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Review

Coconut Waste: Discovering Sustainable Approaches to Advance a Circular Economy

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Abstract: The coconut tree *(Cocos nucifera*) stands as a pivotal resource in tropical regions, playing a crucial role in both subsistence and economic activities across Asia, the Pacific Islands, and South America. While the harvesting of coconut fruit is essential for producing globally utilized edible products, such as coconut oil, by small owners and large producers around the world in the food, cosmetics, and pharmaceutical industries, concerns have arisen due to the substantial amount of agro-industrial residue generated in this process, posing environmental risks if they are not properly managed. Recognizing the environmental challenges, this paper emphasizes the transformative potential inherent in coconut waste, characterized by its lignocellulosic composition rich in lignin and multifunctional groups. By delving into the historical context of coconut economic exploration and its chemical composition, this review explores the diverse applications of coconut products, focusing on the utilization and processing of residues to generate sustainable products and byproducts. Ultimately, this comprehensive review underscores the significance of repurposing coconut waste, not only to mitigate the environmental impact but also as a valuable contributor to a circular economy, promoting the use of the lignocellulosic biomass in research and bolstering its role as a raw material in the chemical and energy sectors.

Keywords: coconut waste; circular economy; sustainability; lignocellulosic biomass; bioproducts; environmental stewardship

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1. Introduction

Coconut palm tree (*Cocos nucifera*), the only recorded species of the genus Cocos, is a perennial plant with multiple uses and is widely disseminated on almost all continents [1]. It can easily adapted to and can be cultivated under many soil types and climate conditions. Nonetheless, the coconut tree grows best under a humid tropical climate, being extensively found in tropical areas, wherein it is considered one of the main crops and plays a vital role in the economic and subsistence activities of the lower Pacific Islands [2]. From coconut fruit, it is possible to generate, directly or indirectly, different value-added products with applications across several sectors, whether made from its mature or immature state and *in natura* or processed [3].

The coconut fruit is a fibrous drupe comprising five parts [4]: a solid endosperm (coconut meat or kernel) and liquid endosperm (coconut water), both known as the edible parts of the coconut, and three hierarchical layers of peel enclosing the seed: the endocarp (hard inner shell), mesocarp (a thick husk), and exocarp (outer shell) (Figure 1) [5,6]. Coconut meat is the most exploited fruit component; however, every part of the plant, from the stems to husk and shells, can be used to make value-added products and byproducts [3].

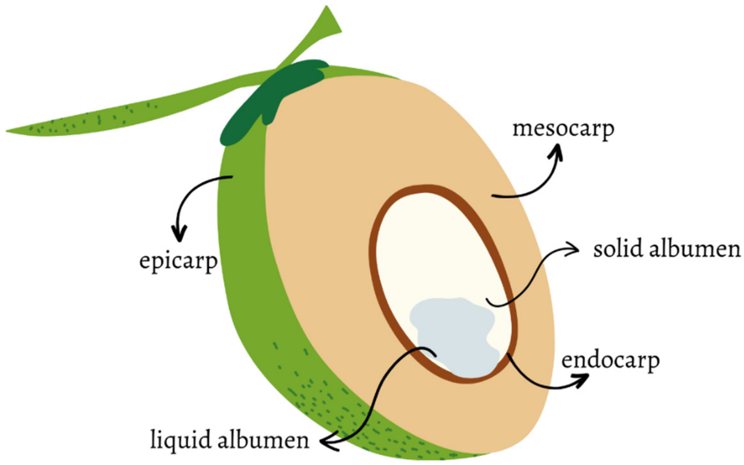

Figure 1. Constituent parts of coconut (*Cocos nucifera*).

Copra, the dried mature kernel, is the source of coconut oil, the primary marketable product of the coconut industry [6]. Coconut oil is commercialized in different forms and has wide applications in food, cosmetics, pharmaceutics, hair care products, and paint [7,8]. Other non-oil kernel applications include the obtention of desiccated coconut (grated and dehydrated coconut meat), coconut milk, coconut cream, and coconut flour. In the international coconut trade, the oil and desiccated coconut account for 60% and 17.3% of exported products and 57.4% and 15.6% of imported products, respectively [9]. The tender coconut water in fresh fruit is a nutritionally rich and refreshing liquid that has been commercialized as a natural isotonic beverage. In Brazil, the per capita consumption of coconut water is 0.74 L/habitant/year [10]. Because of the sugar content, coconut water is also used as a substrate for vinegar production [11].

A non-traditional application of coconut is the use of its residues, which have a heterogeneous chemical composition mainly composed of cellulose, hemicellulose, and lignin [4,12]. Since the mesocarp and endocarp represent about 35% and 15% of the total fruit weight [13], respectively, the processing of coconut water and meat leads to the annual generation of 1,400,980 tons of shell [14,15], which has a slow degradation rate and when mismanaged, whether by direct disposal or open burning, causes environmental pollution, which has implications for human health [16]. Therefore, a circular economy approach, involving recycling coconut residues to create valuable products, can help mitigate these negative impacts by avoiding the burning and improper disposal of these wastes [17]. By adopting this approach, coconut residues can be transformed into value-added products such as handicrafts, organic fertilizers [18], bioethanol [19], cementitious materials [20], bioadsorbents for water pollutants [21], and alternative solid fuels [22]. This not only helps reduce the amount of waste sent to landfills but it also promotes resource conservation and mitigates the effects of climate change. Thus, the circular economy offers a sustainable solution for handling coconut residues, benefiting both the environment and society as a whole [23].

Recently, to improve the sustainability and economic value of the coconut supply chain, numerous scientific studies have been conducted to develop more efficient technology pathways that allow for the exploration of the whole potential of the physicochemical properties of coconut biomass residues. The mesocarp has been evaluated as an additive to produce thermal and acoustic insulation in building construction [24], as a biosorbent to adsorb rhodamine B [25], in ethanol production [26], and to improve the mechanical properties of biocomposites [27]. Meanwhile, the endocarp, the innermost rigid layer, has been reported as a raw material for the production of porous carbon [28], the preparation of bio-additives to improve the thermal and UV-blocking properties of epoxy resins [29], and the generation of thermal energy [30].

