyzed by a fermented solid with lipolytic activity in a packed-bed bioreactor in a closed-loop batch system. Fuel 159:364–372. https://doi.org/10.1016/j.fuel.2015.06.087
157. Yadegary M Hamidi A Alavi SA et al. (2013) Citric Acid Production from Sugarcane Bagasse through Solid State Fermentation Method Using Aspergillus niger Mold and Optimization of Citric Acid Production by Taguchi Method. Jundishapur J Microbiol 6. https://doi.org/10.5812/jjm.7625
158. Muso Cachumba JJ, Terán Hilares R, Brumano LP et al (2019) Extracellular L-asparaginase production in solid-state fermentation by using sugarcane bagasse as support material. Prep Biochem Biotechnol 49:328–333. https://doi.org/10.1080/10826068.2019.1566152
159. Liu J, Chen S, Ding J et al (2015) Sugarcane bagasse as support for immobilization of Bacillus pumilus HZ-2 and its use in bioremediation of mesotrione-contaminated soils. Appl Microbiol Biotechnol 99:10839–10851. https://doi.org/10.1007/s00253-015-6935-0
160. John RP, Nampoothiri KM, Pandey A (2006) Solid-state fermentation for l-lactic acid production from agro wastes using Lactobacillus delbrueckii. Process Biochem 41:759–763. https://doi.org/10.1016/j.procbio.2005.09.013
161. López-Ortega MG, Guadalajara Y, Junqueira TL et al (2021) Sustainability analysis of bioethanol production in Mexico by a retrofitted sugarcane industry based on the Brazilian expertise. Energy 232:121056. https://doi.org/10.1016/j.energy.2021.121056

162. Silalertruksa T, Pongpat P, Gheewala SH (2017) Life cycle assessment for enhancing environmental sustainability of sugarcane biorefinery in Thailand. J Clean Prod 140:906–913. https://doi.org/10.1016/j.jclepro.2016.06.010
163 Mandegari MA, Farzad S, Görgens JF (2017) Recent trends on techno-economic assessment (TEA) of sugarcane biorefineries. Biofuel Res J 4:704–712. https://doi.org/10.18331/BRJ2017.4.3.7
164. Moncada J, El-Halwagi MM, Cardona CA (2013) Techno-economic analysis for a sugarcane biorefinery: Colombian case. Biores Technol 135:533–543. https://doi.org/10.1016/j.biortech.2012.08.137
165. (2016) Ministerio de Agricultura y Ganadería de la República de Costa Rica., 2016. Cultivo de Cafe. Resultados del IV Censo nacional agropecuario
166. (2018) Food and Agriculture Organization of the United Nations: Banana facts and figures
167. Ferdous T Quaiyyum MA Jin Y et al. (2021) Pulping and bleaching potential of banana pseudo stem, banana leaf and banana peduncle. Biomass Conv Bioref. https://doi.org/10.1007/s13399-020-01219-6
168. Toh PY Leong FS Chang SK et al. (2016) Optimization of extraction parameters on the antioxidant properties of banana waste. Acta Scientiarum Polonorum, Technologia Alimentaria. https://doi.org/10.17306/J.AFS.2016.1.7
169. Babatunde GM (1991) Availability of banana and plantain products for animal feeding. In: Roots, tubers, plantains and bananas in animal feeding - Proceedings of the FAO Expert Consultation, Colombia
170. Cordeiro N, Belgacem MN, Torres IC et al (2004) Chemical composition and pulping of banana pseudo-stems. Ind Crops Prod 19:147–154. https://doi.org/10.1016/j.indcrop.2003.09.001
171. Anirudhan TS, Noeline BF, Manohar DM (2006) Phosphate removal from wastewaters using a weak anion exchanger prepared from a lignocellulosic residue. Environ Sci Technol 40:2740–2745. https://doi.org/10.1021/es052070h
172. Neravathu Sivan R, Harikumaran Thampi BS (2021) Extraction, rheological and textural analyses and grading of pectin from stem pith of banana. Ukr food j 10:124–135. https://doi.org/10.24263/2304-974X-2021-10-1-11
173. Shukla RN (1972) Enzymes of the Banana Plant 11
174. Wohlt D Schwarz E Schieber A et al. (2021) Effects of Extraction Conditions on Banana Peel Polyphenol Oxidase Activity and Insights into Inactivation Kinetics Using Thermal and Cold Plasma Treatment. Foods 10. 10.3390/foods10051022
