

Review

Integration of Emerging and Conventional Technologies for Obtaining By-Products from Cocoa Pod Husk and Their Application

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Abstract: This review discusses the potential of emerging technologies, as well as their integration with conventional methods, to optimize the extraction of lignocellulosic compounds from cocoa pod hull (CPH), an agro-industrial residue that represents approximately 76% of the total weight of the fruit. CPH is primarily composed of cellulose, hemicellulose, lignin, and pectin. Emerging technologies such as microwave-assisted extraction, hydrothermal treatment, subcritical water, ionic liquids, deep eutectic solvents, and ultrasound treatment have proven effective in recovering value-added compounds, especially when combined with conventional techniques to improve process efficiency. Furthermore, the use of technologies such as high-voltage electric discharge (HVED) is proposed to reduce inorganic contaminants, such as cadmium, ensuring the safety of by-products. The CPH compounds' applications include use in the food, pharmaceutical, cosmetics, agricultural, biopolymer, and environmental industries. The conversion of CPH to biochar and biofuels via pyrolysis and supercritical extraction is also discussed. The integration of technologies presents an opportunity to valorize CPH and optimize by-product development; however, as research continues, process scalability and economic viability must be assessed.

Keywords: cocoa; emerging technology; hydrothermal treatment; lignocellulosic biomass; biomass treatment



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1. Introduction

Cocoa is a fruit widely used in the food industry, primarily known for its use in chocolate production. Like other fruits used in the food industry, cocoa generates waste, such as cocoa pod husks, which account for 76% of the fruit [1–3]. Figure 1 gives an estimation of the total production of cocoa husks generated in the Ivory Coast, which is the country with the highest cocoa production worldwide. Figure 1 illustrates the vast number of cocoa husks available, highlighting the need to find a purpose for this residue to prevent it from becoming a problem [4].

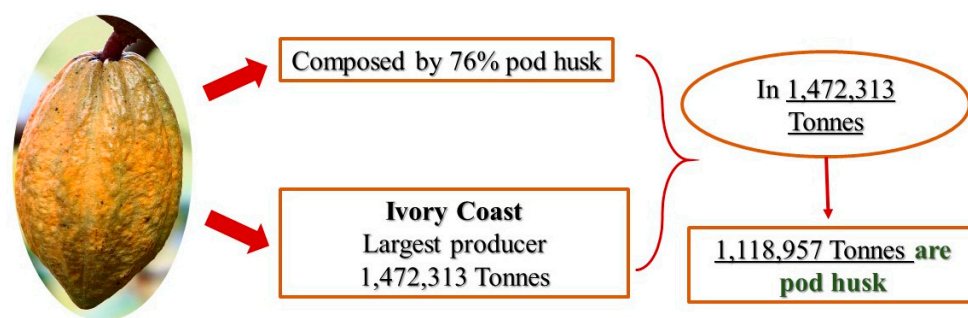


Figure 1. Relationship between the quantity of cocoa produced in the Ivory Coast and comparison with the amount of cocoa husk waste.

Despite being considered waste, cocoa pod husk (CPH) contains various constituents with diverse applications, including antioxidant compounds, minerals (sodium, calcium, zinc, iron, and copper), pectin, dietary fiber, and proteins [4]. Additionally, its lignocellulosic components (cellulose, hemicellulose, and lignin) can be utilized to produce biomaterials and renewable energy [5]. However, chemical processes are required to separate CPH compounds for industrial use [6,7]. Chemical and enzymatic pretreatments can be used [8], followed by a fermentation process [9], to obtain these constituents and then use them to produce products such as fuels, chemicals, and biodegradable materials.

Emerging technologies such as microwave-assisted extraction, hydrothermal treatment, subcritical water, ionic liquids, deep eutectic solvents, and ultrasonic treatment have proven effective in extracting structural polymers from CPH. In addition, combined methodologies optimize pretreatment, improving extraction efficiency and ensuring compliant by-products [10].

However, effective valorization requires not only efficient extraction but also ensuring the safety and compliance of the resulting products. To extract CPH compounds safely, technologies must first reduce cadmium levels in the raw material due to its toxicity [11]. Cadmium is one of the heavy metals that pose the greatest risks to human health [12] and can be found in soil and food, with several studies indicating high concentrations of it in food, including cocoa [13]. Subsequently, pretreatments isolate target molecules [14] for integration into final products [15]. Pretreatments vary from conventional (acid/base solvents) to innovative methods that enhance yield while minimizing environmental impact [9].

This review analyzes the integration of emerging and conventional technologies, specifically, applied to the case of CPH, as an efficient approach for optimizing structural compounds extraction. The objectives are to (i) explore the technologies applied to the extraction of lignocellulosic compounds from CPH, considering conventional and emerging methods; (ii) identify how the synergistic integration of these technologies can improve efficiency and optimize the extraction of lignocellulosic compounds; and (iii) evaluate the potential of the technologies applied for obtaining by-products and their application in various industrial sectors.

2. Cocoa Pod Husk Compounds

CPH is composed primarily of structural polysaccharides found in the plant cell wall. These compounds are mainly cellulose (24–35%), hemicellulose (8.7–11%), lignin (14.6–23.38%), and pectin (6.1–9.2%) [14,16]. These structural compounds represent the most important fraction from a biotechnological perspective, enabling the production of by-products [15]. Figure 2 shows the structural components of the cell walls of CPH plants.

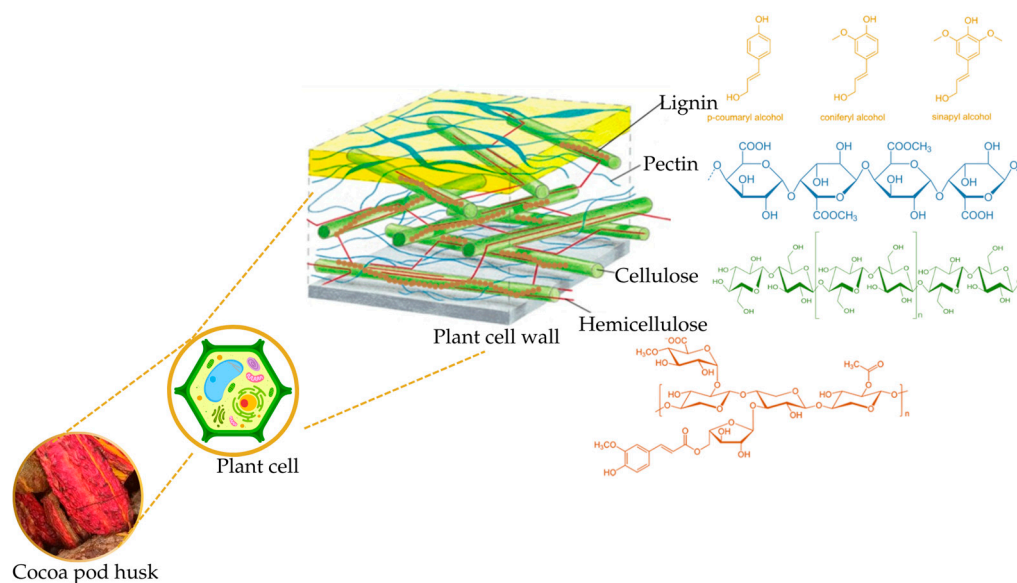


Figure 2. Lignocellulosic compounds located in the cell wall of CPH plant cells.

2.1. Cellulose

Cellulose is an unbranched biopolymer found in the cell wall of plants, consisting of glucose molecules linked by a β -1,4-glycosidic linkage [17,18]. These molecules form a linear homopolymer of high molecular weight, meaning that several cellulose molecules can be joined together by hydrogen bonds, forming an extremely strong network [19,20]. It exhibits high mechanical strength, durability, and thermal stability [1]; biocompatibility and biodegradability [21]; and low abrasiveness and wide availability [22]. Cellulose has hygroscopic properties due to the presence of hydroxyl groups in its molecular structure with a tendency to form hydrogen bonds with water; thus, cellulose-based materials have a greater capacity to absorb water than other materials [23]. However, cellulose is not soluble in water because of interactions between intermolecular hydrogen bonds, making it difficult to dissolve in water. [24]. It also possesses a significant degree of polymerization based on glucose units between 10,000 units [25] and 15,000 units [23], but its derivatives are soluble in water due to additional functional groups, such as carboxyls, which interact with water differently from pure cellulose [24].

Cellulose fibers are characterized by their low density, low cost [23], and high crystallinity (42.84%), characteristics that allow them to replace synthetic fibers and be used as reinforcement in synthetic matrices [22]. Moreover, cellulose exhibits low density (1.58–1.59 g/cm³), high specific stiffness, and enhanced thermal stability. On the other hand, cellulose microfibrils exhibit low water absorption and can be used to form strong but lightweight composite materials [22].

Synthetic derivatives such as methylcellulose, carboxymethylcellulose, hydroxypropylmethylcellulose, and hydroxypropyl cellulose can be obtained from cellulose and can be obtained from agricultural waste [21], such as CPH, which would reduce the environmental impact and work under a circular economy approach [22].

2.2. Hemicellulose

Hemicellulose is a heterogeneous carbohydrate. Its molecular chain is composed of pyranose and furanose sugar units, including d-xylose, d-mannose, d-glucose, d-galactosyl, l-arabinose, galacturonic acid, and glucuronic acid, and the structures are different depending on the raw material; also, different extraction methods allow different types and contents of side chains to be obtained [26]. Hemicellulose is an amorphous polymer that contributes to the stability and flexibility of plant fibers because it is strongly bound to

cellulose [27]. This polysaccharide is characterized by a polymerization degree typically ranging from 100 to 200 U; other properties are associated with biodegradability and biocompatibility, although they are thermally unstable [28]. Hemicelluloses include xylans, mannans, xyloglucans, and β -glucans of mixed bonds [29,30].

Xylans are abundant in agricultural residues, such as CPH [9]. This derives a by-product with hydrophobicity characteristics, thermal conformability, and film-forming ability, allowing for its application as a material to make packaging [31]. Xylans are composed of xylose linked by β -(1,4)-bonds and other molecules, such as arabinose [32], glucuronic acid, and glucose; and small groups, such as acetyl, phenolic, ferulic, and coumaric acids [29]. Xylans are the main form of hemicellulose in biomass and are associated with the structure and composition of the secondary cell wall, playing an important role in the biomass's resistance to decomposition processes [33].

Arabinose is a monosaccharide that belongs to the pentose group, a class of sugars containing five carbon atoms [34]. It is a key component of hemicelluloses, particularly in plant cell walls, where it is linked to other sugars, like xylose, to form polymers. It can also form branched structures when bonded with other sugars, such as arabinogalactan, and is found in some fruits, vegetables, and grains [35].

Hemicellulose can be extracted using different types of pretreatments employing organic solvents and emerging technologies. These pretreatments separate the hemicellulose molecule by breaking glycosidic bonds [36]. There are emerging technologies, such as microwaves, ultrasonic treatment, subcritical and supercritical solvents, and deep eutectic solvent-based pretreatment, that are used to optimize the extraction of hemicellulose [8,37]. After that, hydrolysis processes are used to obtain xylooligosaccharides, which can be used as probiotics [38] or as an active ingredient in packaging [39].

2.3. Lignin

Lignin is an aromatic, amorphous molecule composed of three monomeric units by phenylpropane units [40], through chemical bonds of alkyl-alkyl, alkyl-aryl, and aryl-aryl groups. The precursors of lignin synthesis in nature include coniferyl, sinapyl, and p-coumaryl alcohols [41]. There are five main types of linkages in lignin: β -O-4 ether, β -5 phenylcoumaran, β - β' pinosresinol, diphenyl ether 4-O5', and β -1' diphenyl methane. These covalent carbon-carbon bonds are strong and confer rigidity, making solubility in water difficult [42].

The structural units of lignin are p-hydroxyphenyl (H), syringyl (S), and guaiacyl (G), and the distribution of compositional fraction structural units vary depending on the raw material [42]. Cocoa, being of the dicotyledonous group, has a lignin with a higher number of G and S units, while H units are found in a minimum proportion [43]. Lignin with a higher content of G and S units has highly stable condensed substructures, which are partially responsible for the higher thermal stability. In addition, they have lower glass transition temperatures and provide flexibility and malleability, allowing for their application as an additive in packaging, as well as for the production of impact-resistant and more durable materials [44].

Lignin is the molecule found in the outermost part of the lignocellulosic material, so the removal of lignin becomes the first step in any lignocellulosic material separation process [45]. Lignin extraction methods from biomass are divided into chemical and mechanical [46]. Chemical extraction is influenced by solvents such as ethanol, acetic acid, and formic acid, which improve purity and extraction rate. Although 95% ethanol is effective, high concentrations affect the β -O-4 bonds, while the acids break the ether bonds. Dioxane is also effective, but its use is limited due to the formation of hazardous peroxides, which are avoided by adding water and hydrochloric acid [41]. On the other hand, mechanical

lignin extraction methods include refining and grinding, which depend on conditions such as pressure, temperature, and speed. Disc refiners affect energy consumption and pulp quality, and in the grinding process, speed and energy regulation are important factors [46].