Coconut residues play a crucial role in a circular economy, offering numerous opportunities for repurposing waste and maximizing resource efficiency. By integrating these residues into circular economy practices, such as recycling and upcycling initiatives, valuable products can be created while reducing waste generation [31]. This not only stimulates economic growth and job creation but it also contributes to environmental conservation by minimizing carbon footprints and promoting sustainable alternatives to conventional materials. Embracing coconut residues within a circular economy framework facilitates sustainable development and fosters a regenerative approach to resource management [23].

There has been an upward trend in research focusing on expanding the potential of coconut residues for new applications and improving the efficiency of a well-known conversion process. However, although remarkable advances have been achieved in this direction, many of the innovative technologies in coconut residue processing for value-added products are still at an early stage and some challenges must be overcome, such as the lack of adequate infrastructure for the collection, transportation, and processing of residues and further research to demonstrate large-scale feasibility from a technical-economic perspective. Improving and integrating the coconut lignocellulosic residue value chain into a growing economy and biorefineries are essential foe sustainability and to reduce the environmental impact of residue disposal.

This study focused on optimizing the utilization of coconut residues, highlighting the infrastructure and logistics challenges, and exploring the feasibility of developing economically viable value-added products. It also examined the integration of coconut residue valorization into the circular bioeconomy, advocating for sustainable residue management. The objective was to provide a comprehensive overview of coconut historical insights, planting characteristics, chemical compositions, and applications, with a focus on generating value-added products from residues. Recognizing the paramount importance of coconuts in the global economy and the abundance of their residues, this paper offers a concise literature review on key aspects and highlights the current status, challenges, and future prospects of integrating agro-industrial coconut residues into the circular bioeconomy. Overall, this study aims to promote sustainable practices, particularly by emphasizing the economic and industrial reintegration of the lignocellulosic biomass as a key raw material for value-added products.

2. Research Method and Approach

This study comprised a broad literature review to summarize, evaluate, and integrate the previous research on the main aspects associated with the coconut industry and its agro-industrial residues. The adopted methodology was based on the identification and in-depth analysis of original research articles, reviews, and technical notes related to the topic. First, the search for high-quality scientific publications was carried out using scientific databases such as Scopus, Web of Science, Scielo, and Google Scholar. The following Boolean searches were used: (Coconut), (Coconut fiber Or Coconut coir fiber), (Coconut endocarp), (Coconut waste Or Coconut residue) and (Coconut shells Or Coconut husk). A total of 1104 results were found for Scielo, 357 for Web of Science, 4327 on Scopus, and 967 on Google Scholar. Then, the selected articles were carefully evaluated to retrieve the relevant information and identify the chief aspects of the coconut plant and its whole value chain. The major topics evaluated were coconut history, cultivation characteristics, industrial applications, processing technologies, forms of commercialization, and the progress in the field of coconut residue valorization, which includes chemical composition analyses, current and potential applications, and future perspectives toward a sustainable bioeconomy. Thus, this methodology allowed for a complete analysis of the reuse of agro-industrial coconut residues, establishing a solid basis for boosting the coconut industry's integration into the circular economy. Figure 2 summarizes the overall and detailed aspects of coconut residue uses that were reviewed in this study.

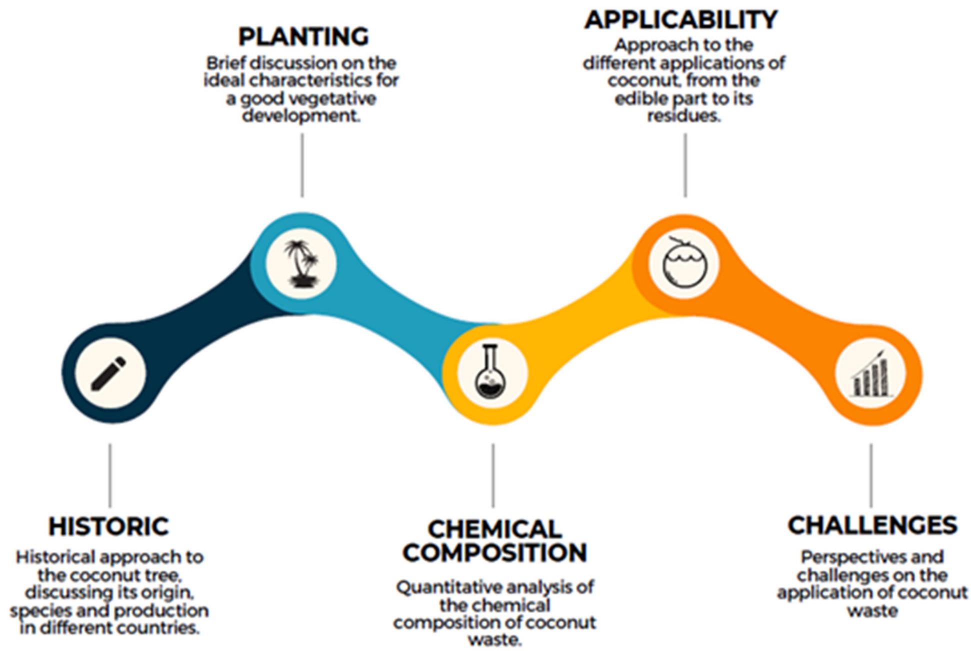

Figure 2. Aspects addressed and discussed in this study.

3. Coconut History, Cultivation, and Value Chain

3.1. Historical Records of Coconut

The origin of coconut is assigned to the Indo-Pacific region [32]. It is a native species of the Indian and Pacific ocean regions, showing a long-standing and independent evolutionary presence in both ocean basins [33]. Coconut has been cultivated in the lowland tropics of West Africa and the Neotropics, where the soil and climatic conditions favor its development [34].