175. Agama-Acevedo E, Sañudo-Barajas JA, Vélez De La Rocha R et al (2016) Potential of plantain peels flour (Musa paradisiaca L.) as a source of dietary fiber and antioxidant compound. Cyta - J Food 14:117–123. https://doi.org/10.1080/19476337.2015.1055306
176. Yan L, Fernando WMADB, Brennan M et al (2016) Effect of extraction method and ripening stage on banana peel pigments. Int J Food Sci Technol 51:1449–1456. https://doi.org/10.1111/ijfs.13115
177. Aboul-enein AM Salama ZA Gaafar AA et al. (2016) Research Article Identification of phenolic compounds from banana peel (Musa paradaisica L .) as antioxidant and antimicrobial agents. Journal of Chemical and Pharmaceutical Research
178. Anhwange BA (2008) Chemical composition of Musa sapientum (banana) peels. J Food Technol 6:263–266
179. Khamsucharit P, Laohaphatanalert K, Gavinlertvatana P et al (2018) Characterization of pectin extracted from banana peels of different varieties. Food Sci Biotechnol 27:623–629. https://doi.org/10.1007/s10068-017-0302-0
180. Subagio A, Morita N, Sawada S (1996) Carotenoids and Their Fatty Acid Esters in Banana Peel. J Nutr Sci Vitaminol 42:553–566
181. Knapp FF, Nicholas HJ (1969) The Sterols and Triterpenes of Banana Pulp. J Food Sci 34:584–586. https://doi.org/10.1111/j.1365-2621.1969.tb12095.x
182. Kayisu K, Hood LF, Vansoest PJ (1981) Characterization of Starch and Fiber of Banana Fruit. J Food Sci 46:1885–1890
183. Wills RBH, Lim JSK, Greenfield H (1984) Changes in chemical composition in 'Cavendish' banana (Musa acuminata) during ripening.pdf. J Food Biochem 8:69–77
184. Prabha TN, Bhagylakshmi N (1991) CARBOHYDRATE METABOLISM IN RIPENING BANANA FRUIT. Phytochemistry 48:915–919
185. Kanazawa K, Sakakibara H (2000) High content of dopamine, a strong antioxidant, in cavendish banana. J Agric Food Chem 48:844–848. https://doi.org/10.1021/jf9909860
186. Ohla S, Schulze P, Fritzsche S et al (2011) Chip electrophoresis of active banana ingredients with label-free detection utilizing deep UV native fluorescence and mass spectrometry. Anal Bioanal Chem 399:1853–1857. https://doi.org/10.1007/s00216-010-4557-z
187. Passo Tsamo CV, Herent MF, Tomekpe K et al (2015) Phenolic profiling in the pulp and peel of nine plantain cultivars (Musa sp.). Food Chem 167:197–204. https://doi.org/10.1016/j.foodchem.2014.06.095
188. Someya S, Yoshiki Y, Okubo K (2002) Antioxidant compounds from bananas (Musa Cavendish). Food Chem 79:351–354. https://doi.org/10.1016/S0308-8146(02)00186-3
189. Chinchilla OC (2013) Proyecto "Uso de los Residuos Agrícolas Orgánicos como Fuente de Energía: Aprovechamiento de Recursos y Reducción de Gases de Efecto Invernadero en Costa Rica", Informe de Consultoría Producto 2: Prácticas Actuales de Tratamiento y Disposición de los Resi, San José, Costa Rica
190. Phirke NV, Patil RP, Chincholkar SB et al (2001) Recycling of banana pseudostem waste for economical production of quality banana. Resour Conserv Recycl 31:347–353. https://doi.org/10.1016/S0921-3449(00)00092-6
191. Dahl CF (1884) PROCESS OF MANUFACTURING CELLULOSE FROM WOOD(Patent No. 296,935)
192. Gabhane J, Prince William SPM, Gadhe A et al (2014) Pretreatment of banana agricultural waste for bio-ethanol production: Individual and interactive effects of acid and alkali pretreatments with autoclaving, microwave heating and ultrasonication. Waste Manage 34:498–503. https://doi.org/10.1016/j.wasman.2013.10.013
193. Guerrero AB, Ballesteros I, Ballesteros M (2017) Optimal conditions of acid-catalysed steam explosion pretreatment of banana lignocellulosic biomass for fermentable sugar production. J Chem Technol Biotechnol 92:2351–2359. https://doi.org/10.1002/jctb.5239
194. Ingale S, Joshi SJ, Gupte A (2014) Production of bioethanol using agricultural waste: Banana pseudo stem. Braz J Microbiol 45:885–892. https://doi.org/10.1590/S1517-83822014000300018