2.4. Pectin

Pectin is a macromolecule composed of different amounts of monosaccharide through varieties of bonds, including D-galactose, L-rhamnose, and L-arabinose; it is considered a molecule with a diversity of forms [47]. The primary structure of pectin consists of galacturonic acid and rhamnose monomers [48]. These basic units combine to form the following polysaccharides: homogalacturonan (HG), rhamnogalacturonans type I (RG-I), and rhamnogalacturonans type II (RG-II), which together form pectin [49]. Pectin is classified according to the degree of esterification (DE) as high methoxyl pectin (HMP, $DE \geq 50\%$) and low methoxyl pectin (LMP, $DE < 50\%$) [50]. HM pectins gel under low pH conditions (2.5–3.5) and in the presence of soluble solids or co-solutes, they are water soluble and thermally reversible, while LM pectins in the presence of divalent cations, such as calcium (Ca^{2+}), regardless of sugar content, and are more stable than HM pectins when subjected to high temperatures [51].

Pectin is extracted with acid solvents; however, the use of mineral acids such as sulfuric, hydrochloric, and nitric acid should be avoided because they generate corrosive effluents and negative health effects and deteriorate the quality of the polymer [52]. The extraction of pectin is carried out using acetic, malic, tartaric, or citric acid. The latter not only produces a higher amount of methoxy groups (Table 1); it also improves its viscosity and increases the yield of the process [53].

Mineral acids such as HCl, H_2SO_4 , and HNO_3 have a more pronounced effect on reducing the degree of esterification (DE) of pectin due to their higher acidity, causing more intense de-esterification (Table 1), especially at higher concentrations (0.1 M and 1.0 M). In comparison, organic acids (such as acetic, citric, and tartaric acids) produce a higher and more stable DE, as their larger and less strong molecular structure allows for a less aggressive de-esterification [54].

Table 1. Degree of esterification of CPH pectins at different pH values and with different extraction methods.

Extraction Methods	pH	DE (%)	References
Acid hydrolysis with citric acid	2.0	83.99	[55]
	2.5	69.25	[55]
	3.0	48.84	[55]
	3.71	52.20	[9]
	3.0	40.3	[56]
Acid hydrolysis with acetic acid	2.0	15.26	[55]
	2.5	18.43	[55]
	3.0	20.22	[55]
Alkaline extraction	12.0	40.1	[57]
Enzymatic extraction	5.0	48.5	[57]
Hot aqueous extraction	6.7	26.8	[58]

3. Conventional Technology for Obtaining By-Products from the Cocoa Pod Husk

Traditional pretreatments involving acidic and alkaline reagents have been commonly used [59]. Conventional pretreatments with acid and alkaline reagents generate high oper-

ating costs, cause equipment corrosion, and generate toxic effluents [60]. However, they can be used as a complement to emerging technologies to improve the extraction of lignocellulosic compounds [61]. On the other hand, traditional techniques, such as aerobic and anaerobic fermentation, have also been used to obtain by-products [62,63].

3.1. Acidic Treatment

Acidic treatment is considered an effective chemical pretreatment aimed at breaking down lignocellulosic material by breaking glucose bonds [64]. This technique uses acids like nitric, hydrochloric, or sulfuric acids in the process. However, caution must be practiced with this type of pretreatment, as high acid concentrations can lead to the destruction of polymer sugars, causing the release of toxic compounds, such as furfural and organic acids [65]. Acidic treatment is also widely used for obtaining pectin, xylitol, biohydrogen [66], and biobutanol from CPH [14]. The acid pretreatment was used in the process of obtaining biobutanol from cocoa husks. Sulfuric acid was employed, and an induction heating technique was adopted, concluding the treatment's efficiency in releasing sugars before the fermentation process [14].

Acidic treatment technique offers the advantage of hemicellulose hydrolysis and inhibitor production. Some disadvantages are seen, such as high equipment and acid costs involved in the process. Among conventional pretreatments, it is considered the most applied in biomass substrates [65].

3.2. Alkaline Treatment

Alkaline treatment, like acid pretreatment, is a chemical process considered traditional and highly efficient in lignin and hemicellulose solubilization, as well as in removing cellulose crystallization. The advantages of this technique include a simple process, efficiency in cellulose extraction, and reduced process time. However, its disadvantages encompass high costs, not being environmentally friendly due to the high production of toxic compounds, and the generation of polluting waste [65].

Alkaline pretreatment was used to obtain by-products from the cocoa pod shell, such as propionic acid, obtaining a maximum propionic acid yield of 10.28 ± 1.05 g/L, thus demonstrating the potential of the cocoa pod shell for generating organic acids [66]. This pretreatment was also applied in the process of obtaining bioethanol from cocoa husks, showing that the ideal condition for the pretreatment was a 5% NaOH concentration, a temperature of 120 °C, and a 30-min processing, which increased the cellulose content of the biomass [67]. The alkaline pretreatment, like other pretreatments, was previously applied to the co-digestion process for biogas production from cocoa husk biomass. It showed a 68% increase in biogas volume with alkaline pretreatment compared to acidic pretreatment and a 40% increase compared to untreated biomass [68].

3.3. Fermentation

Fermentation is a process where the action of microorganisms generates the oxidation of compounds. It is a technique that can be used to produce compounds from various biomasses, such as cocoa pod husks [69]. The solid-state fermentation process was used to obtain citric acid from cocoa pod husk residue, showing a promise for acid production, which was 978.52 g kg⁻¹ [70]. Table 2 presents examples of products obtained from cocoa pod husks.

Table 2. Products obtained from the fermentation process of cocoa pod husks.

Product	Fermentation	Reference
Citric acid	Solid-state fermentation	[70]
Phenolic compounds	Solid-state fermentation	[71]
Biogas	Anaerobic digestion	[72]
Bioethanol	Alcoholic fermentation	[73]
Methane	Anaerobic digestion	[72]
Propionic acid	Submerged fermentation	[66]
Biobutanol	Extractive fermentation	[3]

3.3.1. Aerobic Fermentation

Aerobic fermentation occurs in the presence of oxygen, and various products can be obtained from cocoa pod husks, such as biodiesel, xylitol, lactic acid, succinic acid, and citric acid [70]. Citric acid was produced from cocoa pod husks using fermentation with *Aspergillus niger* Tiegh F359. The process efficiency was confirmed, as it was possible to produce approximately 7530 ppm of citric acid from 1 g of cocoa pod husks. It is worth emphasizing that the use of a pretreatment of the residue before fermentation is essential for the efficiency of compound production [74].

Hemicellulosic hydrolysates from cocoa husks were used to obtain xylitol compound through fermentation using *Candida boidinii* XM02G yeast, achieving an efficiency of 56.6% in fermentation. This demonstrates that fermenting the hydrolysates of cocoa husk residues can be an efficient alternative for producing this compound, as well as providing proper disposal of the waste [75]. Through the spontaneous fermentation of cocoa pod husks, it is possible to obtain an extract capable of exhibiting antibacterial and antifungal activity due to the production of bioactive compounds that can combat bacteria and fungi of significant medical importance [76].

3.3.2. Anaerobic Fermentation

The anaerobic digestion fermentation process, occurring without the presence of oxygen, is an efficient method for treating various cocoa residues, including cocoa pod husks. Anaerobic fermentation is the most suitable technology for converting biomass residues into biogas. The potential of cocoa residues in biogas production was tested using batch reactors at laboratory scales with conditions of low and high solid content, thereby converting 50% of cocoa residues into biogas [72]. The cocoa pods underwent pretreatment followed by anaerobic digestion to obtain biogas, demonstrating that anaerobic digestion was effective in treating cocoa pods, showcasing their potential for use as a biogas source [77]. The production of biogas from cocoa pod husks was performed using the anaerobic co-digestion process, involving pretreatment with hydrogen peroxide and sulfuric acid beforehand. With alkaline pretreatment, there was a 68% increase in biogas production compared to acidic pretreatment and a 40% increase compared to untreated husks [69,78].

4. Emerging Technology for Obtaining By-Products from the Cocoa Pod Husk

Emerging technologies offer innovative pathways for optimizing the recovery of by-products and the extraction of structural compounds from cocoa pod husk (CPH). For instance, pyrolysis enables the thermochemical conversion of CPH into high-value products such as bio-oil, biogas, and biochar, with yields and characteristics influenced by processing parameters (Table 3). Separately, high-voltage electric discharges (HVEDs) have shown

promising results in reducing cadmium levels, reducing safety concerns associated with the use of such by-products.

In parallel, emerging technologies can be applied to enhance the extraction efficiency and quality of recovered compounds. These processes include supercritical and subcritical fluid extraction, microwave-assisted treatment, hydrothermal processes, ionic liquids, deep eutectic solvents, ultrasound-assisted extraction, and enzymatic hydrolysis (Tables 4 and 5). When integrated with conventional methods, such as acid or alkaline hydrolysis and fermentation, they contribute to more efficient fractionation of structural compounds of CPH and improved functional properties of the resulting products (Tables 5 and 6).

4.1. High-Voltage Electric Discharge Pretreatment

High-voltage electric discharge (HVED) is an emerging technology that uses high-intensity electric pulses to generate short-term plasma. This technique relies on applying high voltages to create electrical discharges through a medium [79], producing plasma capable of degrading contaminants [80]. In addition to its decontamination capabilities, HVED is a promising technology due to its ability to increase cell membrane permeability, thereby improving mass transfer efficiency [81].

The equipment used for this kind of technique is a high-voltage electric shock device that contains a 30 kV high-voltage pulse generator with a variable pulse frequency from 20 Hz to 100 Hz; an energy tank; a high-voltage switch; a chamber with high-voltage electrodes; and an automatic control unit to control the treatment time, pulse frequency, and mixing speed [11]. Experimental studies recommend treating the raw material for 15 min, at a concentration of 3% (in demineralized water) and a frequency of 40 Hz, allowing for a reduction in heavy metal levels [82].

CPH tends to adsorb metals because of its carboxyl, hydroxyl, and amine groups. In this regard, the proposed technology can reduce cadmium levels [83]. The HVDE method was able to decrease the levels of cadmium in cocoa by 30.33%, because pretreatment with HVDE generates reactive species that could have an oxidative effect on the treated material [82].

4.2. Pyrolysis

Pyrolysis has emerging potential for CPH valorization due to its ability to convert lignocellulosic materials, such as agricultural residues, into valuable products through thermal decomposition under non-oxidative conditions. According to the process parameters, such as heating rate, temperature, and solid residence time, it can be classified into slow pyrolysis, fast pyrolysis, and flash pyrolysis [84]. This process involves heating the biomass to high temperatures, which decompose the complex lignocellulosic structure into simpler compounds. This thermal treatment produces three main products: solid char (charcoal or biochar), liquid bio-oil, and gaseous by-products [85].

This technology is a simple alternative for converting lignocellulosic biomass into liquid, solid, and gas. There are studies associated with obtaining by-products derived from cocoa pod husk using pyrolysis, and they are described in Table 3. Its future is likely to hinge on a blend of simple technological innovations and advanced scientific research to reliably process the naturally heterogeneous lignocellulosic feedstock [86].

Table 3. By-products derived from cocoa pod husk using pyrolysis.

By-Product from CPH	Characteristics	Parameters	Yield (%)	References
Biochar	High nutrient content (calcium and potassium)	Slow pyrolysis T: 450 °C	31.1%	[87]
	Increased porosity due to post-acid treatment	Slow pyrolysis T: 400 °C Integrate posttreatment with HCl 0.25 M	40.70%	[88]
	It has polycondensed aromatic structures, which are responsible for the stability of biochar when applied to soils More rigid and porous structure	Fast pyrolysis T: 800 °C Integrate posttreatment with HCl 0.25 M	30.22%	
Bio-oil	pH: 2.8 Density: 1150 kg m ⁻³ Viscosity: 140 mm ² s ⁻¹ High heating value: 8.64 MJ/kg High water content: 30%	Fast pyrolysis Feed rate: 110 g/h T: 600 °C	58%	[89]
	High water content: 50% Contain chemicals grouped into ketones, carboxylic acids, aldehydes, furans, heterocyclic aromatics, phenols, benzenediols, and other chemicals. Requires stabilization with catalysts	Slow pyrolysis T: 500 °C	59.63%	[90]

4.3. Fluid-Assisted Extraction Techniques

4.3.1. Supercritical Fluids (SCFs)

This technology employs supercritical fluids, typically carbon dioxide (CO₂) and water, to extract compounds from biomass under conditions of high pressure and temperature, where the fluid exhibits properties of both liquid and gas [91]. Supercritical fluids can be used both for pretreatment processes and as a method for reactive extraction to produce high-value by-products [92]. SFC technology is recognized for its high efficiency, minimal solvent usage, and reduced extraction times compared to traditional techniques. However, a notable drawback of this method is its reliance on elevated temperatures, often reaching or exceeding the boiling point of the solvent used, which may lead to the thermal degradation of thermolabile biocompounds [91].

SCF was used as a pretreatment to obtain biofuels and biochar from CPH, for which a temperature of 100 °C and a pressure of 30 MPa are reached, considering an extraction time of 2 h. The studies were carried out the extraction under 3 conditions (using CO₂, CO₂ + ethanol, and CO₂ + water). The solid and liquid fractions were hydrothermally liquefied after SCF pretreatment. Due to the reduction of oxygen in lignocellulosic biomass treated with SCF (CO₂ + water), a bio-oil with higher energy value was obtained [93].