Coconut was disseminated along much of the tropics, possibly due to the movement of ocean currents and navigators [1]. By the end of the XVI century, coconut palm was already present in all tropic regions, except for the tropical coast of Australia, which was still unknown to European navigators [35].

Currently, coconut is produced and commercially exploited in over 90 countries [32], accounting for an annual worldwide production of 64 million tons of fruits [36]. Indonesia, the Philippines, and India are the largest producers with 17.5 Mt, 14.7 Mt, and 11 Mt of coconut produced per year in a harvest area of 2.8, 3.6, and 2.2 million ha, respectively. Indonesia and the Philippines are also the leading suppliers of coconut fruit (fresh, dried, or dissected) and its derived products (32.1% and 24.2% of the total amount of exported products). Other important players in the global market are Sri Lanka (2.2 million tons) and Brazil (2.4 million tons) (Figure 3) [36]. In Brazil, the northeast is the central producing region, responsible for an annual production of 1.44 Mt of coconut fruits (78% total production), which is cultivated in a harvest area of 157,403 ha (82% total area) and generates a production value of BRL 1.12 billion (70% total value). The cultivation is predominant in the coastal areas of the Ceará, Bahia, Pernambuco, and Sergipe states [37].

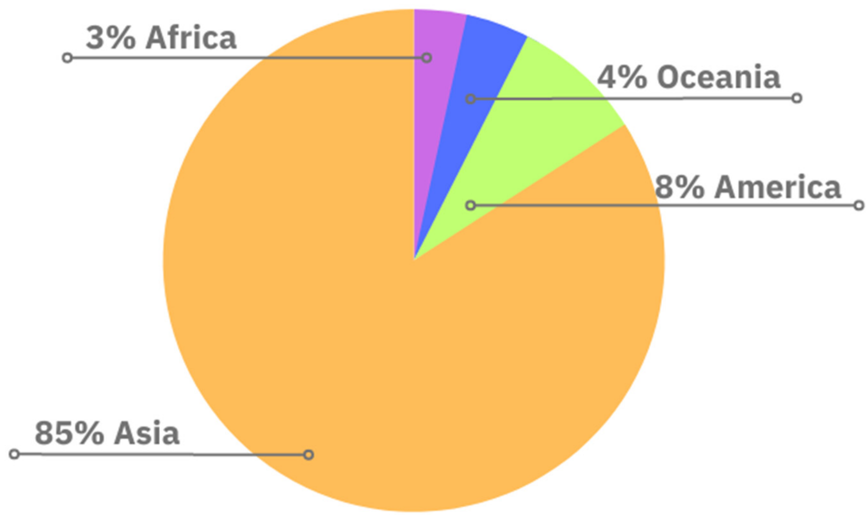

Figure 3. Average percentage contribution of coconut-producing continents from 2000 to 2021, according to FAO [15].

The contribution of each continent to global coconut production, on average between 2000 and 2021, is distributed according to the information present in Figure 4. Notably, coconut production is heavily concentrated on the Asian continent, particularly in the southeastern and southern subregions. Europe does not participate significantly in this industry, while the Antarctic is not ranked, and neither appear in the graph.

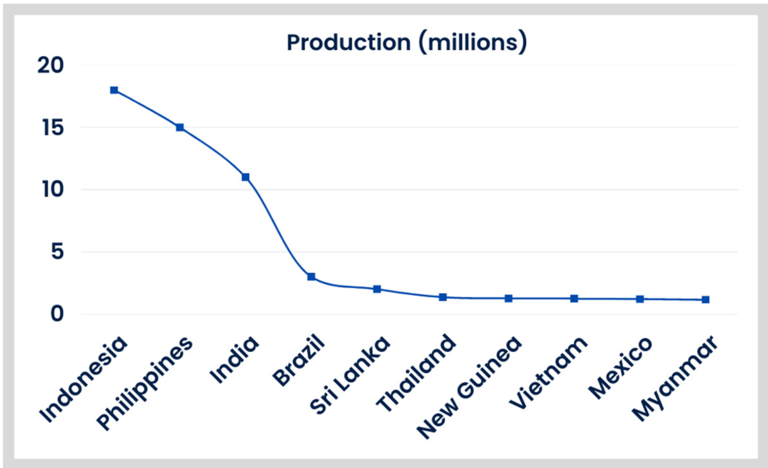

Figure 4. Average coconut production by country from 2000 to 2021, according to FAO [15].

3.2. The Main Aspects of Coconut Cultivation

The monotypic species *Cocos nucifera* belongs to the palm tree family *Arecaceae* [34] and its species can be broadly classified into *Typica*, the tall type, and *Nana*, the dwarf type. Crossing these two types result in hybrid varieties [38]. As presented in Table 1, the palm plant has different characteristics according to its variety, in which, height and lifespan are the most relevant and can reach up to 10 m and 20 years.

Table 1. Characteristics of coconut tree (*Cocos nucifera*) varieties.

Characteristic	*Typica*	*Nana*	Hybrid
Height	30 m	10–12 m	20 m
Life cycle	60–80 years	30 years	50 years
Growth	Fast	Slow	Intermediate
Fluorescence time	5–7 years	2–3 years	3–4 years
Applications	Agro-industry/food preparation	Water consumption	Water consumption/agro-industry/food preparation

Source: adapted from Niral and Jerard [39]; Donadio et al. [40]; and Embrapa [14].

The successful development of coconuts, mostly in the world's tropical areas, requires warm conditions and high humidity for their proper growth and yield [32]. Optimal coconut production occurs under a well-distributed rainfall of 1500–2500 mm/year, mean annual temperatures of 27–30 °C, and relative humidity above 60% [3]. Weak to moderate winds also favor coconut development since they increase transpiration and, consequently, the roots' absorption of water and nutrients [41].