195. Putra AEE Amaliyah N Nomura S et al. (2020) Plasma generation for hydrogen production from banana waste. Biomass Conv Bioref. https://doi.org/10.1007/s13399-020-00765-3
196. Idrees M, Adnan A, Malik F et al (2013) Enzymatic saccharification and lactic acid production from banana pseudo-stem through optimized pretreatment at lowest catalyst concentration. Excli J 12:269–281
197. Ramírez-Bolaños S Pérez-Jiménez J Díaz S et al. (2021) A potential of banana flower and pseudo-stem as novel ingredients rich in phenolic compounds. Int J Food Sci Technol. https://doi.org/10.1111/ijfs.15072

198. Samad KA Zainol N (2016) Release of Ferulic Acid from Banana Stem Waste by Ferulic Acid Esterase from Co-culture:819–823
199. Sharif NS, Mohd A, Thor ES, Zainol N et al (2017) Optimization of Ferulic Acid Production from Banana Stem Waste Using Central Composite Design. Environ Prog Sustain Energy 36:1217–1223. 10.1002/ep
200. Shin H-D, McClendon S, Le T et al (2006) A Complete Enzymatic Recovery of Ferulic Acid From Corn Residues With Extracellular Enzymes From Neosartorya spinosa NRRL185. Biotechnol Bioeng 95:1108–1115. https://doi.org/10.1002/bit
201. Sharma M, Patel SN, Sangwan RS et al (2017) Biotransformation of banana pseudostem extract into a functional juice containing value added biomolecules of potential health benefits. Indian J Exp Biol 55:453–462
202. Ramu R, Shirahatti PS, Zameer F et al (2015) Investigation of antihyperglycaemic activity of banana (Musa sp. var. Nanjangud rasa bale) pseudostem in normal and diabetic rats. J Sci Food Agric 95:165–173. https://doi.org/10.1002/jsfa.6698
203. Sheng Z, Shen Y, Dai H et al (2018) Physicochemical characterization of raw and modified banana pseudostem fibers and their adsorption capacities for heavy metal Pb2+and Cd2+in water. Polym Compos 39:1869–1877. https://doi.org/10.1002/pc.24140
204. Vishnu Vardhini KJ, Murugan R, Surjit R (2018) Effect of alkali and enzymatic treatments of banana fibre on properties of banana/polypropylene composites. J Ind Text 47:1849–1864. https://doi.org/10.1177/1528083717714479
205. Faradilla RHF, Lee G, Roberts J et al (2018) Effect of glycerol, nanoclay and graphene oxide on physicochemical properties of biodegradable nanocellulose plastic sourced from banana pseudo-stem. Cellulose 25:399–416. https://doi.org/10.1007/s10570-017-1537-x
206. Ramesh M, Sri Ananda Atreya T, Aswin US et al (2014) Processing and mechanical property evaluation of banana fiber reinforced polymer composites. Procedia Eng 97:563–572. https://doi.org/10.1016/j.proeng.2014.12.284
207. Mumthas ACSI, Wickramasinghe GLD, Gunasekera USW (2019) Effect of physical, chemical and biological extraction methods on the physical behaviour of banana pseudo-stem fibres: Based on fibres extracted from five common Sri Lankan cultivars. J Eng Fibers Fabr 14:155892501986569. https://doi.org/10.1177/1558925019865697
208. Velumani A, Kandhavadivu P, Parthiban M (2021) Influence of blend proportion on mechanical properties of banana/cotton blended knit fabric. Indian J Fibre Text Res 46:41–47
209. Gebregergs A, Gebresemati M, Sahu O (2016) Industrial ethanol from banana peels for developing countries: Response surface methodology. Pac Sci Rev Nat Sci Eng 18:22–29. https://doi.org/10.1016/j.psra.2016.06.002
210. Choi IS, Lee YG, Khanal SK et al (2015) A low-energy, cost-effective approach to fruit and citrus peel waste processing for bioethanol production. Appl Energy 140:65–74. https://doi.org/10.1016/j.apenergy.2014.11.070
211. Shah SP, Kalia KS, Patel JS (2015) Optimization of cellulase production by Penicillium oxalicum using banana agrowaste as a substrate. J Gen Appl Microbiol 61:35–43. https://doi.org/10.2323/jgam.61.35
212. Krishna C, Chandrasekaran M (1996) Banana waste as substrate for ??-amylase production by Bacillus subtilis (CBTK 106) under solid-state fermentation. Appl Microbiol Biotechnol 46:106–111. https://doi.org/10.1007/s002530050790