4.3.2. Subcritical Water Extraction (SWE)

This technology employs high temperature and pressure; it causes significant changes in the physical and chemical properties of water, that is, an increase in diffusivity, decrease in viscosity, surface tension, and dielectric constant, weakening hydrogen bonds [94]. The temperature parameters varied between 100 °C and 374 °C, and the pressure varied between 1 and 22 MPa. These conditions generate variations in the dielectric constant of

the water ($\epsilon = 80$) as subcritical water reaches $\epsilon = 25$ [95], approaching the values of organic solvents. This enables it to act as a good solvent for less polar compounds, whose solubility in water is low under normal conditions [96].

The SWE method allows extraction of pectin from CPH with a higher yield compared to that extracted by conventional methods. In addition, the pectin obtained by SWE has a higher galacturonic acid content and a higher degree of methyl esterification. Furthermore, using SWE, pectin with fewer interfering compounds, derived from other CPH polysaccharides, is obtained. SWE constitutes an efficient waste management approach to obtain by-products that can be applied to other industries [97].

4.3.3. Ionic Fluid

Ionic liquid treatment is considered an emerging chemical process that has gained increasing attention in biomass processing due to its efficiency and environmental compatibility [98]. These low-melting-point salts, consisting of a cation and a corresponding anion, are capable of disrupting the lignocellulosic structure, thereby allowing for the selective solubilization of cellulose, hemicellulose, and lignin [99].

The effectiveness of ILs on biomass structural components is dependent on the ionic components. Anions such as acetates form strong hydrogen bonds with hydroxyl groups, enhancing cellulose dissolution, while cations influence key physicochemical properties, such as viscosity, density, and melting point. [100].

Among the cations used for the treatment of CPH lignocellulosic biomass is imidazolium + [101]. Commonly used ionic liquids include 1,3-dimethylimidazolium, 1-butyl-3-methylimidazolium, 1-benzyl-3-methylimidazolium chloride, and 1-butyl-3-methylimidazolium methyl sulfate [102]. Predominantly, 1-ethyl-3-methylimidazolium methanesulfonate ($C_7H_{14}N_2O_3S$) has demonstrated the ability to preserve the crystallinity index of cellulose and its thermal stability during treatment [103]. Furthermore, this treatment allows the quantification of monomeric and polymeric sugars released after hydrolysis, facilitating their integration into biorefinery system [104]. These properties make IL treatment an attractive candidate for integration with fermentation to obtain CPH by-products.

4.3.4. Deep Eutectic Solvents (DESs)

Deep eutectic solvents are green solvents formed by combining one or more hydrogen bond acceptors (HBAs) and hydrogen bond donors (HBDs), in most cases, through mild warming [105]. The resulting eutectic solvent exhibits a lower melting point than the melting points of HBA and HBD separately [106,107]. DES gained attention because it has low volatility, is not flammable, has a high boiling point [105], uses “safer solvents and additives”, and is therefore considered to be an environmentally friendly technology [108].

In lignocellulosic biomass, pretreatment using DES has demonstrated the solubilization of hemicellulose and lignin. However, extracts with more complex compositions are obtained and are more difficult to apply in by-products and valorize. These challenges can be mitigated through rational design and selection of DES components [37].

For CPH, effective treatment requires it to be dehydrated and ground. A DES formulation combining acids with choline chloride (ChCl) as hydrogen bond acceptors (HBAs), and formic acid (FA), citric acid (CA), lactic acid (LA), and p-toluenesulfonic acid (pTSA) as hydrogen bond donors (HBDs) was prepared in a 1:1 ratio between HBAs and HBDs by heating at 80 °C for 2 h, until a transparent liquid phase was obtained. The mixture of DES and biomass was heated for 15 min at 121 °C, using an autoclave; after cooling, the sample was separated into a liquid and a solid part [109].

4.4. Separately from Intensification Techniques

4.4.1. Ultrasound (US)

Ultrasound is a mechanical acoustic wave with frequencies above 16 kHz that propagates through liquids via alternating compression and rarefaction cycles [45]. For lignocellulosic biomass, low frequencies from 20 to 40 kHz induce acoustic cavitation, generating microscopic bubbles that collapse violently, creating localized high-pressure and temperature zones. These effects break the cell wall and allow the release of intracellular compounds. Ultrasound also increases the contact surface between the solvent and the compounds to be extracted, favoring mass transfer [110].

The US improves the accessibility of cellulose and hemicellulose for enzymatic hydrolysis, generating higher yields of the derived sugars [111]. This method offers a non-thermal, energy-efficient alternative that can be integrated with acidic or alkaline solvents, enhancing overall process productivity.

4.4.2. Microwave-Assisted Extraction

This technology uses microwave radiation to heat the biomass rapidly and uniformly, enabling efficient breakdown of complex lignocellulosic structures. During microwave treatment, the dielectric properties of the material cause rapid heating, which accelerates the decomposition of cellulose, hemicellulose, and lignin into simpler compounds [112]. Microwave treatment has garnered significant interest as a thermal method for biorefinery applications because of its numerous advantages. These include non-contact heating, uniform volumetric heating, reduced reaction times, minimal solvent usage, fewer side reactions, and simplified operational parameters without complex variations. However, it faces significant challenges, such as the need for large processing facilities [113], high energy consumption, and overheating [114].

4.5. Hydrothermal Treatment

Hydrothermal pretreatment is classified as a thermo-physical treatment, considered an emerging process of transforming cocoa husks into carbon-rich solids. The advantages include high energy efficiency because there is greater contact between the lignocellulosic material and the solvent, thus allowing for a higher yield of cellulose, hemicellulose, and lignin. In turn, when combined with acid, it reduced the extraction time and treatment temperature [33]. This treatment has shown promise in the development of pores and oxygen functional groups (OFGs) in the produced activated carbons, and it can be used to obtain activated carbon [115]. A novel hydrothermal pretreatment assisted by citric acid demonstrated efficiency in recovering pectin [9].

4.6. Enzymatic Hydrolysis

Enzymatic treatment is an alternative to alter the structure of lignocellulosic biomass structural polymers. Specific enzymes hydrolyze glycosidic bonds, especially those of cellulose and hemicellulose, thereby reducing structural complexity and increasing substrate accessibility. By breaking down these structural polymers, enzymatic treatment enhances the accessibility of cellulose, facilitating its conversion into fermentable sugars through subsequent hydrolysis and fermentation processes. This enhancement is crucial for producing bioethanol and other biobased chemicals, making enzymatic treatment a pivotal technology in the bioconversion industry [116].

Table 4. By-products obtained by enzymatic hydrolysis.

Enzymatic Hydrolysis	By-Products Obtained from Hydrolysis	By-Products Obtained After Fermentation	References
Cellic HTec 2 [®] /Cellic CTec [®] from Novozymes—Araucaria, Brazil (1/9 ratio)	Glucose (58.9%) Xylose (16.1%)	Bioethanol	[9]
Xylanase-X2753, 1500 U/g (Pentopan Mono BG [®]) and Cellulase-C2730, 700 U/g (Celluclast [®]) from Sigma-Aldrich, Taiwan	Glucose Xylose	Not applicable	[109]
Celluclast [®]	Pectin (8.28%)	Not applicable	[117]
Cellulase enzyme Viscozyme Cassava CL (Novozymes A/S, Denmark)	Reducing sugars	Butanol, acetone–butanol–ethanol	[3]
Cellic Ctec2, Novozyme	Sugars (98.75%)	Ethanol	[68]

It is considered a more ecological and environmentally friendly option due to its lower energy consumption and the milder reactions involved compared to chemical acid treatments [118], which represent the central base of most biorefineries that carry out their operations based on lignocellulosic raw material [119].

Table 5. By-products derived from cocoa pod husk using emerging methods.

Emerging Technology	Parameters	By-Products Obtain	Characteristics	Yield	References
Subcritical water extraction	T:121 °C Pressure: 103.4 bar Time: 30 min	Pectin	Higher pectin yield, higher galacturonic acid content, and higher degree of methyl esterification; fewer interfering compounds derived from other cell wall polysaccharides	10.9%	[97]
Microwave-assisted extraction	Time extraction: 30 min Microwave power: 450 W Solvent concentration: 10% T: 104 °C	Pectin	Galacturonic acid content of 72.86%	21.1%	[120]
Microwave-assisted extraction + deep eutectic solvents	Time extraction: 30 min Microwave irradiation: 200 W DES proportion: 2:1:1 (p-toluenesulfonic acid/choline chloride/glycerol) Relation solid/liquid: 5%	Lignin	Larger particle sizes and structural diversity and higher H/G sub-unit ratio	95.5% *	[121]
	T: 121 °C Time: 15 min Microwave irradiation: 450 W DES proportion: 1:1 (choline chloride/citric acid)	Cellulose	Increased cellulose crystallinity due to the removal of amorphous components	28.12%	[109]
		Hemicellulose	Removal of acetyl and uronic groups from hemicellulose	7.76%	
		Lignin	DES treatment allows lignin to be removed; it was not characterized	16.31%	

Table 5. Cont.

Emerging Technology	Parameters	By-Products Obtain	Characteristics	Yield	References
Ionic fluids	Ionic fluid: 100 mL ionic liquid, 1-ethyl-3-methylimidazolium methanesulfonate (C ₇ H ₁₄ N ₂ O ₃ S) T1: room temperature (2 h) T2: 121 °C (15 min)	Cellulose	Minimum decrease in cellulose crystallinity	47%	[101]
		Hemicellulose	Was not characterized	25%	
		Lignin	Was not characterized	9%	

* Percentage of the amount of compound available in CPH.

Obtaining products from cocoa pod husk using conventional technologies causes problems for the environment, as most of these processes use chemical substances. Therefore, the use of emerging technologies such as microwave-assisted extraction, subcritical water extraction, ionic fluid, and ultrasound-assisted extraction is safer in terms of the environment, in addition to providing higher extraction yields. Through these technologies, it is also possible to save both on energy spent and on costs, which is possible through careful energy management during the process [122].

Subcritical water extraction is a technology that does not use acidic or alkaline solutions. It extracts compounds from the rupture of biomass molecules through water at different temperatures and pressures. It has the advantages of low cost and low energy consumption; being environmentally friendly, as it uses water as a solvent in the process; producing high yields; and being more efficient when compared to conventional technologies, such as extraction using citric acid in the extraction of pectins from cocoa pod husk [123].

Microwave-assisted extraction is another emerging method. It uses the energy generated by microwaves to separate compounds from a given biomass. The main advantage of the method is the possibility of rapidly heating the solvents in a mixture. This method is effective in degrading lignin from cocoa pod husk [124]. The technology adopting ionic liquids is an alternative to the use of organic solvents, thus providing less environmental impact. These liquids have solvent properties and are miscible in water, in addition to being non-flammable. Due to these advantages, it becomes an emerging technology alternative that can be used in the extraction of products from different biomasses and also residual biomass such as cocoa [101].

Emerging techniques such as microwave-assisted extraction, subcritical water extraction, ionic fluid extraction, and ultrasound-assisted extraction can also be combined to provide an increase in extraction yield, as well as reduce extraction time, in processes aimed at extracting pectins and other products [125].

In addition to the emerging treatments and the synergies between them, we could consider studies that guarantee higher yields when using emerging technologies integrating acid or alkaline extraction (conventional treatments), allowing for a slightly higher yield, as shown in Table 6.

Processes that combine conventional technologies with emerging technologies can bring higher yields in obtaining products of interest. Yadav et al. [109] integrated the microwave-assisted method with deep eutectic acid solvent pretreatment (ChCl/citric acid) to extract xylooligosaccharides from cocoa pod husk. When only deep eutectic acid solvent pretreatment (ChCl/citric acid) was used, the yield of xylooligosaccharides was lower (48.89 mg/g) than when used together with microwave-assisted at 300 W (56.41 mg/g) and 400 W (68.22 mg/g). In another study conducted by Valladares-Diestra, Porto de Souza

Vandenberghe et al. [9], acid treatment associated with hydrothermal treatment was used. It was efficient in extracting compounds that led to the production of 45.2 g of bioethanol.

Table 6. By-products derived from cocoa pod husk using the integration of emerging and conventional technology.

Emerging Technology	Conventional Technology	By-Products Obtain	Yield (%)	References
Ultrasonic-assisted treatment (T, 50 °C; 15 min; frequency, 40 kHz)	Acidic treatment (pH 3.0, using citric acid)	Pectin	9.31% from epicarp, 6.57% from mesocarp, 8.22% from endocarp	[126]
Hydrothermal treatment	Acidic treatment (pH 2.0–4.0, using citric acid)	Cellulose	14.14%	[9]
		Hemicellulose	10.41%	
		Lignin	27.75%	
		Pectin	19.26%	
Microwave-assisted	Acidic deep eutectic solvent (ChCl/citric acid)	Xylooligosaccharides	68.22 mg/g	[109]
Enzymatic hydrolysis	Alkaline treatment	Reducing sugars	98.75%	[68]

The integration of alkaline treatment, followed by enzymatic hydrolysis, was also demonstrated to be efficient in obtaining products such as ethanol obtained from cocoa pod husk. This integration contributes to yields of up to 98.75% of sugars obtained from cocoa pod husk that were consumed during fermentation to obtain ethanol. These studies show the potential of using emerging technologies integrated with acid or alkaline extraction, thus generating higher yields in the extraction of products of interest.

5. Application of By-Products from the Cocoa Pod Husk

After identifying different emerging techniques—often combined with traditional processes—for the separation of valuable structural compounds from CPH, it is important to highlight HVED as a mechanism to reduce cadmium levels. This is particularly relevant for enabling the safe incorporation of CPH structural compounds into various industrial applications without compromising consumer health.