On the other hand, long dry spells and extreme weather events with high temperatures adversely affect coconut productivity [42], primarily when they occur during the initial stage of inflorescence. In their work, Hebbar et al. [43] identified stress during the pollen germination phase due to the influence of temperatures higher than 33.7 °C. Also, coconut is known as a cold-intolerant plant, as it can only support short and mild cold periods and should not face seasons of cool temperatures (below 21 °C) longer than three months [44].

Solar radiation is also considered a climate variable that significantly influences coconut yields. These palms require abundant sunshine and do not develop well under poor luminosity conditions [45]. Apart from climate factors, the coconut palm tree grows best in soils that are well-draining and rich in chloride [3,46], but it is adaptable to a wide range of soil textures such as laterite, alluvial, sandy loam, coastal sandy, and clayey, and it can tolerate acidic and alkaline soils (pH 5–8) and the presence of different levels of nitrogen, potassium, and phosphorous [44].

Besides being determinants in the survival and growth of coconut, all the mentioned variables and properties regarding genotypes, maturity level, and cultivation conditions significantly influence the chemical composition of coconut fibers and seeds [47,48]. In the earlier stages, coconut fruit develops a husk and shell with a cavity that reaches the maximum water amount and sugar content at 6–8 months. Water gradually reduces in volume with aging, and the husk and shell turn brown and more fibrous [39]. During nut maturation, the content of extractives in the pericarp tends to decrease while the content of lignin and carbohydrates increases, wherein the measurement of a gradual increase in the glucose level is due to the formation of cellulose [49]. Kernel formation starts 5–6 months after fertilization as a thin jelly-like material that, with development, turns white and becomes a thicker solid (10–15 mm). The formation of the copra is complete at 11–12 months when the oil content has increased from traces to 40–70% of the fruit [50,51].

Regarding genotype, Corradini et al. [52] studied the characteristics of green coconut fibers from five different cultivars of the dwarf variety and identified differences in the chemical compositions of cellulose and lignin. Although all samples were richer in lignin than cellulose, the cultivar "Brazilian Green Dwarf—Jiqui" was found to have the lowest lignin content of 37.2 ± 0.8% while "Brazilian Yellow Dwarf—Gramame" was found to have the highest lignin content of 43.9 ± 0.7. The cultivar "Malayan Red Dwarf" presented the highest level of cellulose (37.4 ± 0.5%) and "Cameroon Red Dwarf" the lowest (31.5 ± 0.1%).

In general, the selection of cultivars and maturity stage for harvest must consider the specific utilization of coconut kernels. Fruits from dwarf cultivars are smaller and have a lower copra and oil content [53]. Because of the quality of its tender nut, the young coconut of dwarf type is destined for water consumption, with harvest occurring in the eighth-month post flowering [50,54]. Dwarf palms are also more sensitive to environmental stresses. The harvest of tall and hybrid varieties happens at 11–13 months when their fruits have an optimal maturation state with thicker kernels, good-quality copra, and a high oil content (65–70%). These are mainly used for agro-industrial and domestic uses [50,54].

3.3. Coconut's Main Products

As discussed in the previous sections, coconut fruit in all its forms (water, kernel, and residues) has been widely exploited for several uses and in several industrial segments, e.g., coconut oil production, food, cosmetics, and as a water source. Figure 5 presents some of the applications of coconut.

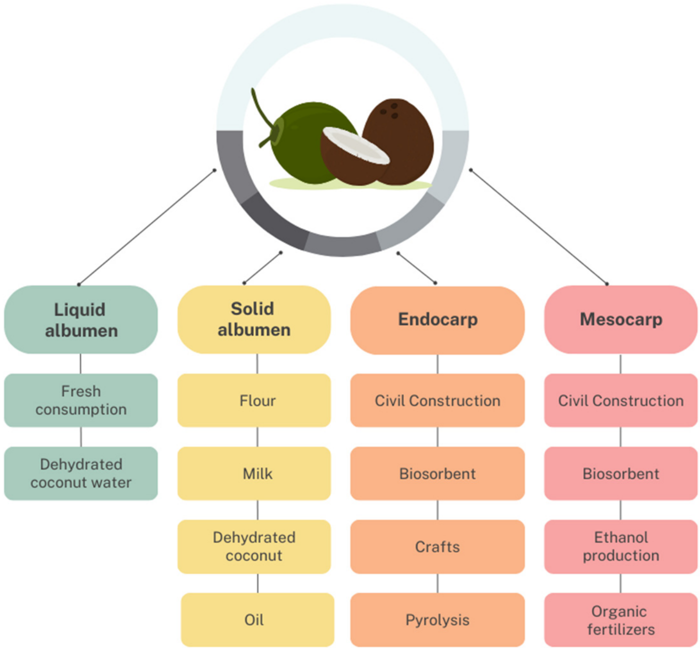

Figure 5. Various applications of the constituent parts of coconut.

The liquid endosperm or coconut water is a natural functional beverage that is widely consumed due to its significant nutritional qualities, antioxidant potential, and low carbohydrate and fat content [55]. The composition of coconut water varies depending on the maturity stage, coconut variety, and other aspects [56]. Coconut water is commercially available fresh directly from fruits, bottled, canned, frozen, or as powder, and has long been consumed in tropical countries such as Sri Lanka, India, Thailand, and Brazil, where it is cultivated in abundance. In more recent years, exportation to markets in the United States and Europe has also increased [51].

Solid albumen is the primary coconut product because it is a major commercial source of vegetable oil (coconut oil). The world demand for coconut oil is approximately 3 Mt per year [15], which is used in food industries as an alternative cooking fat [57]; in the cosmetics industry for hair products and body moisturizers, improving skin barrier function, and anti-inflammatory activity in the skin [58]; and in the pharmaceutical industry, as it has antioxidant, anti-inflammatory, and cytoprotective efficacy due to its polyphenolics [59–61].