213. Zehra M, Syed MN, Sohail M (2020) Banana Peels: A Promising Substrate for the Coproduction of Pectinase and Xylanase from Aspergillus fumigatus MS16. Pol J Microbiol 69:19–26. https://doi.org/10.33073/pjm-2020-002
214. Swamy GJ, Muthukumarappan K (2017) Optimization of continuous and intermittent microwave extraction of pectin from banana peels. Food Chem 220:108–114. https://doi.org/10.1016/j.foodchem.2016.09.197
215. Nurhayati N, Maryanto M, Tafrikhah R (2016) Ekstraksi Pektin dari Kulit dan Tandan Pisang dengan Variasi Suhu dan Metode (Pectin Extraction from Banana Peels and Bunch with Various Temperatures and Methods). Agritech 36:327. https://doi.org/10.22146/agritech.16605
216. Oliveira TÍS, Rosa MF, Ridout MJ et al (2017) Bionanocomposite films based on polysaccharides from banana peels. Int J Biol Macromol 101:1–8. https://doi.org/10.1016/j.ijbiomac.2017.03.068
217. Lee EH, Yeom HJ, Ha MS et al (2010) Development of banana peel jelly and its antioxidant and textural properties. Food Sci Biotechnol 19:449–455. https://doi.org/10.1007/s10068-010-0063-5
218. Gomes Rebello LP, Mota Ramos A, Becker Pertuzatti P et al (2014) Flour of banana (Musa AAA) peel as a source of antioxidant phenolic compounds. Food Res Int 55:397–403. https://doi.org/10.1016/j.foodres.2013.11.039
219. Eshak NS (2016) Sensory evaluation and nutritional value of balady flat bread supplemented with banana peels as a natural source of dietary fiber. Ann Agric Sci 61:229–235. https://doi.org/10.1016/j.aoas.2016.07.002
220. Kurhade A, Patil S, Sonawane SK et al (2016) Effect of banana peel powder on bioactive constituents and microstructural quality of chapatti: unleavened Indian flat bread. J Food Meas Charact 10:32–41. https://doi.org/10.1007/s11694-015-9273-0
221. Segundo C, Román L, Gómez M et al (2017) Mechanically fractionated flour isolated from green bananas (M. cavendishii var. nanica) as a tool to increase the dietary fiber and phytochemical bioactivity of layer and sponge cakes. Food Chem 219:240–248. https://doi.org/10.1016/j.foodchem.2016.09.143
222. González-Montelongo R, Gloria Lobo M, González M (2010) Antioxidant activity in banana peel extracts: Testing extraction conditions and related bioactive compounds. Food Chem 119:1030–1039. https://doi.org/10.1016/j.foodchem.2009.08.012
223. Hernández-Carranza P, Ávila-Sosa R, Guerrero-Beltrán JA et al (2016) Optimization of Antioxidant Compounds Extraction from Fruit By-Products: Apple Pomace, Orange and Banana Peel. J Food Process Preserv 40:103–115. https://doi.org/10.1111/jfpp.12588
224. Valérie Passo Tsamo C, Andre CM, Ritter C et al (2014) Characterization of Musa sp. fruits and plantain banana ripening stages according to their physicochemical attributes. J Agric Food Chem 62:8705–8715. https://doi.org/10.1021/jf5021939
225. Maduwanthi SDT, Marapana RAUJ (2021) Total phenolics, flavonoids and antioxidant activity following simulated gastrointestinal digestion and dialysis of banana (Musa acuminata, AAB) as affected by induced ripening agents. Food Chem 339:127909. https://doi.org/10.1016/j.foodchem.2020.127909
226. Luliński P, MacIejewska D (2012) Effective separation of dopamine from bananas on 2-(3,4-dimethoxyphenyl) ethylamine imprinted polymer. J Sep Sci 35:1050–1057. https://doi.org/10.1002/jssc.201100910
227. Ortiz L, Dorta E, Gloria Lobo M et al (2017) Use of Banana (Musa acuminata Colla AAA) Peel Extract as an Antioxidant Source in Orange Juices. Plant Foods Hum Nutr 72:60–66. https://doi.org/10.1007/s11130-016-0591-0
228. Devatkal SK, Kumboj R, Paul D (2014) Comparative antioxidant effect of BHT and water extracts of banana and sapodilla peels in raw poultry meat. J Food Sci Technol 51:387–391. https://doi.org/10.1007/s13197-011-0508-8