As illustrated in Figure 3, CPH can be valorized across five main groups: the food industry, biopolymers sector, biofuels sector, medicine and cosmetics industry, and agriculture and environment sector.

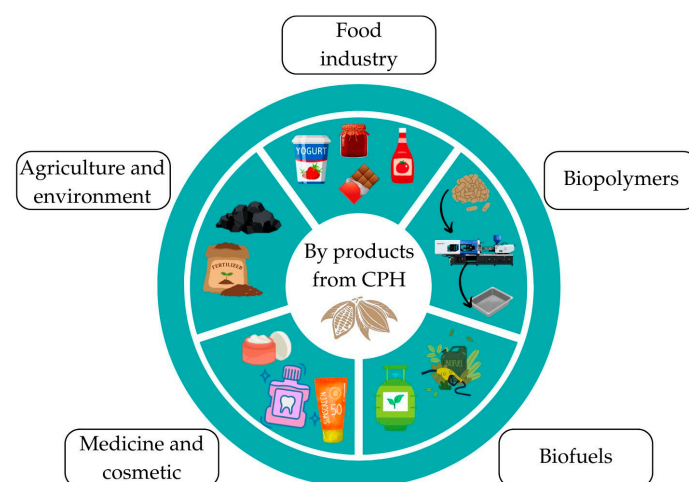


Figure 3. Application of by-products obtained from cocoa pod husk (CPH).

5.1. Food Industry

CPH is a value source of low-methoxyl pectin. This type of pectin forms shear-reversible gels, and it is extensively used in the food industry because of its gelling, thickening, and stabilizing properties, making it an important source of dietary fiber [122]. This isolated functional ingredient can be used in foods, for instance, in jellies, sauces, and jams, and to improve texture in dairy products, such as yogurt [127]. CPH can be used in chocolate production as a source of dietary fiber [128]. On the other hand, structural compounds from CPH act as a source of fiber, and in doses of 4%, they contribute to improving the biodigestibility of certain domestic animals, such as dogs [129].

In meat products, CPH pectin has been used to improve emulsion stability in sausages due to its ability to inhibit the oxidation of products with high lipid content [11]. Experimental studies show that it is possible to replace up to 3% of the starch with CPH flour. In addition, its remarkable products characteristics, such as good emulsion stability, increase fiber content, increase hardness and adhesiveness, and decrease cohesion. Although sensory acceptability remained positive, it did not fully match that of traditional sausage formulations [130].

CPH is rich in antioxidants and minerals, making it valuable for both human and plant nutrition. Therefore, these husks have the potential to help combat hunger and malnutrition in cocoa-producing countries [131]. Despite concerns about cadmium accumulation, studies show that when CPH by-products are consumed in low doses, there are no significant adverse effects on organs and tissue histopathology [132]. Also, it has been demonstrated by genotoxicity testing following the Organisation for Economic Cooperation and Development (OECD)'s guidelines that CPH was neither a direct nor indirect mutagen, demonstrating that this product is safe for human consumption, even when maximum permitted doses are used [133].

5.2. Biopolymers

Biopolymers represent a more environmentally sustainable option to traditional plastics due to their biodegradability, which helps reduce solid waste and leads to the formation of less toxic products during decomposition. In addition, their production generates fewer pollutants and can be carried out using agricultural residues such as CPH [134].

There are several methods to convert CPH into biopolymers, mainly through the extraction and modification of its components using traditional or emerging techniques, or a combination of both [135]. Additionally, structural compounds extracted from CPH can be converted into biomaterials through extrusion or injection processes to form films or bioplastic composites. These bioplastics have various applications, including packaging, consumer products, and the medical industry, and can be further optimized through modification techniques, such as blending, polymerization, and reinforcement with natural additives, like algae, keratin, and alginate [136].

Studies show that the use of CPH compounds makes it possible to achieve packages with specific characteristics. Pectin and lignin make it possible to modulate the thermal stability of the final product. In particular, formulations with lower pectin and higher lignin content exhibit enhanced thermal stability, while increased cellulose content improves tensile strength [137].

Additionally, hemicellulose (mainly xylans) is key in the production of biomaterials [8]. The xylans present in this biomass can be hydrolyzed to obtain xylooligosaccharides (XOSs), which are xylose oligomers [138]. Studies have demonstrated the potential for the application of these compounds in edible film packaging, as they exhibit slightly increased water vapor permeability; reduced oxygen permeability; and no changes in hydrophobicity, thermal stability, or transparency [139].

5.3. Biofuels

Biofuel is a renewable energy source produced from organic matter (such as CPH). Biofuels are primarily used for generating electricity and heat, and as sustainable alternatives or additives to fossil fuels in transportation [140]. Their use contributes to the reduction of greenhouse gas emissions and promoting the valorization of agricultural waste [141].

The most well-known biofuels are biogas and bioethanol. Biogas is produced through the anaerobic digestion of organic matter, such as agricultural residues or manure, generating a gas primarily composed of methane and carbon dioxide that can be used for generating electricity and heat [142]. On the other hand, bioethanol is obtained through the fermentation of sugars and is primarily used as an additive in gasoline for vehicles [141].

Another important form of biofuel is bio-oil, which is obtained through the pyrolysis of CPH. Bio-oil has a high calorific value and potential as a feedstock for producing bio-resins, lubricants, and advanced biofuels [90]. However, its practical use is limited due to its high water content [89] and the presence of aromatic compounds. Therefore, additional posttreatment techniques, such as electrostatic precipitation, are required to improve its physical and chemical stability [143].

5.4. Medicine and Cosmetic Industry

There are few studies on the application of CPH in the medical industry. However, some have demonstrated that the pectin extracted from this by-product is suitable for use as a pharmaceutical excipient due to its physicochemical properties [131].

In addition, studies conclude that CPH extract contains compounds such as flavonoids and tannins, which have antioxidant and antimicrobial properties. These compounds are capable of inhibiting the growth of bacteria like *P. gingivalis* and *S. mutans*, which are responsible for dental diseases. Its antioxidant and antibacterial activities suggest that CPH could be a promising alternative for treating dental problems [144].

In the cosmetic industry, structural compounds from CPH show promise due to their ability to inhibit enzymes like elastase and collagenase, which break down collagen and elastin in the skin, contributing to aging. A study showed that CPH extract blocks these enzymes; thus, CPH extract could help prevent wrinkles and sagging [145]. These characteristics make it an ideal candidate for the development of cosmetic products focused on skin care, particularly in anti-aging treatments. Also, clinical evaluations related to 0.1% and 1% concentrations of CPH extract demonstrated that the application of the product is safe for maintaining skin hydration and reducing transepidermal water loss [146].

Moreover, its UV-absorbing properties make it a natural ingredient for sunscreen formulations. In particular, lignin extracted from CPH contributes to photoprotection due to its unique chemical structure: it contains phenolic groups that absorb UV radiation in the 280–290 nm range, and double bonds that extend absorption into the 300–400 nm region. This dual mechanism broadens the UV-protective spectrum of lignin, enhancing its effectiveness as a natural ingredient in sunscreen production [147]. Studies affirm that CPH lignin has a sunscreen effect (UV 200–400 nm), and when applied to the skin, it also helps prevent wrinkles [10]. For instance, one study showed that the addition of 5% lignin in sunscreens doubles the sun protection factor value of a pure cream and increases the UV protection factor by five times compared to a commercial sunscreen [147].

Additionally, its ability to combat bacteria and reduce inflammation makes it a viable option for medical treatments, especially in dental care and improving skin health. CPH extract can be added to a mouthwash (10 mL of 0.1%) to inhibit *Streptococcus mutans* in saliva and has similar effects to commercial products; it is also effective in inhibiting *E. faecalis* (3.12%) [10].

5.5. Agriculture and Environment Sector

Fertilizers derived from CPH are produced through various valorization strategies that transform this agricultural waste into useful inputs for sustainable agriculture. One of the most common methods is composting, where CPH is mixed with other organic materials and decomposed by microorganisms to yield compost. This compost is rich in essential nutrients, like nitrogen (N), phosphorus (P), and potassium (K), improving soil structure and promoting plant health [148].

In addition to composting, pyrolysis is employed to produce CPH-derived biochar, a carbon-rich material characterized by its ability to raise soil pH—particularly beneficial for acidic soils [149]. These characteristics increase agricultural yield and productivity [150]. Experimental studies reflect the use of pyrolyzed CPH biochar in acidic soil (using Ferrasol) and alkaline soil (using Nitrasol) and demonstrates the positive effects of using CPH biochar (Figure 4), as it increases the availability of K⁺ and P⁺, thus improving soil fertility. In addition, it increases N uptake in plants. One study mentions that pyrolyzed CPH could be used as a strategy to reduce GHG emissions (CO₂ plus N₂O), thus helping to reduce the environmental impact of crop planting [149].

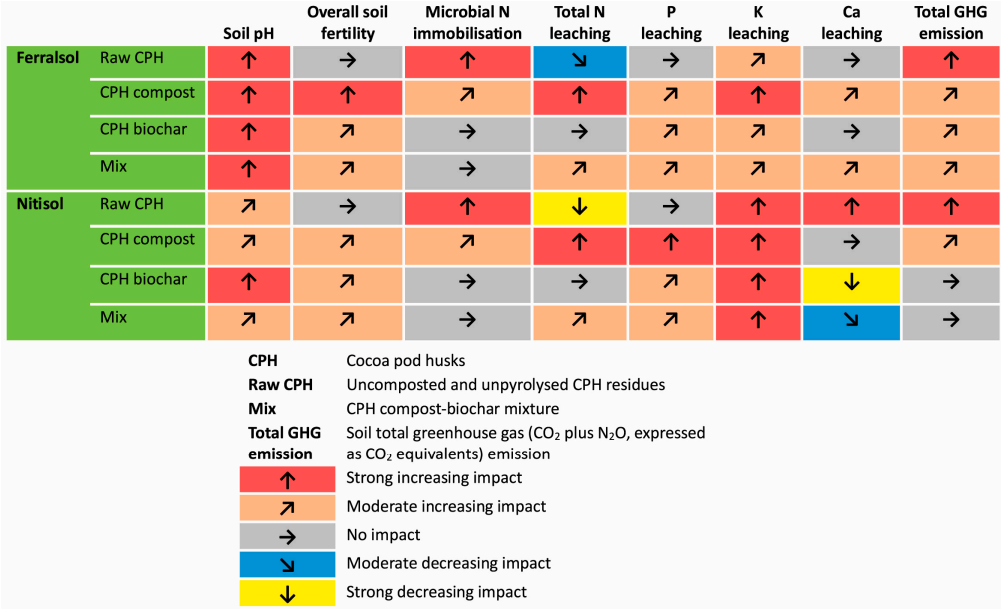


Figure 4. Characteristics of biochar and biocompost from cocoa pod husk [149].

Also, biochar from CPH can efficiently adsorb lead (Pb²⁺), mercury (Hg²⁺), and cadmium (Cd²⁺) from the aqueous phase, and the removal efficiency of CPH biochar for Pb²⁺, Hg²⁺, and Cd²⁺ is higher than 99% [151], highlighting its potential as an eco-friendly material for remediating water contaminated by heavy metals. This multifunctionality positions cocoa pod husk biochar as an effective solution for both improving agricultural productivity and reducing environmental pollution.

6. Concluding Remarks and Future Trends

This review article demonstrates the importance of using new technologies to achieve an adequate utilization of CPH. Considering that cocoa has a high level of cadmium, technologies such as high electrical discharges should be used to reduce the levels to permissible limits for application in products that can be sold in any industry. In addition, after obtaining a safe raw material, it is advisable to use extraction methods that allow for maximum advantage to be taken of the compounds of interest contained in CPH, such as cellulose, hemicellulose, lignin, and pectin. To this end, this bibliographic review

emphasizes new technologies and how new techniques can be created to obtain by-products by combining conventional methods with more modern proposals. These new technologies present advantages over conventional technologies. Methods such as SCF and microwaves stand out in the protection of CPH compounds due to the limited use of solvent, high efficiency, and shorter removal time. The SWE method also stands out compared to conventional methods, being able to obtain higher yields of compounds, such as pectin extracted from CPH. Despite this, conventional technologies can serve as an alternative to be used in combination with emerging technologies to increase the extraction yield. The result is not only to obtain products with low cadmium content but also molecules extracted under optimal conditions that can be added as active compounds in the elaboration of products for the food industry, such as jams and sauces; for the packaging industry; for biofuels, such as biogas and bioethanol; for the pharmaceutical industry and cosmetics, such as sunscreens and lotions; and for the fertilizer industry and other applications in agriculture to improve soil and water quality.

Despite these advances, several technological limitations persist. These include the need for parameter optimization in cadmium-reducing techniques, and limited scalability of emerging methods under industrial conditions. Future research should prioritize optimization of HVED parameters for effective cadmium removal, scale-up studies of combined emerging and traditional technologies, techno-economic and environmental assessments of integrated extraction chains, and physicochemical and microbiological validation of CPH by-products.

Finally, the valorization of CPH contributes to a circular bioeconomy by converting lignocellulosic biomass into safe, high-value products applicable in food, pharmaceuticals, cosmetics, agriculture, and packaging. These strategies are aligning with global sustainability goals to ensure the development of eco-efficient and socially beneficial bioproducts.