Coconut oil is rich in saturated fatty acids (up to 91%), which mainly consist of medium-chain fatty acids (MCFAs) with small percentages of unsaturated fatty acids (UFAs) and polyunsaturated acids. The MCFAs include lauric (the major contributor in fully matured fruits—up to 52%), capric, and caprylic acids, while the UFAs comprises linoleic and oleic acids [62,63]. During fruit growth and development, there is a progressive increase in the oil percentage and a significant change in the fatty acid profile [64]. Due to this chemical profile of MCFAs, coconut oil is more resistant to oxidative rancidity during storage, more thermally stable, and more quickly metabolized than the fatty acids found in animal fat [65].

Various methods have been employed to extract coconut oil: (i) mechanical, generally by pressing the copra; (ii) traditional, by boiling with water; and (iii) leaching out with a solvent [66]. Coconut oil can present different characteristics and applications depending on the extraction method and post-treatment. Chemical means are applied to obtain refining, bleaching, and deodorizing (RBD) oil. Using solvents and high temperatures deactivates the high-value components in oil, reducing the aroma and taste and some health-promoting effects. On the other hand, virgin coconut oil (VCO) is solvent-free and extracted from fresh meat or milk through natural or mechanical techniques, with or without heat application. The absence of chemicals allows the oil to retain its natural sensory and functional characteristics [67]. Therefore, unrefined oil has increased in popularity around the world because of its versatility and health benefits, and is one of the most prominent coconut products in the in the main coconut-producing countries.

Flour, milk, and desiccated (disintegrated and dehydrated) coconut are the other coconut kernel versions that are applied in the food industry. Coconut milk is a natural oil-in-water emulsion that can be prepared domestically by manually pressing the grated solid albumen on industrial and commercial scales using a hydraulic or mechanical pressing process [68]. Coconut flour is a good source of dietary fiber and protein; it is produced from the byproducts of the coconut milk and oil industries. It is obtained after the leftovers go through bleaching, pressing, and grinding to reduce their size [69]. Desiccated coconut is produced from mature kernel following three main steps: drying to about 2.5% moisture, sterilization, and shredding. It is estimated that, to produce 1 ton of desiccated coconut, 8000 coconut nuts are needed; this product is widely used in the bakery and confectionery industries [70].

Coconut sugar is another marketable *Cocos nucifera* product with significant utility in the food and beverage industry. Instead of being obtained from the fruit, the sugar is tapped from the palm tree inflorescence sap, popularly known as 'neera'. This sap contains approximately 16% sucrose and, hence, upon heating at a high temperature, forms crystalline or amorphous sugar. Coconut sugar is brown, contains 2–3% moisture, has high nutritional value, and is rich in amino acids, vitamins, minerals, polyphenols, and antioxidants. In addition, it has a low glycemic index compared to sugar cane, and is considered a suitable sweetener for some health conditions [71,72].

The worldwide exportation and importation of coconut products total about USD 5.7 billion and USD 6.1 billion, respectively. In 2021, Brazil imported 13.3 kt (trade value of USS 29.6 million) and exported 1.2 kt (trade value of USS 29.6 million) of coconut products, changes of −33% and +24% compared to 2019. Although Brazil is among the top five coconut-producing countries, most of the production is destined for the commercialization of green fruits. In this sense, to supply the domestic demand, desiccated coconut and coconut oil are imported from Indonesia, Malaysia, the Philippines, and Uruguay [36].

4. Coconut Residues

4.1. Lignocellulosic Composition

The chemical composition is the most critical characteristic of lignocellulosic materials [73], which are mostly composed of cellulose, hemicellulose, and lignin [4,12].

Cellulose is a naturally occurring polymer and is the main component of the plant cell wall and the most abundant organic compound found in nature [74]. Structurally, it is a linear-chain polysaccharide formed by monomeric units of D-glucose linked by β 1–4 bonds. Natural cellulose chains consist of individual fibers in a parallel arrangement of crystalline (ordered) and amorphous (less-ordered) regions [75,76].

The molecular orientation and hydrogen bonding networks in crystalline regions of the cellulose chain can vary greatly and occur as different polyforms, whose structure depends on the cellulose source and extraction/treatment method used. Type I polyform cellulose has a higher degree of crystallinity and organization and is used to prepare nanocomposites with higher mechanical properties; meanwhile, type II and III cellulose presents an amorphous morphology and is applied in pharmaceuticals, as food thickening agents, and in biomedical products [77]. The high availability of cellulose in inedible parts of the plants (lignocellulosic biomass) makes it highly desired as a commercial source of chemical compounds with economic value [78].

Hemicellulose is also a polysaccharide in the plant cell wall, but contrary to cellulose, its chain is highly branched and comprises diverse sugar units (pentose and hexoses) [79]. The main sugar units are xylose (the most representative component), glucose, and galactose, which are readily hydrolyzed by dilute acids and soluble in alkaline solutions [80,81]. Thus, hemicelluloses confer to the structure of the lignocellulosic biomass properties such as increased flexibility and a high fiber bonding area, which are essential when processing lignocellulosic materials and make it a desirable resource for applications in coatings and composite materials [82].

Lignin, the third polymer found in the lignocellulosic biomass and the second most abundant organic compound on Earth, is an amorphous molecule that is gradually incorporated into the plant cell wall. It has an aromatic tridimensional structure composed of phenyl propane units synthesized by a radical route from three precursor *p*-hydroxycinnamyl alcohols: *p*-coumaryl, sinapyl, and coniferyl [79]. Lignin confers resistance and rigidity to plant cell walls, allowing for the transport of water, nutrients, and metabolites to the different regions of the plants. Further, it protects the cell against the destructive action of microorganisms and enzymes [83].

The quantity of cellulose, hemicellulose, and lignin that occurs in the lignocellulosic biomass can vary with species, as well as among samples of the same species depending on the climate and environmental cultivation conditions, due to the different physiological functions of these molecules in the plant [12,73,84,85]. These changes have a strong influence on the mechanical properties of lignocellulosic byproducts [86].