229. Mordi RC, Fadiaro AE, Owoeye TF et al (2016) Identification by GC-MS of the Components of Oils of Banana Peels Extract,

Phytochemical and Antimicrobial Analyses. Res J Phytochem 10:39–44. https://doi.org/10.3923/rjphyto.2016.39.44

230. Rattanavichai W, Cheng W (2015) Dietary supplement of banana (Musa acuminata) peels hot-water extract to enhance the growth, anti-hypothermal stress, immunity and disease resistance of the giant freshwater prawn, Macrobrachium rosenbergii. Fish Shellfish Immunol 43:415–426. https://doi.org/10.1016/j.fsi.2015.01.011
231. Navghare VV, Dhawale SC (2017) In vitro antioxidant, hypoglycemic and oral glucose tolerance test of banana peels. Alexandria J Med 53:237–243. https://doi.org/10.1016/j.ajme.2016.05.003
232. Majid MSA, Amin SDI, Dahham SS, Agha MT et al (2015) Antioxidant Activities and Anticancer Screening of Extracts from Banana Fruit (Musa sapientum). Acad J Cancer Res 8:28–34. https://doi.org/10.5829/idosi.ajcr.2015.8.2.95162
233. Ibrahim HMM (2015) Green synthesis and characterization of silver nanoparticles using banana peel extract and their antimicrobial activity against representative microorganisms. J Rad Res Appl Sci 8:265–275. https://doi.org/10.1016/j.jrras.2015.01.007
234. Kokila T, Ramesh PS, Geetha D (2015) Biosynthesis of silver nanoparticles from Cavendish banana peel extract and its antibacterial and free radical scavenging assay: a novel biological approach. Appl Nanosci 5:911–920. https://doi.org/10.1007/s13204-015-0401-2
235. Vijayakumar S, Vaseeharan B, Malaikozhundan B et al (2017) Therapeutic effects of gold nanoparticles synthesized using Musa paradisiaca peel extract against multiple antibiotic resistant Enterococcus faecalis biofilms and human lung cancer cells (A549). Microb Pathog 102:173–183. https://doi.org/10.1016/j.micpath.2016.11.029
236. Pelissari FM, Andrade-Mahecha MM, Sobral PJ, Amaral Do et al (2017) Nanocomposites based on banana starch reinforced with cellulose nanofibers isolated from banana peels. J Colloid Interface Sci 505:154–167. https://doi.org/10.1016/j.jcis.2017.05.106
237. Zhang Y, Gao Z, Song N et al (2016) High-performance supercapacitors and batteries derived from activated banana-peel with porous structures. Electrochim Acta 222:1257–1266. https://doi.org/10.1016/j.electacta.2016.11.099
238. Ali A, Saeed K, Mabood F (2016) Removal of chromium (VI) from aqueous medium using chemically modified banana peels as efficient low-cost adsorbent. Alex Eng J 55:2933–2942. https://doi.org/10.1016/j.aej.2016.05.011
239. Oyewo OA, Onyango MS, Wolkersdorfer C (2016) Application of banana peels nanosorbent for the removal of radioactive minerals from real mine water. J Environ Radioact 164:369–376. https://doi.org/10.1016/j.jenvrad.2016.08.014
240. Alaa El-Din G, Amer AA, Malsh G et al (2017) Study on the use of banana peels for oil spill removal. Alex Eng J 57:2061–2068. https://doi.org/10.1016/j.aej.2017.05.020
241. Getachew T, Hussen A, Rao VM (2015) Defluoridation of water by activated carbon prepared from banana (Musa paradisiaca) peel and coffee (Coffea arabica) husk. Int J Environ Sci Technol 12:1857–1866. https://doi.org/10.1007/s13762-014-0545-8
242. Hernández-Borges J, Cabrera JC, Rodríguez-Delgado MÁ et al (2009) Analysis of pesticide residues in bananas harvested in the Canary Islands (Spain). Food Chem 113:313–319. https://doi.org/10.1016/j.foodchem.2008.07.042
243. Martínez-Ruano JA, Caballero-Galván AS, Restrepo-Serna DL et al (2018) Techno-economic and environmental assessment of biogas production from banana peel (Musa paradisiaca) in a biorefinery concept. Environ Sci Pollut Res Int 25:35971–35980. https://doi.org/10.1007/s11356-018-1848-y
244. Alzate Acevedo S Díaz Carrillo ÁJ Flórez-López E et al. (2021) Recovery of Banana Waste-Loss from Production and Processing: A Contribution to a Circular Economy. Molecules 26. https://doi.org/10.3390/molecules26175282