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References

1. Brahma, R.; Ray, S. Optimization of Extraction Conditions for Cellulose from Jackfruit Peel Using RSM, Its Characterization and Comparative Studies to Commercial Cellulose. *Meas. Food* **2024**, *13*, 100130. [\[CrossRef\]](#)
2. Gutiérrez-Macías, P.; Mirón-Mérida, V.A.; Rodríguez-Nava, C.O.; Barragán-Huerta, B.E. Chapter 13-Cocoa: Beyond Chocolate, a Promising Material for Potential Value-Added Products. In *Valorization of Agri-Food Wastes and By-Products*; Bhat, R., Ed.; Academic Press: Cambridge, MA, USA, 2021; pp. 267–288, ISBN 978-0-12-824044-1.
3. Muharja, M.; Darmayanti, R.F.; Fachri, B.A.; Palupi, B.; Rahmawati, I.; Rizkiana, M.F.; Amini, H.W.; Putri, D.K.Y.; Setiawan, F.A.; Asrofi, M.; et al. Biobutanol Production from Cocoa Pod Husk through a Sequential Green Method: Depectination, Delignification, Enzymatic Hydrolysis, and Extractive Fermentation. *Bioresour. Technol. Rep.* **2023**, *21*, 101298. [\[CrossRef\]](#)
4. Campos-Vega, R.; Nieto-Figueroa, K.H.; Oomah, B.D. Cocoa (*Theobroma cacao* L.) Pod Husk: Renewable Source of Bioactive Compounds. *Trends Food Sci. Technol.* **2018**, *81*, 172–184. [\[CrossRef\]](#)
5. Kley Valladares-Diestra, K.; Porto De Souza Vandenbergh, L.; Ricardo Soccol, C. A Biorefinery Approach for Pectin Extraction and Second-Generation Bioethanol Production from Cocoa Pod Husk. *Bioresour. Technol.* **2022**, *346*, 126635. [\[CrossRef\]](#)
6. Santiago-Gómez, I.; Carrera-Lanestosa, A.; González-Alejo, F.A.; Guerra-Que, Z.; García-Alamilla, R.; Rivera-Armenta, J.L.; García-Alamilla, P. Pectin Extraction Process from Cocoa Pod Husk (*Theobroma cacao* L.) and Characterization by Fourier Transform Infrared Spectroscopy. *ChemEngineering* **2025**, *9*, 25. [\[CrossRef\]](#)

7. Jarrín-Chacón, J.P.; Núñez-Pérez, J.; Espín-Valladares, R.d.C.; Manosalvas-Quiroz, L.A.; Rodríguez-Cabrera, H.M.; Pais-Chanfrau, J.M. Pectin Extraction from Residues of the Cocoa Fruit (*Theobroma cacao* L.) by Different Organic Acids: A Comparative Study. *Foods* **2023**, *12*, 590. [\[CrossRef\]](#)
8. Rao, J.; Lv, Z.; Chen, G.; Peng, F. Hemicellulose: Structure, Chemical Modification, and Application. *Prog. Polym. Sci.* **2023**, *140*, 101675. [\[CrossRef\]](#)
9. Valladares-Diestra, K.K.; Porto De Souza Vandenberghe, L.; Zevallos Torres, L.A.; Zandoná Filho, A.; Lorenci Woiciechowski, A.; Ricardo Soccol, C. Citric Acid Assisted Hydrothermal Pretreatment for the Extraction of Pectin and Xylooligosaccharides Production from Cocoa Pod Husks. *Bioresour. Technol.* **2022**, *343*, 126074. [\[CrossRef\]](#)
10. Belwal, T.; Cravotto, C.; Ramola, S.; Thakur, M.; Chemat, F.; Cravotto, G. Bioactive Compounds from Cocoa Husk: Extraction, Analysis and Applications in Food Production Chain. *Foods* **2022**, *11*, 798. [\[CrossRef\]](#)
11. Barišić, V.; Jozinović, A.; Flanjak, I.; Šubarić, D.; Babić, J.; Miličević, B.; Doko, K.; Ačkar, Đ. Difficulties with Use of Cocoa Bean Shell in Food Production and High Voltage Electrical Discharge as a Possible Solution. *Sustainability* **2020**, *12*, 3981. [\[CrossRef\]](#)
12. Srivastava, R.; Singh, Y.; White, J.C.; Dhankher, O.P. Mitigating Toxic Metals Contamination in Foods: Bridging Knowledge Gaps for Addressing Food Safety. *Trends Food Sci. Technol.* **2024**, *153*, 104725. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Zhou, M.; Li, Z. Recent Advances in Minimizing Cadmium Accumulation in Wheat. *Toxics* **2022**, *10*, 187. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Porto De Souza Vandenberghe, L.; Kley Valladares-Diestra, K.; Amaro Bittencourt, G.; Fátima Murawski De Mello, A.; Sarmiento Vásquez, Z.; Zwiercheczewski De Oliveira, P.; Vinícius De Melo Pereira, G.; Ricardo Soccol, C. Added-Value Biomolecules' Production from Cocoa Pod Husks: A Review. *Bioresour. Technol.* **2022**, *344*, 126252. [\[CrossRef\]](#)
15. Baidoo, M.F.; Asiedu, N.Y.; Darkwah, L.; Arhin-Dodoo, D.; Zhao, J.; Jerome, F.; Amaniampong, P.N. Conventional and Unconventional Transformation of Cocoa Pod Husks into Value-Added Products. In *Biomass Biorefineries Bioeconomy*; IntechOpen: London, UK, 2022. [\[CrossRef\]](#)
16. Meza-Sepúlveda, D.C.; Hernandez-Urrea, C.; Valencia-Sanchez, H. Caracterización Termoquímica de La Celulosa Extraída de La Cáscara de La Mazorca de Cacao de *Theobroma cacao* L. *Ind. Crops Prod.* **2025**, *226*, 120579. [\[CrossRef\]](#)
17. Hasan, M.H.; Hossain, S.; Rahman, M.L.; Rahman, G.M.S.; Khan, M.A.; Al Mamun, M.A. Effect of Hydrolysis Agitation and Suspension Drying Temperature on the Synthesis of Crystalline Cellulose from Jute Fiber. *Carbohydr. Polym. Technol. Appl.* **2025**, *10*, 100769. [\[CrossRef\]](#)
18. Jain, B.; Jain, R.; Jha, R.R.; Ghosh, A.; Basu, D.; Abourehab, M.A.S.; Bajaj, A.; Chauhan, V.; Kaur, S.; Sharma, S. Cellulose Paper Sorptive Extraction (CPSE): A Simple and Affordable Microextraction Method for Analysis of Basic Drugs in Blood as a Proof of Concept. *J. Chromatogr. B* **2023**, *1214*, 123551. [\[CrossRef\]](#)
19. Islam, M.N.; Rahman, F. Production and Modification of Nanofibrillated Cellulose Composites and Potential Applications. In *Green Composites for Automotive Applications*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 115–141, ISBN 978-0-08-102177-4.
20. Zhu, J.; Shao, C.; Hao, S.; Zhang, J.; Ren, W.; Wang, B.; Xiao, L.; Wang, C.; Shao, L. Recent Progress on the Dissolution of Cellulose in Deep Eutectic Solvents. *Ind. Crops Prod.* **2025**, *228*, 120844. [\[CrossRef\]](#)
21. Zabot, G.L.; Schaefer Rodrigues, F.; Polano Ody, L.; Vinícius Tres, M.; Herrera, E.; Palacin, H.; Córdova-Ramos, J.S.; Best, I.; Olivera-Montenegro, L. Encapsulation of Bioactive Compounds for Food and Agricultural Applications. *Polymers* **2022**, *14*, 4194. [\[CrossRef\]](#)
22. Hozman-Manrique, A.S.; Garcia-Brand, A.J.; Hernández-Carrión, M.; Porras, A. Isolation and Characterization of Cellulose Microfibers from Colombian Cocoa Pod Husk via Chemical Treatment with Pressure Effects. *Polymers* **2023**, *15*, 664. [\[CrossRef\]](#)
23. Seddiqi, H.; Oliaei, E.; Honarkar, H.; Jin, J.; Geonzon, L.C.; Bacabac, R.G.; Klein-Nulend, J. Cellulose and Its Derivatives: Towards Biomedical Applications. *Cellulose* **2021**, *28*, 1893–1931. [\[CrossRef\]](#)
24. Hosny, K.M.; Alkhalidi, H.M.; Alharbi, W.S.; Md, S.; Sindi, A.M.; Ali, S.A.; Bakhaidar, R.B.; Almeahmady, A.M.; Alfayez, E.; Kurakula, M. Recent Trends in Assessment of Cellulose Derivatives in Designing Novel and Nanoparticulate-Based Drug Delivery Systems for Improvement of Oral Health. *Polymers* **2021**, *14*, 92. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Pacheco, A.; Evangelista-Osorio, A.; Muchaypiña-Flores, K.G.; Marzano-Barreda, L.A.; Paredes-Concepción, P.; Palacin-Baldeón, H.; Dos Santos, M.S.N.; Tres, M.V.; Zabot, G.L.; Olivera-Montenegro, L. Polymeric Materials Obtained by Extrusion and Injection Molding from Lignocellulosic Agroindustrial Biomass. *Polymers* **2023**, *15*, 4046. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Huang, L.-Z.; Ma, M.-G.; Ji, X.-X.; Choi, S.-E.; Si, C. Recent Developments and Applications of Hemicellulose From Wheat Straw: A Review. *Front. Bioeng. Biotechnol.* **2021**, *9*, 690773. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Roldi-Oliveira, M.; Diniz, L.M.; Elias, A.L.; Luz, S.M. Hemicellulose Films from Curaua Fibers (*Ananas Erectifolius*): Extraction and Thermal and Mechanical Characterization. *Polymers* **2022**, *14*, 2999. [\[CrossRef\]](#)
28. Luo, Y.; Li, Z.; Li, X.; Liu, X.; Fan, J.; Clark, J.H.; Hu, C. The Production of Furfural Directly from Hemicellulose in Lignocellulosic Biomass: A Review. *Catal. Today* **2019**, *319*, 14–24. [\[CrossRef\]](#)
29. Qaseem, M.F.; Shaheen, H.; Wu, A.-M. Cell Wall Hemicellulose for Sustainable Industrial Utilization. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110996. [\[CrossRef\]](#)