Moreover, according to Guleria et al. [87], the three components, cellulose, hemicellulose, and lignin, are connected by strong interactions due to the non-covalent forces and cross-linked covalent linkages between them, where hemicellulose acts as a linkage agent between cellulose and lignin molecules to form the so-called lignocellulosic matrix. This complex assembly is rigid and recalcitrant, making accessing and separating the fibers difficult.

Therefore, much of the work in the scientific literature on lignocellulosic material has concentrated on the characterization of their chemical composition in terms of cellulose, hemicellulose, lignin, other fractions of ashes, and moisture, and in finding efficient pre-treatments to promote the recovery of lignocellulosic components without compromising their integrity [88,89].

In particular, evaluating the lignin content in the biomass is important for optimizing the physical–chemical parameters in the pre-treatment process. Lignin and polysaccharides are isolated when macromolecules are fragmented into smaller parts, which involves the rupture of their chemical linkages and a reduction in their molecular masses. During the delignification of lignocellulosic materials, some of the solvents used promote the cleavage of the covalent bonds in lignin–carbohydrate complexes [90,91].

4.2. Coconut Residues Characterization

As mentioned, the coconut fruit weight comprises 55% to 80% non-edible parts that are rich in lignocellulosic biomass, which is characterized by a fibrous and heterogeneous structure. Most of the work on coconut residues has focused on the husk (mesocarp), whether for the characterization of chemical compositions, exploration of potential applications, or evaluation of different chemical pre-treatments to fractionate lignocellulose components [4,92,93]. This attention to the fibers is related to its easy handling and chopping procedures, since it only needs to be separated from the inner shell, and its high volume.

Table 2 summarizes the distribution of the main components of the different coconut residues; it is possible to note that the chemical compound profiles are different even for the same type of residues. Borel et al. [4] and Nascimento et al. [92] found similar values of lignin, cellulose, and hemicellulose content for coconuts collected in Brazil; however, they were lower when compared to those found in the work by Anuchi, Campbell, and Hallet [93] using samples from Costa Rica. These differences are due to several factors (genotypes, environmental and physiological conditions, and harvest techniques) and to the chosen methods and conditions of both the pre-treatment and extraction.

Table 2. Chemical composition of coconut residues.

Authors	Residue	Hemicellulose (%)	Lignin (%)	Cellulose (%)
Nascimento et al. [92]	Mesocarp	25.5	35.1	31.6
Borel et al. [4]	Mesocarp	30	32	31
Anuchi et al. [93]	Mesocarp	15	41	38
Andrade et al. [94]	Endocarp	15.2	33.7	10.4
Alharbi et al. [86]	Leaves	19	21	33
Jose and Beevi [95]	Coir pith *	14.2	41.3	34

* residue generated during coconut coir defibrillation.

Borel et al. [4] subjected coconut fibers to Soxhlet extraction using acetone as a solvent for the determination of the lignin content in moisture- and extractive-free samples, which was performed utilizing acid hydrolysis and sulfuric acid according to TAPPI standard T222 [96]. The cellulose was quantified by treating holocellulose with 5% and 24% potassium hydroxide solutions and hemicellulose by subtracting the cellulose content from the holocellulose fraction. In the work of Nascimento et al. [92], the determination of lignin also followed the TAPPI T222 [96] standard, and cellulose and hemicellulose followed TAPPI T203 [97]. Anuchi, Campbell, and Hallet [93] determined the chemical composition of fibers according to the NREL protocol NREL/TP-510-42618 [98].

Kochova et al. [99] evaluated the influence of the quantity and types of sugar units from coconut fibers on cement hydration; they concluded that the presence of arabinose, galactose, glucose, xylose, and mannoses (the main hydrolysis products of cellulose and hemicellulose and also components of the plant) corresponds well with the total heat released during cement hydration, as measured with calorimetry. Due to its rich sugar content, Mariano, Unpaprom, and Ramaraj [100] utilized coconut to produce bioethanol. In that study, they demonstrated that subjecting coconut pulp to sequential hydrothermal and acid pre-treatments can improve saccharification and maximize the release of sugar for fermentation into ethanol.

The use of agro-industrial residues is also of interest given their mechanical properties, which vary depending on the specific byproduct generated and its chemical properties. The mechanical properties commonly evaluated are tensile strength, modulus of elasticity, and density/specific weight. Danso et al. [101] measured the mechanical and physical properties of natural fibers and found that coconut fibers have 6.4% moisture, a tensile strength of 222 MPa, a modulus of elasticity of 2.8 GPa, and a density of 0.81 g/cm^3. The fibers were investigated for their ability to reinforce soil building blocks, showing an improvement in the compressive strength of 41% compared to unreinforced blocks.

Robert et al. [102] analyzed the thermal and mechanical properties of boards made from coconut husks to investigate their use in building projects. The results showed that composite boards containing any percentage of coconut husk could be a good alternative to conventional thermal building insulators like ceiling boards and partition boards. Treated coconut husk presented an apparent density of 0.333 g/cm^3, flexural strength of 435 MPa, and compression strength of 321 MPa. Then, they found that untreated husks produced boards with better thermal properties, while husks treated with NaOH improved the mechanical properties of boards.

Pereira et al. [103] found that coconut husk samples had a density of 0.169 g/cm^3, a value lower than that reported for other natural fibers, such as sugarcane bagasse, kenaf, and bamboo. This density can create difficulties in obtaining homogeneous mixtures, and cause the agglomeration of fibers and problems in production processes. This problem, however, can be solved by crushing the husks in mills [104].

4.3. From Waste to Value: Byproducts from Coconut Lignocellulosic Residues

Exploiting the potential of coconut residues has become an important matter in the coconut industry. Besides the residues' aggregate economic value to the coconut supply chain, renewable raw materials and waste management are major concerns in terms of environmental problems, and it is necessary to stimulate studies to find alternatives to avoid their incorrect disposal. Coconut residues can be used in the generation of handicraft goods for sale, such as carpets, mattresses, and upholstery, and they can undergo a process that changes their chemical compositions allowing them to be used as green alternatives to other natural resources extracted from the environment. Several studies have attempted to use coconut residues, whether *in natura*, minimally processed by physical pre-treatment, or when submitted to chemical pre-treatments that lead to chemical structural alterations.

Due to the structural complexity of cellulose, hemicellulose, and lignin, as discussed in Section 4.1, the conversion of the lignocellulosic biomass into value-added products generally involves a multi-stage process and requires pre-treatment steps [105]. However, an appropriate choice must be made regarding the nature of the separation process of the lignocellulosic components, which can be physical, chemical, biological, or a combination of them, as the degree of separation depends on the process used [106]. In this sense, the high potential and availability of coconut residues encourage the search for cost-competitive and efficient pre-treatment technologies that could promote the fragmentation, recovery, and utilization of the lignocellulosic biomass in large-scale biorefineries [107].

In the scientific literature, the studies on coconut residue applications, using as-obtained or pre-treated residues, have focused on the following strategies: (i) application in civil construction [108–111]; (ii) use as filtering and adsorbent materials [112–117]; (iii) in ethanol production [19,26,118]; (iv) obtention of pyrolysis products [22,119–122]; and (v) other applications [123–126].

4.3.1. Civil Constructions

Umoren et al. [108] reported the inhibitory effect of a coconut coir dust extract, produced using chemical and electrochemical techniques, on mild steel in a sulfuric acid solution. Coir dust was produced from shredded husks, and an extract was obtained using methanol and water as free acid extractive solvents; the experiments were carried out in solution at different temperatures and extract concentrations. As a result, the extracts of coconut coir dust exhibited a corrosion inhibition effect for mild steel in 0.5 MH_2SO_4. There was an increase in efficiency with increasing concentration of the inhibitor and decreasing temperature.

Ramasubramani and Gunasekaran [109] used coconut endocarp as a substitute for crushed stone aggregate for coarse aggregate concrete production. The microstructural characteristics and properties of conventional concrete (CC) and coconut shell concrete (CSC) were analyzed. For CC and CSC, the flexural strength was 5.38 N/mm^2 and 5.20 N/mm^2; tensile strength was 3.70 N/mm^2 and 2.92 N/mm^2; and the average impact resistance to form initial cracks was 398 Joules (20 blows) and 616 Joules (31 blows). The results showed that the mechanical properties of CSC were inferior to those of CC; however, the differences were not significant, indicating the feasible use of coconut endocarp as a sustainable alternative to coarse aggregate.

Narciso et al. [110] used coconut husk combined with *Pinus oocarpa* wood to produce medium-density particleboards. The physical and thermal properties of the particleboards were positively affected by husk addition, producing lower thermal conductivity values. Although the increase in coconut fiber concentration promoted a decrease in the mechanical properties (strength and stiffness) of the panels, all treatments met the market standards, indicating the potential of coconut waste as a sustainable raw material to produce panels.

Souza et al. [111] studied different coconut husk fiber levels (0%, 10%, 20%, 30%, 40% and 50%) to replace eucalyptus wood in producing wood–cement particleboards. From each board, the specimens were subjected to physical–mechanical tests. Regarding physical properties, the addition of coconut fibers improved the dimensional stability, decreased water absorption, and increased thickness swelling, while for mechanical properties, a decreased modulus of elasticity and modulus of rupture were observed as the percentage of coconut fibers increased. In general, the boards were considered inappropriate for structural uses but suitable for indoor uses.

It is important to highlight that, in both studies that used coconut waste to produce panels, it was observed that the physical properties of water absorption and thickness swelling, and the mechanical properties of modulus of rupture and modulus of elasticity decreased with increasing of residue content.

4.3.2. Filtering Material and Adsorbent

Hoang et al. [112] used coconut shells as raw materials to produce activated carbon loaded with cobalt ferrite composites via a single-step refluxing router method. The carbon was used to manufacture adsorbents to remove rhodamine B (RhB), a cationic xanthene fluorescent dye, from aqueous environments via adsorption. This method proved promising, and the coconut fiber-activated carbon showed a maximum efficiency capacity for the rhodamine B adsorption of 94.08 mg/g.

Padilha et al. [113] subjected green coconut fibers to an organosolv pre-treatment and used the obtained liquor for the synthesis of lignin/Fe_3O_4 nanoparticles to be used as an immobilization support for fungal β-glucosidase, which was evaluated as an adsorbent for textile dyes in aqueous solutions. Due to the physicochemical properties of the lignin from the coconut fibers, the obtained nanoparticles showed efficient support for improving β-glucosidase stability and synergism with cellulases during enzymatic hydrolysis and as a bioabsorbent with a high adsorption capacity for textile dyes: 203.66 mg/g for methylene blue, 112.36 mg/g for cibacron blue, and 96.46 mg/g for remazol red dyes. Both evaluated liquor uses proved to be sustainable pathways for the valorization of lignin as a raw material.

Esfandiar et al. [114] evaluated low-cost materials, including coconut coir fibers, as a sorbent for removing a mixture of polycyclic aromatic hydrocarbons (PAHs) from simulated stormwater. The sorption capacity was investigated, and the outcome revealed the strong potential of the coconut coir-based sorbent. The authors concluded that using widely available sorbent materials from agricultural waste can provide a low-cost option to address pollutant challenges.

Marín-Velásquez and Cóndor-Salvatierra [115] used coconut shells as a granular filtering material to remove oil and fat from water contaminated with diesel. The water samples were contaminated with diesel oil at 5, 10, and 15% concentrations. In this study, the properties analyzed were density, pH, water adsorption, and porosity by gravimetric determination. The use of coconut shells as filtering material provided a maximum oil removal of 85.10%, classifying the filtered water sample as drinking water according to the country's tolerance levels.