30. Zheng, B.; Zhang, L.; Zhou, Z.; Chen, S.; Chen, L.; Li, Y.; Wu, A.; Li, H. Understanding the Dynamic Evolution of Hemicellulose during *Pinus taeda* L. Growth. *Int. J. Biol. Macromol.* **2024**, *273*, 132914. [\[CrossRef\]](#)
31. Nechita, P.; Mirela, R.; Ciolacu, F. Xylan Hemicellulose: A Renewable Material with Potential Properties for Food Packaging Applications. *Sustainability* **2021**, *13*, 13504. [\[CrossRef\]](#)
32. Bajpai, P. Chapter 2-Xylan Occurrence and Structure. In *Microbial Xylanolytic Enzymes*; Bajpai, P., Ed.; Progress in Biochemistry and Biotechnology; Academic Press: Cambridge, MA, USA, 2022; pp. 13–28, ISBN 978-0-323-99636-5.
33. Scapini, T.; Dos Santos, M.S.N.; Bonatto, C.; Wancura, J.H.C.; Mulinari, J.; Camargo, A.F.; Klanovicz, N.; Zabot, G.L.; Tres, M.V.; Fongaro, G.; et al. Hydrothermal Pretreatment of Lignocellulosic Biomass for Hemicellulose Recovery. *Bioresour. Technol.* **2021**, *342*, 126033. [\[CrossRef\]](#)
34. Jacob, S.; Dilshani, A.; Rishivanthi, S.; Khaitan, P.; Vamsidhar, A.; Rajeswari, G.; Kumar, V.; Rajak, R.C.; Din, M.F.M.; Zambare, V. Lignocellulose-Derived Arabinose for Energy and Chemicals Synthesis through Microbial Cell Factories: A Review. *Processes* **2023**, *11*, 1516. [\[CrossRef\]](#)
35. Fehér, C. Novel Approaches for Biotechnological Production and Application of L-Arabinose. *J. Carbohydr. Chem.* **2018**, *37*, 251–284. [\[CrossRef\]](#)
36. Puițel, A.C.; Suditu, G.D.; Drăgoi, E.N.; Danu, M.; Ailiesei, G.-L.; Balan, C.D.; Chicet, D.-L.; Nechita, M.T. Optimization of Alkaline Extraction of Xylan-Based Hemicelluloses from Wheat Straws: Effects of Microwave, Ultrasound, and Freeze–Thaw Cycles. *Polymers* **2023**, *15*, 1038. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Chen, Z.; Wang, Y.; Cheng, H.; Zhou, H. Hemicellulose Degradation: An Overlooked Issue in Acidic Deep Eutectic Solvents Pretreatment of Lignocellulosic Biomass. *Ind. Crops Prod.* **2022**, *187*, 115335. [\[CrossRef\]](#)
38. Valladares-Diestra, K.K.; De Souza Vandenbergh, L.P.; Vieira, S.; Goyzueta-Mamani, L.D.; De Mattos, P.B.G.; Manzoki, M.C.; Soccol, V.T.; Soccol, C.R. The Potential of Xylooligosaccharides as Prebiotics and Their Sustainable Production from Agro-Industrial by-Products. *Foods* **2023**, *12*, 2681. [\[CrossRef\]](#)
39. Manicardi, T.; Baioni E Silva, G.; Longati, A.A.; Paiva, T.D.; Souza, J.P.M.; Pádua, T.F.; Furlan, F.F.; Giordano, R.L.C.; Giordano, R.C.; Milessi, T.S. Xylooligosaccharides: A Bibliometric Analysis and Current Advances of This Bioactive Food Chemical as a Potential Product in Biorefineries' Portfolios. *Foods* **2023**, *12*, 3007. [\[CrossRef\]](#)
40. Obrzut, N.; Hickmott, R.; Shure, L.; Gray, K.A. The Effects of Lignin Source and Extraction on the Composition and Properties of Biorefined Depolymerization Products. *RSC Sustain.* **2023**, *1*, 2328–2340. [\[CrossRef\]](#)
41. Huang, J.; Fu, S.; Gan, L. (Eds.) Chapter 2-Structure and Characteristics of Lignin. In *Lignin Chemistry and Applications*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 25–50, ISBN 978-0-12-813941-7.
42. Erfani Jazi, M.; Narayanan, G.; Aghabozorgi, F.; Farajidizaji, B.; Aghaei, A.; Kamyabi, M.A.; Navarathna, C.M.; Mlsna, T.E. Structure, Chemistry and Physicochemistry of Lignin for Material Functionalization. *SN Appl. Sci.* **2019**, *1*, 1094. [\[CrossRef\]](#)
43. Chelliah, R.; Wei, S.; Vijayalakshmi, S.; Barathikannan, K.; Sultan, G.; Liu, S.; Oh, D.-H. A Comprehensive Mini-Review on Lignin-Based Nanomaterials for Food Applications: Systemic Advancement and Future Trends. *Molecules* **2023**, *28*, 6470. [\[CrossRef\]](#)
44. Suota, M.J.; da Silva, T.A.; Zawadzki, S.F.; Sassaki, G.L.; Hansel, F.A.; Paleologou, M.; Ramos, L.P. Chemical and Structural Characterization of Hardwood and Softwood LignoForce™ Lignins. *Ind. Crops Prod.* **2021**, *173*, 114138. [\[CrossRef\]](#)
45. Flores, E.M.M.; Cravotto, G.; Bizzzi, C.A.; Santos, D.; Iop, G.D. Ultrasound-Assisted Biomass Valorization to Industrial Interesting Products: State-of-the-Art, Perspectives and Challenges. *Ultrason. Sonochem.* **2021**, *72*, 105455. [\[CrossRef\]](#)
46. Lobato-Peralta, D.R.; Duque-Brito, E.; Villafán-Vidales, H.I.; Longoria, A.; Sebastian, P.J.; Cuentas-Gallegos, A.K.; Arancibia-Bulnes, C.A.; Okoye, P.U. A Review on Trends in Lignin Extraction and Valorization of Lignocellulosic Biomass for Energy Applications. *J. Clean. Prod.* **2021**, *293*, 126123. [\[CrossRef\]](#)
47. Liang, W.; Liao, J.; Qi, J.-R.; Jiang, W.; Yang, X. Physicochemical Characteristics and Functional Properties of High Methoxyl Pectin with Different Degree of Esterification. *Food Chem.* **2022**, *375*, 131806. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Zdunek, A.; Pieczywek, P.M.; Cybulska, J. The Primary, Secondary, and Structures of Higher Levels of Pectin Polysaccharides. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 1101–1117. [\[CrossRef\]](#)
49. Forouhar, A.; Hamdami, N.; Djelveh, G.; Gardarin, C.; Pierre, G.; Ursu, A.V.; Michaud, P. The Effect of Ultrasound Pretreatment on Pectin Extraction from Watermelon Rind Using Microwave-Assisted Extraction. *Appl. Sci.* **2023**, *13*, 5558. [\[CrossRef\]](#)
50. Cui, Y.; Chen, J.; Zhang, S. The Effect of Degree of Esterification of Pectin on the Interaction between Pectin and Wheat Gluten Protein. *Food Hydrocoll.* **2023**, *136*, 108272. [\[CrossRef\]](#)
51. Lara-Espinoza, C.; Carvajal-Millán, E.; Balandrán-Quintana, R.; López-Franco, Y.; Rascón-Chu, A. Pectin and Pectin-Based Composite Materials: Beyond Food Texture. *Molecules* **2018**, *23*, 942. [\[CrossRef\]](#)
52. Iñiguez-Moreno, M.; Pizaña-Aranda, J.J.P.; Ramírez-Gamboa, D.; Ramírez-Herrera, C.A.; Araújo, R.G.; Flores-Contreras, E.A.; Iqbal, H.M.N.; Parra-Saldívar, R.; Melchor-Martínez, E.M. Enhancing Pectin Extraction from Orange Peel through Citric Acid-Assisted Optimization Based on a Dual Response. *Int. J. Biol. Macromol.* **2024**, *263*, 130230. [\[CrossRef\]](#)

53. Valdivia-Rivera, S.; Herrera-Pool, I.E.; Ayora-Talavera, T.; Lizardi-Jiménez, M.A.; García-Cruz, U.; Cuevas-Bernardino, J.C.; Cervantes-Uc, J.M.; Pacheco, N. Kinetic, Thermodynamic, Physicochemical, and Economical Characterization of Pectin from *Mangifera indica* L. cv. Haden Residues. *Foods* **2021**, *10*, 2093. [\[CrossRef\]](#)
54. Jong, S.H.; Abdullah, N.; Muhammad, N. Effect of Acid Type and Concentration on the Yield, Purity, and Esterification Degree of Pectin Extracted from Durian Rinds. *Results Eng.* **2023**, *17*, 100974. [\[CrossRef\]](#)
55. Marsiglia, D.E.; Ojeda, K.A.; Ramírez, M.C.; Sánchez, E. Pectin Extraction from Cocoa Pod Husk (*Theobroma cacao* L.) by hydrolysis with citric and acetic acid. *Int. J. ChemTech Res.* **2016**, *9*, 97–507.
56. Vriesmann, L.C.; Teófilo, R.F.; Lúcia de Oliveira Petkowicz, C. Extracción y Caracterización de Pectina de Cáscaras de Mazorca de Cacao (*Theobroma cacao* L.) Con Ácido Cítrico. *LWT* **2012**, *49*, 108–116. [\[CrossRef\]](#)
57. Girón-Hernández, J.; Tombe, A.; Chemban Koyilot, M.; Salas-Calderón, K.T.; Charlton, A.; Wills, C.; Gentile, P. From Cocoa Waste to Sustainable Bioink: Valorising Pectin for Circular Economy-Driven Tissue Engineering. *Eur. Polym. J.* **2024**, *210*, 112967. [\[CrossRef\]](#)
58. Adi-Dako, O.; Ofori-Kwakye, K.; Frimpong Manso, S.; Boakye-Gyasi, M.E.; Sasu, C.; Pobee, M. Physicochemical and Antimicrobial Properties of Cocoa Pod Husk Pectin Intended as a Versatile Pharmaceutical Excipient and Nutraceutical. *J. Pharm.* **2016**, *2016*, 7608693. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Javanmard, A.; Wan Daud, W.M.A.; Patah, M.F.A.; Zuki, F.M.; Ai, S.P.; Azman, D.Q.; Chen, W.-H. Breaking Barriers for a Green Future: A Comprehensive Study on Pre-Treatment Techniques for Empty Fruit Bunches in the Bio-Based Economy. *Process Saf. Environ. Prot.* **2024**, *182*, 535–558. [\[CrossRef\]](#)
60. Basak, B.; Kumar, R.; Bharadwaj, A.V.S.L.S.; Kim, T.H.; Kim, J.R.; Jang, M.; Oh, S.-E.; Roh, H.-S.; Jeon, B.-H. Advances in Physicochemical Pretreatment Strategies for Lignocellulose Biomass and Their Effectiveness in Bioconversion for Biofuel Production. *Bioresour. Technol.* **2023**, *369*, 128413. [\[CrossRef\]](#)
61. Ong, V.Z.; Wu, T.Y.; Chu, K.K.L.; Sun, W.Y.; Shak, K.P.Y. A Combined Pretreatment with Ultrasound-Assisted Alkaline Solution and Aqueous Deep Eutectic Solvent for Enhancing Delignification and Enzymatic Hydrolysis from Oil Palm Fronds. *Ind. Crops Prod.* **2021**, *160*, 112974. [\[CrossRef\]](#)
62. Beluhan, S.; Mihajlovski, K.; Šantek, B.; Ivančić Šantek, M. The Production of Bioethanol from Lignocellulosic Biomass: Pretreatment Methods, Fermentation, and Downstream Processing. *Energies* **2023**, *16*, 7003. [\[CrossRef\]](#)
63. Chandel, A.K.; Garlapati, V.K.; Singh, A.K.; Antunes, F.A.F.; da Silva, S.S. The Path Forward for Lignocellulose Biorefineries: Bottlenecks, Solutions, and Perspective on Commercialization. *Bioresour. Technol.* **2018**, *264*, 370–381. [\[CrossRef\]](#)
64. Díaz-González, A.; Luna, M.Y.P.; Morales, E.R.; Saldaña-Trinidad, S.; Blanco, L.R.; de la Cruz-Arreola, S.; Pérez-Sariñana, B.Y.; Robles-Ocampo, J.B. Assessment of the Pretreatments and Bioconversion of Lignocellulosic Biomass Recovered from the Husk of the Cocoa Pod. *Energies* **2022**, *15*, 3544. [\[CrossRef\]](#)
65. Lorenci Woiciechowski, A.; Dalmas Neto, C.J.; Porto de Souza Vandenberghe, L.; de Carvalho Neto, D.P.; Novak Sydney, A.C.; Letti, L.A.J.; Karp, S.G.; Zevallos Torres, L.A.; Soccol, C.R. Lignocellulosic Biomass: Acid and Alkaline Pretreatments and Their Effects on Biomass Recalcitrance—Conventional Processing and Recent Advances. *Bioresour. Technol.* **2020**, *304*, 122848. [\[CrossRef\]](#)
66. Sarmiento-Vásquez, Z.; Vandenberghe, L.; Rodrigues, C.; Tanobe, V.O.A.; Marín, O.; de Melo Pereira, G.V.; Ghislain Rogez, H.L.; Góes-Neto, A.; Soccol, C.R. Cocoa Pod Husk Valorization: Alkaline-Enzymatic Pre-Treatment for Propionic Acid Production. *Cellulose* **2021**, *28*, 4009–4024. [\[CrossRef\]](#)
67. Hernández-Mendoza, A.G.; Saldaña-Trinidad, S.; Martínez-Hernández, S.; Pérez-Sariñana, B.Y.; Láinez, M. Optimization of Alkaline Pretreatment and Enzymatic Hydrolysis of Cocoa Pod Husk (*Theobroma cacao* L.) for Ethanol Production. *Biomass Bioenergy* **2021**, *154*, 106268. [\[CrossRef\]](#)
68. Dahunsi, S.O.; Osueke, C.O.; Olayanju, T.M.A.; Lawal, A.I. Co-Digestion of *Theobroma cacao* (Cocoa) Pod Husk and Poultry Manure for Energy Generation: Effects of Pretreatment Methods. *Bioresour. Technol.* **2019**, *283*, 229–241. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Igbinadolor, R.O.; Onilude, A.A. Bioprocess Systems Applied for the Production of Bio-Ethanol from Lignocellulosic Biomass of Cocoa Pod Husk (*Theobroma cacao* L.) and Other Agricultural Residues: A Review. *Afr. J. Biotechnol.* **2013**, *12*, 5375–5388. [\[CrossRef\]](#)
70. de Oliveira, P.Z.; de Souza Vandenberghe, L.P.; Rodrigues, C.; de Melo Pereira, G.V.; Soccol, C.R. Exploring Cocoa Pod Husks as a Potential Substrate for Citric Acid Production by Solid-State Fermentation Using *Aspergillus Niger* Mutant Strain. *Process Biochem.* **2022**, *113*, 107–112. [\[CrossRef\]](#)
71. Velásquez-Jiménez, D.; Luzardo-Ocampo, I.; Gaytán-Martínez, M.; Campos-Vega, R. Design and Characterization of a Solid-State Fermented Cacao Pods and Husk-Based Functional Ingredient to Potentially Modulate Circadian Rhythm-Associated Proteins. *Food Biosci.* **2023**, *56*, 103199. [\[CrossRef\]](#)
72. Acosta, N.; De Vrieze, J.; Sandoval, V.; Sinche, D.; Wierinck, I.; Rabaey, K. Cocoa Residues as Viable Biomass for Renewable Energy Production through Anaerobic Digestion. *Bioresour. Technol.* **2018**, *265*, 568–572. [\[CrossRef\]](#)
73. Alvarez-Barreto, J.F.; Larrea, F.; Pinos, M.C.; Benalcázar, J.; Oña, D.; Andino, C.; Viteri, D.A.; Leon, M.; Almeida-Streitwieser, D. Chemical Pretreatments on Residual Cocoa Pod Shell Biomass for Bioethanol Production. *Bionatura* **2021**, *6*, 1490–1500. [\[CrossRef\]](#)

74. Perwitasari, U.; Agustina, N.T.; Pangestu, R.; Amanah, S.; Saputra, H.; Andriani, A.; Fahrurrozi; Juanssilfero, A.B.; Thontowi, A.; Widyaningsih, T.D.; et al. Cacao Pod Husk for Citric Acid Production under Solid State Fermentation Using Response Surface Method. *Biomass Convers. Biorefinery* **2023**, *13*, 7165–7173. [\[CrossRef\]](#)
75. Santana, N.B.; Teixeira Dias, J.C.; Rezende, R.P.; Franco, M.; Silva Oliveira, L.K.; Souza, L.O. Production of Xylitol and Bio-Detoxification of Cocoa Pod Husk Hemicellulose Hydrolysate by *Candida Boidinii* XM02G. *PLoS ONE* **2018**, *13*, e0195206. [\[CrossRef\]](#)
76. Santos, R.X.; Oliveira, D.A.; Sodr , G.A.; Gosmann, G.; Brendel, M.; Pungartnik, C. Antimicrobial Activity of Fermented Theobroma Cacao Pod Husk Extract. *Genet. Mol. Res.* **2014**, *13*, 7725–7735. [\[CrossRef\]](#) [\[PubMed\]](#)
77. Antwi, E.; Engler, N.; Nelles, M.; Sch ch, A. Anaerobic Digestion and the Effect of Hydrothermal Pretreatment on the Biogas Yield of Cocoa Pods Residues. *Waste Manag.* **2019**, *88*, 131–140. [\[CrossRef\]](#) [\[PubMed\]](#)
78. da Cruz Ferraz Dutra, J.; Passos, M.F.; Garc a, G.J.Y.; Gomes, R.F.; Magalh es, T.A.; dos Santos Freitas, A.; Laguna, J.G.; da Costa, F.M.R.; da Silva, T.F.; Rodrigues, L.S.; et al. Anaerobic Digestion Using Cocoa Residues as Substrate: Systematic Review and Meta-Analysis. *Energy Sustain. Dev.* **2023**, *72*, 265–277. [\[CrossRef\]](#)
79. Boussetta, N.; Vorobiev, E. Extraction of Valuable Biocompounds Assisted by High Voltage Electrical Discharges: A Review. *Comptes Rendus Chim.* **2014**, *17*, 197–203. [\[CrossRef\]](#)
80. Sanito, R.C.; You, S.-J.; Wang, Y.-F. Degradation of Contaminants in Plasma Technology: An Overview. *J. Hazard. Mater.* **2022**, *424*, 127390. [\[CrossRef\]](#)
81. Mar ek, T.; Kova , T.; Juki , K.; Lon ari , A.; I akovi , M. Application of High Voltage Electrical Discharge Treatment to Improve Wheat Germination and Early Growth under Drought and Salinity Conditions. *Plants* **2021**, *10*, 2137. [\[CrossRef\]](#)
82. Bari i , V.; Kerovec, D.; Flanjak, I.; Jozinovi , A.; Babi , J.; Lon ari , Z.;  ubari , D.; Mili evi , B.; A kar,  . Effect of High-Voltage Electrical Discharge Treatment on Multi-Element Content in Cocoa Shell and Chocolates with Cocoa Shell. *LWT* **2022**, *155*, 112944. [\[CrossRef\]](#)
83. Pinzon-Nu ez, D.A.; Adarme-Duran, C.A.; Vargas-Fiallo, L.; Rodriguez-Lopez, N.; Rios-Reyes, C.A. Biochar as a Waste Management Strategy for Cadmium Contaminated Cocoa Pod Husk Residues. *Int. J. Recycl. Org. Waste Agric.* **2022**, *11*, 101–115. [\[CrossRef\]](#)
84. Yogalakshmi, K.N.; Sivashanmugam, P.; Kavitha, S.; Kannah, Y.; Varjani, S.; AdishKumar, S.; Kumar, G. Lignocellulosic Biomass-Based Pyrolysis: A Comprehensive Review. *Chemosphere* **2022**, *286*, 131824. [\[CrossRef\]](#)
85. Yu, S.; Wang, L.; Li, Q.; Zhang, Y.; Zhou, H. Sustainable Carbon Materials from the Pyrolysis of Lignocellulosic Biomass. *Mater. Today Sustain.* **2022**, *19*, 100209. [\[CrossRef\]](#)
86. Pecha, M.B.; Garcia-Perez, M. Pyrolysis of Lignocellulosic Biomass: Oil, Char, and Gas. In *Bioenergy*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 581–619, ISBN 978-0-12-815497-7.
87. Luper n, L.M.; Rodr guez, M.H.; Hern ndez, J.F.; Otero-Calvis, A. Obtaining Bioproducts by Slow Pyrolysis of Coffee and Cocoa Husks as Suitable Candidates for Being Used as Soil Amendment and Source of Energy. *Rev. Colomb. Qu m.* **2020**, *49*, 23–29. [\[CrossRef\]](#)
88. Tsai, W.-T.; Hsu, C.-H.; Lin, Y.-Q.; Tsai, C.-H.; Chen, W.-S.; Chang, Y.-T. Enhancing the Pore Properties and Adsorption Performance of Cocoa Pod Husk (CPH)-Derived Biochars via Post-Acid Treatment. *Processes* **2020**, *8*, 144. [\[CrossRef\]](#)
89. Adjin-Tetteh, M.; Asiedu, N.; Dodoo-Arhin, D.; Karam, A.; Amaniampong, P.N. Thermochemical Conversion and Characterization of Cocoa Pod Husks a Potential Agricultural Waste from Ghana. *Ind. Crops Prod.* **2018**, *119*, 304–312. [\[CrossRef\]](#)
90. Mansur, D.; Tago, T.; Masuda, T.; Abimanyu, H. Conversion of Cacao Pod Husks by Pyrolysis and Catalytic Reaction to Produce Useful Chemicals. *Biomass Bioenergy* **2014**, *66*, 275–285. [\[CrossRef\]](#)
91. Kumar, P.; Kermanshahi-pour, A.; Brar, S.K.; Brooks, M.S. Conversion of Lignocellulosic Biomass to Reducing Sugars in High Pressure and Supercritical Fluids: Greener Alternative for Biorefining of Renewables. *Adv. Sustain. Syst.* **2021**, *5*, 2000275. [\[CrossRef\]](#)
92. Escobar, E.L.N.; Da Silva, T.A.; Pirich, C.L.; Corazza, M.L.; Pereira Ramos, L. Supercritical Fluids: A Promising Technique for Biomass Pretreatment and Fractionation. *Front. Bioeng. Biotechnol.* **2020**, *8*, 252. [\[CrossRef\]](#)
93. Lee, S.E.; Lim, J.S.; Park, Y.-K.; Shong, B.; Lee, H. Utilizing Cocoa Bean Husk Residues from Supercritical Extraction for Biofuel Production through Hydrothermal Liquefaction. *J. Supercrit. Fluids* **2025**, *215*, 106416. [\[CrossRef\]](#)
94. Ferreira, C.; Moreira, M.M.; Delerue-Matos, C.; Sarragu a, M. Subcritical Water Extraction to Valorize Grape Biomass—A Step Closer to Circular Economy. *Molecules* **2023**, *28*, 7538. [\[CrossRef\]](#)
95. Park, J.-S.; Han, J.-M.; Park, S.-W.; Kim, J.-W.; Choi, M.-S.; Lee, S.-M.; Haq, M.; Zhang, W.; Chun, B.-S. Subcritical Water Extraction of *Undaria Pinnatifida*: Comparative Study of the Chemical Properties and Biological Activities across Different Parts. *Mar. Drugs* **2024**, *22*, 344. [\[CrossRef\]](#)
96.  agar, T.; Frlan, R.; Ko ev r Glava , N. Using Subcritical Water to Obtain Polyphenol-Rich Extracts with Antimicrobial Properties. *Antibiotics* **2024**, *13*, 334. [\[CrossRef\]](#)

97. Muñoz-Almagro, N.; Valadez-Carmona, L.; Mendiola, J.A.; Ibáñez, E.; Villamiel, M. Structural Characterisation of Pectin Obtained from Cacao Pod Husk. Comparison of Conventional and Subcritical Water Extraction. *Carbohydr. Polym.* **2019**, *217*, 69–78. [[CrossRef](#)] [[PubMed](#)]
98. Yang, Y.; Wang, Y.; Lu, X.; Zheng, X.; Yan, D.; Xin, J.; El-Tantawy El-Sayed, I.; Kang, Y.; Yang, J. Highly Efficient Enzymolysis and Fermentation of Corn Stalk into L-Lactic Acid by Enzyme-Bacteria Friendly Ionic Liquid Pretreatment. *Green Chem. Eng.* **2022**, *3*, 321–327. [[CrossRef](#)]
99. Amini, E.; Valls, C.; Roncero, M.B. Ionic Liquid-Assisted Bioconversion of Lignocellulosic Biomass for the Development of Value-Added Products. *J. Clean. Prod.* **2021**, *326*, 129275. [[CrossRef](#)]
100. Hou, Q.; Ju, M.; Li, W.; Liu, L.; Chen, Y.; Yang, Q. Pretreatment of Lignocellulosic Biomass with Ionic Liquids and Ionic Liquid-Based Solvent Systems. *Molecules* **2017**, *22*, 490. [[CrossRef](#)]
101. Idi, A.; Salleh, M.M.; Ibrahim, Z.; Mohamad, S.E. Pretreatment of Cocoa Waste for Bioethanol Production Using Ionic Liquid. *J. Teknol. Sci. Eng.* **2012**, *59*, 49–56. [[CrossRef](#)]
102. Sathitsuksanoh, N.; George, A.; Zhang, Y.H.P. New Lignocellulose Pretreatments Using Cellulose Solvents: A Review. *J. Chem. Technol. Biotechnol.* **2013**, *88*, 169–180. [[CrossRef](#)]
103. Marin-Batista, J.D.; Mohedano, A.F.; de la Rubia, A. Pretreatment of Lignocellulosic Biomass with 1-Ethyl-3-Methylimidazolium Acetate for Its Eventual Valorization by Anaerobic Digestion. *Resources* **2021**, *10*, 118. [[CrossRef](#)]
104. Quesada-Salas, M.C.; Vuillemin, M.E.; Dillies, J.; Dauwe, R.; Firdaus, L.; Bigan, M.; Lambertyn, V.; Cailleu, D.; Jamali, A.; Froidevaux, R.; et al. 1-Ethyl-3-Methyl Imidazolium Acetate, Hemicellulolytic Enzymes and Laccase-Mediator System: Toward an Integrated Co-Valorization of Polysaccharides and Lignin from *Miscanthus*. *Ind. Crops Prod.* **2023**, *197*, 116627. [[CrossRef](#)]
105. Lomba, L.; Ribate, M.P.; Sangüesa, E.; Concha, J.; Garralaga, M.P.; Errazquin, D.; García, C.B.; Giner, B. Deep Eutectic Solvents: Are They Safe? *Appl. Sci.* **2021**, *11*, 10061. [[CrossRef](#)]
106. Ganorkar, S.B.; Hadole, P.M.; Patil, M.R.; Pardeshi, C.V.; Bobade, P.S.; Shirkhedkar, A.A.; Heyden, Y.V. Deep Eutectic Solvents in Analysis, Delivery and Chemistry of Pharmaceuticals. *Int. J. Pharm.* **2025**, *672*, 125278. [[CrossRef](#)]
107. Ijardar, S.P.; Singh, V.; Gardas, R.L. Revisiting the Physicochemical Properties and Applications of Deep Eutectic Solvents. *Molecules* **2022**, *27*, 1368. [[CrossRef](#)] [[PubMed](#)]
108. Li, P.; Zhang, Z.; Zhang, X.; Li, K.; Jin, Y.; Wu, W. DES: Their Effect on Lignin and Recycling Performance. *RSC Adv.* **2023**, *13*, 3241–3254. [[CrossRef](#)] [[PubMed](#)]
109. Yadav, A.; Sharma, V.; Tsai, M.-L.; Sharma, D.; Nargotra, P.; Chen, C.-W.; Sun, P.-P.; Dong, C.-D. Synergistic Microwave and Acidic Deep Eutectic Solvent-Based Pretreatment of *Theobroma Cacao* Pod Husk Biomass for Xylooligosaccharides Production. *Bioresour. Technol.* **2024**, *400*, 130702. [[CrossRef](#)]
110. Sharma, D.; Sharma, V.; Tsai, M.-L.; Nargotra, P.; Yadav, A.; Sun, P.-P.; Chen, C.-W.; Dong, C.-D. Recent Advances in Ultrasound-Assisted Technologies for Improved Bioproduct Recovery in Lignocellulosic and Microalgal Biorefineries. *J. Ind. Eng. Chem.* **2025**, *in press*. [[CrossRef](#)]
111. Ramirez Cabrera, P.A.; Lozano Pérez, A.S.; Guerrero Fajardo, C.A. Innovative Design of a Continuous Ultrasound Bath for Effective Lignocellulosic Biomass Pretreatment Based on a Theoretical Method. *Inventions* **2024**, *9*, 105. [[CrossRef](#)]
112. Hoang, A.T.; Nižetić, S.; Ong, H.C.; Mofijur, M.; Ahmed, S.F.; Ashok, B.; Bui, V.T.V.; Chau, M.Q. Insight into the Recent Advances of Microwave Pretreatment Technologies for the Conversion of Lignocellulosic Biomass into Sustainable Biofuel. *Chemosphere* **2021**, *281*, 130878. [[CrossRef](#)]
113. Haldar, D.; Purkait, M.K. A Review on the Environment-Friendly Emerging Techniques for Pretreatment of Lignocellulosic Biomass: Mechanistic Insight and Advancements. *Chemosphere* **2021**, *264*, 128523. [[CrossRef](#)]
114. Puligundla, P.; Oh, S.-E.; Mok, C. Microwave-Assisted Pretreatment Technologies for the Conversion of Lignocellulosic Biomass to Sugars and Ethanol: A Review. *Carbon Lett.* **2016**, *17*, 1–10. [[CrossRef](#)]
115. Susanti, R.F.; Wiratmadja, R.G.R.; Kristianto, H.; Arie, A.A.; Nugroho, A. Synthesis of High Surface Area Activated Carbon Derived from Cocoa Pods Husk by Hydrothermal Carbonization and Chemical Activation Using Zinc Chloride as Activating Agent. *Mater. Today Proc.* **2022**, *63*, S55–S60. [[CrossRef](#)]
116. Vasić, K.; Knez, Ž.; Leitgeb, M. Bioethanol Production by Enzymatic Hydrolysis from Different Lignocellulosic Sources. *Molecules* **2021**, *26*, 753. [[CrossRef](#)]
117. Hennessey-Ramos, L.; Murillo-Arango, W.; Vasco-Correa, J.; Paz Astudillo, I.C. Enzymatic Extraction and Characterization of Pectin from Cocoa Pod Husks (*Theobroma cacao* L.) Using Celluclast® 1.5 L. *Molecules* **2021**, *26*, 1473. [[CrossRef](#)] [[PubMed](#)]
118. Saini, J.K.; Himanshu; Hemansi; Kaur, A.; Mathur, A. Strategies to Enhance Enzymatic Hydrolysis of Lignocellulosic Biomass for Biorefinery Applications: A Review. *Bioresour. Technol.* **2022**, *360*, 127517. [[CrossRef](#)] [[PubMed](#)]
119. Olivieri, G.; Wijffels, R.H.; Marzocchella, A.; Russo, M.E. Bioreactor and Bioprocess Design Issues in Enzymatic Hydrolysis of Lignocellulosic Biomass. *Catalysts* **2021**, *11*, 680. [[CrossRef](#)]
120. Sarah, M.; Hasibuan, I.M.; Misran, E.; Maulina, S. Optimization of Microwave-Assisted Pectin Extraction from Cocoa Pod Husk. *Molecules* **2022**, *27*, 6544. [[CrossRef](#)]

121. Mao, Y.; Gerrow, A.; Ray, E.; Perez, N.D.; Edler, K.; Wolf, B.; Binner, E. Lignin Recovery from Cocoa Bean Shell Using Microwave-Assisted Extraction and Deep Eutectic Solvents. *Bioresour. Technol.* **2023**, *372*, 128680. [\[CrossRef\]](#)
122. Anoraga, S.B.; Shamsudin, R.; Hamzah, M.H.; Sharif, S.; Saputro, A.D. Cocoa by-Products: A Comprehensive Review on Potential Uses, Waste Management, and Emerging Green Technologies for Cocoa Pod Husk Utilization. *Heliyon* **2024**, *10*, e35537. [\[CrossRef\]](#)
123. Anoraga, S.B.; Shamsudin, R.; Hamzah, M.H.; Sharif, S.; Saputro, A.D.; Basri, M.S.M. Optimization of Subcritical Water Extraction for Pectin Extraction from Cocoa Pod Husks Using the Response Surface Methodology. *Food Chem.* **2024**, *459*, 140355. [\[CrossRef\]](#)
124. Muharja, M.; Darmayanti, R.F.; Palupi, B.; Rahmawati, I.; Fachri, B.A.; Setiawan, F.A.; Amini, H.W.; Rizkiana, M.F.; Rahmawati, A.; Susanti, A.; et al. Optimization of Microwave-Assisted Alkali Pretreatment for Enhancement of Delignification Process of Cocoa Pod Husk. *Bull. Chem. React. Eng. Catal.* **2021**, *16*, 31–43. [\[CrossRef\]](#)
125. Cui, J.; Zhao, C.; Feng, L.; Han, Y.; Du, H.; Xiao, H.; Zheng, J. Pectins from Fruits: Relationships between Extraction Methods, Structural Characteristics, and Functional Properties. *Trends Food Sci. Technol.* **2021**, *110*, 39–54. [\[CrossRef\]](#)
126. Yauri, S.; Fissore, E.N.; Chavez, S.G.; Rojas, A.M. Advanced Valorization of Cocoa (*Theobroma cacao* L.) Pod Husks through 40 kHz-Ultrasonic Bath Assisted Extraction of Pectins. *Sustain. Chem. Pharm.* **2024**, *42*, 101869. [\[CrossRef\]](#)
127. Yi, L.; Cheng, L.; Yang, Q.; Shi, K.; Han, F.; Luo, W.; Duan, S. Source, Extraction, Properties, and Multifunctional Applications of Pectin: A Short Review. *Polymers* **2024**, *16*, 2883. [\[CrossRef\]](#) [\[PubMed\]](#)
128. Barišić, V.; Stokanović, M.C.; Flanjak, I.; Doko, K.; Jozinović, A.; Babić, J.; Šubarić, D.; Miličević, B.; Cindrić, I.; Ačkar, Đ. Cocoa Shell as a Step Forward to Functional Chocolates—Bioactive Components in Chocolates with Different Composition. *Molecules* **2020**, *25*, 5470. [\[CrossRef\]](#) [\[PubMed\]](#)
129. Abd El-Wahab, A.; Chuppava, B.; Siebert, D.-C.; Visscher, C.; Kamphues, J. Digestibility of a Lignocellulose Supplemented Diet and Fecal Quality in Beagle Dogs. *Animals* **2022**, *12*, 1965. [\[CrossRef\]](#) [\[PubMed\]](#)
130. Delgado-Ospina, J.; Martuscelli, M.; Grande-Tovar, C.D.; Lucas-González, R.; Molina-Hernandez, J.B.; Viuda-Martos, M.; Fernández-López, J.; Pérez-Álvarez, J.Á.; Chaves-López, C. Cacao Pod Husk Flour as an Ingredient for Reformulating Frankfurters: Effects on Quality Properties. *Foods* **2021**, *10*, 1243. [\[CrossRef\]](#)
131. Barrios-Rodríguez, Y.F.; Salas-Calderón, K.T.; Orozco-Blanco, D.A.; Gentile, P.; Girón-Hernández, J. Cocoa Pod Husk: A High-Pectin Source with Applications in the Food and Biomedical Fields. *ChemBioEng Rev.* **2022**, *9*, 462–474. [\[CrossRef\]](#)
132. Adi-Dako, O.; Ofori-Kwakye, K.; Kukuia, K.K.E.; Asiedu-Larbi, J.; Nyarko, A.; Osei-Asare, C. Subchronic Toxicity Studies of Cocoa Pod Husk Pectin. *J. Pharm. Pharmacogn. Res.* **2018**, *6*, 271–284. [\[CrossRef\]](#)
133. Pinkaew, T.; Inthachai, W.; Khemthong, C.; Kemsawas, V.; On-Nom, N.; Temviriyankul, P. High Pectin Recovery from Cocoa Husks Using an Autoclave Approach: An Analysis of Its Physicochemical, Structural, and Genotoxicity Properties. *Foods* **2024**, *13*, 669. [\[CrossRef\]](#)
134. Jozinović, A.; Panak Balentić, J.; Ačkar, Đ.; Babić, J.; Pajin, B.; Miličević, B.; Guberac, S.; Vrdoljak, A.; Šubarić, D. Cocoa Husk Application in the Enrichment of Extruded Snack Products. *J. Food Process. Preserv.* **2019**, *43*, e13866. [\[CrossRef\]](#)
135. Cruz-Santos, M.M.; Antunes, F.A.F.; Arruda, G.L.; Shibukawa, V.P.; Prado, C.A.; Ortiz-Silos, N.; Castro-Alonso, M.J.; Marcelino, P.R.F.; Santos, J.C. Production and Applications of Pullulan from Lignocellulosic Biomass: Challenges and Perspectives. *Bioresour. Technol.* **2023**, *385*, 129460. [\[CrossRef\]](#)
136. Machineni, L.; Rao Anupolu, G. Review on Valorization of Lignocellulosic Biomass for Green Plastics Production: Sustainable and Cleaner Approaches. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102698. [\[CrossRef\]](#)
137. Holguín Posso, A.M.; Macías Silva, J.C.; Castañeda Niño, J.P.; Mina Hernandez, J.H.; Fajardo Cabrera De Lima, L.D.P. Characterization and Implementation of Cocoa Pod Husk as a Reinforcing Agent to Obtain Thermoplastic Starches and Bio-Based Composite Materials. *Polymers* **2024**, *16*, 1608. [\[CrossRef\]](#) [\[PubMed\]](#)
138. Santibáñez, L.; Henríquez, C.; Corro-Tejeda, R.; Bernal, S.; Armijo, B.; Salazar, O. Xylooligosaccharides from Lignocellulosic Biomass: A Comprehensive Review. *Carbohydr. Polym.* **2021**, *251*, 117118. [\[CrossRef\]](#) [\[PubMed\]](#)
139. Ali, K.; Niaz, N.; Waseem, M.; Ashraf, W.; Hussain, M.; Khalid, M.U.; Tahir, A.B.; Raza, A.; Khan, I.M. Xylooligosaccharides: A Comprehensive Review of Production, Purification, Characterization, and Quantification. *Food Res. Int.* **2025**, *201*, 115631. [\[CrossRef\]](#) [\[PubMed\]](#)
140. Ruan, R.; Zhang, Y.; Chen, P.; Liu, S.; Fan, L.; Zhou, N.; Ding, K.; Peng, P.; Addy, M.; Cheng, Y.; et al. Biofuels: Introduction. In *Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 3–43, ISBN 978-0-12-816856-1.
141. Liu, Y.; Cruz-Morales, P.; Zargar, A.; Belcher, M.S.; Pang, B.; Englund, E.; Dan, Q.; Yin, K.; Keasling, J.D. Biofuels for a Sustainable Future. *Cell* **2021**, *184*, 1636–1647. [\[CrossRef\]](#)
142. Datta, A.; Hossain, A.; Roy, S. An Overview on Biofuels and Their Advantages and Disadvantages. *Asian J. Chem.* **2019**, *31*, 1851–1858. [\[CrossRef\]](#)
143. Sakhakarmy, M.; Kemp, A.; Biswas, B.; Kafle, S.; Adhikari, S. A Comparative Analysis of Bio-Oil Collected Using an Electrostatic Precipitator from the Pyrolysis of Douglas Fir, Eucalyptus, and Poplar Biomass. *Energies* **2024**, *17*, 2800. [\[CrossRef\]](#)

144. Corvianindya, Y.; Maduratna, E.; Pudji, R.; Elsayed, D. Analysis of antioxidant and antibacterial activity of cocoa podhusk extract (*Theobroma cacao* L.). *Dental Journal* **2023**, *4*, 220–225. [[CrossRef](#)]
145. Vásquez, Z.S.; De Carvalho Neto, D.P.; Pereira, G.V.M.; Vandenberghe, L.P.S.; De Oliveira, P.Z.; Tiburcio, P.B.; Rogez, H.L.G.; Góes Neto, A.; Soccol, C.R. Biotechnological Approaches for Cocoa Waste Management: A Review. *Waste Manag.* **2019**, *90*, 72–83. [[CrossRef](#)]
146. Tantapakul, C.; Khat-udomkiri, N.; Sitthichai, P.; Chomsak, A.; Thananusak, N.; Phukhatmuen, P.; Vinardell, M.P.; Sripisut, T. Exploring the Physicochemical Properties of Polysaccharides Extracted from Cocoa Pod Husk Waste and Their Efficacy in Skin Hydration. *Ind. Crops Prod.* **2024**, *222*, 119940. [[CrossRef](#)]
147. Liang, T.; Ma, Y.; Jiang, Z.; Remón, J.; Zhou, Y.; Shi, B. New Insights into Greener Skin Healthcare Protection: Lignin Nanoparticles as Additives to Develop Natural-Based Sunscreens with High UV Protection. *Carbon Resour. Convers.* **2024**, *7*, 100227. [[CrossRef](#)]
148. Ayilara, M.; Olanrewaju, O.; Babalola, O.; Odeyemi, O. Waste Management through Composting: Challenges and Potentials. *Sustainability* **2020**, *12*, 4456. [[CrossRef](#)]
149. Mwafulirwa, L.; Sizmur, T.; Daymond, A.; Atuah, L.; Quaye, A.K.; Coole, S.; Robinson, S.; Hammond, J.; Awudzi, G.; Awunyo-Vitor, D.; et al. Cocoa Pod Husk-Derived Organic Soil Amendments Differentially Affect Soil Fertility, Nutrient Leaching, and Greenhouse Gas Emissions in Cocoa Soils. *J. Clean. Prod.* **2024**, *479*, 144065. [[CrossRef](#)]
150. Tusar, H.M.; Uddin, M.K.; Mia, S.; Suhi, A.A.; Wahid, S.B.A.; Kasim, S.; Sairi, N.A.; Alam, Z.; Anwar, F. Biochar-Acid Soil Interactions—A Review. *Sustainability* **2023**, *15*, 13366. [[CrossRef](#)]
151. Abbey, C.Y.B.; Duwiejuah, A.B.; Quianoo, A.K. Removal of Toxic Metals from Aqueous Phase Using Cacao Pod Husk Biochar in the Era of Green Chemistry. *Appl. Water Sci.* **2022**, *13*, 57. [[CrossRef](#)]

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