Thongsamer et al. [116] produced biochar pellets from coconut husk biochar (CH) to be used as a low-cost adsorbent for nutrient removal from eutrophic surface waters. The pelletized coconut husk biochar was modified with chitosan impregnation (CHC) and mixed with eggshell powder (CHEP) and experiments were carried out to evaluate and compare the performance of the three versions of biochar pellets. CH, CHC, and CHEG were able to adsorb ammonium, but CHC had the greatest potential in removing all nutrients (ammonium, nitrate, and phosphate) from eutrophic surface waters, achieving removal efficiencies of 61.70% and 54.37% for phosphate and nitrate, respectively.

Regarding filtering materials for air pollutants, Pettit et al. [117] evaluated the effectiveness of green walls consisting of differently sized coconut husk-based substrates as a filtering medium for ethyl acetate, benzene, and total volatile organic compounds (VOCs) in the atmosphere. The coconut husk used had a water content of 72.5% or 95% organic matter, a specific surface area of 0.75 m^2/g, and a water holding capacity of 5.5 g[H20]/g dry material, and differing proportions of granular activated carbon were added to the coconut shell substrate. The results showed that including activated carbon can improve the efficiency in removing certain pollutants, and a 50:50 composite medium provided the best VOC removal performance. However, the authors recommended adjusting the use of activated carbon according to the type of pollutant.

4.3.3. Ethanol Production

Cabral et al. [19] investigated the production of bioethanol from green coco husk fibers, which were pre-treated by an alkaline method with NaOH, hydrolyzed enzymatically and subjected to ethanol fermentation with commercial yeasts of *Saccharomyces cerevisiae.* Enzymatic hydrolysis converted 87% of the sugars and the ethanolic fermentation consumed 81% of the substrate in the hydrolysate, leading to a sugar-to-ethanol conversion efficiency of 59.6%. The authors pointed out that green coconut husk is strongly viable as a feedstock for ethanol production.

Ebrahimi et al. [118] examined the effect of an organosolv pre-treatment with acidified aqueous glycerol on coconut coir fibers for ethanol production. A simultaneous saccharification and fermentation procedure with *Saccharomyces cerevisiae* was performed and as a result, the glycerol solvent improved the fiber glucose digestibility from 11.8% (untreated) to 79.7–81.8% and ethanol production from 1.67 g/L to 8.97–8.81 g/L.

Padilha et al. [26] also reported using green coconut fibers pre-treated with glycerol to produce ethanol, lignin, and rhamnolipids, which belong to the class of glycolipid biosurfactants. Ethanol production was performed via semi-saccharification and simultaneous fermentation and the recovery of organosolv lignin by diluting black liquor in acidified deionized water. The washing waters from the organosolv treatment and the precipitation water from lignin were used to prepare the culture medium for producing rhamnolipids, which were obtained with promising emulsifying properties. The fermentations with untreated coconut fiber achieved high concentrations of ethanol (5.97–15.01 g/L), which may be linked to the impregnated sugars. However, the maximum concentration of ethanol (29.64 g/L) was obtained with treated fibers.

4.3.4. Pyrolysis Products

Pyrolysis is a thermochemical process that occurs under medium to high temperatures and in an inert atmosphere to promote the conversion of carbonaceous materials into value-added solid, liquid, and gaseous (rich in methane) products. The solid phase is used in biochar production while the liquid phase, known as bio-oil, has drawn attention due to its potential as a biofuel and its chemical products [127]. The samples with a high volatile matter content, low moisture, and low ash content had favorable outcomes for bio-oil conversion and the overall efficiency of the process [128–131].

Babatabar et al. [22] investigated the pyrolysis conversion of different lignocellulosic biomasses (rice husk, coconut shell, and walnut shell) while maintaining the same operating conditions in a fixed-bed reactor. Coconut shell showed the highest yield of bio-oil at 50.25 wt% (rice husk: 44.10%; walnut shell: 41.50%), which had a higher content of hydrocarbon components (paraffin, olefin, and aromatic hydrocarbons) and phenols due to the biochemical structure of the biomass rich in lignin. The high proportion of hydrocarbons in the coconut shell bio-oil indicates the biomass's potential as a precursor for biofuels, especially diesel and jet fuel.

Sahoo et al. [120] also performed coconut shell pyrolysis to obtain bio-oil to partially replace the silane coupling agent in rubber compounding, which is associated with a few drawbacks, such as the formation of ethanol as a byproduct. From 150 g of coconut shell powder, about 80 g of bio-oil was obtained with a yield of approximately 53%. The main constituents of the coconut shell oil were phenol and its derivatives (49%), followed by ammonium acetate, aniline, and ether. As a result, incorporating the obtained bio-oil into silica-filled styrene butadiene rubber enhanced the salinization reaction; however, it must be combined with a silane coupling agent (40–50%) to improve effectiveness.

Arantes et al. [119] studied the co-pyrolysis of green coconut pericarp (comprising the epicarp, mesocarp, and endocarp) and waste polystyrene for oil production. Experiments were performed in a fixed-bed reactor over an activated biochar catalyst. The results showed that co-processing the biomass and waste plastic (BPS) led to a higher yield of oil (59%) and an oil organic fraction of 39%, when compared to an experiment containing only the coconut pericarp (CP) (7% of the organic fraction). Nonetheless, the CP oil presented a high content of both phenolic (60.67% relative area) and furanic (15.78% relative area) compounds, while the BPS organic fraction mainly constituted aromatic (70.65% relative area) and polyaromatic (10.06% relative area) hydrocarbons. Although the catalyst favored gas formation, it improved the selectivity for monoaromatic hydrocarbons, toluene, and xylene, which are alternative to zeolites.

Chaos-Hernández et al. [121] evaluated the efficiency of char catalysts obtained from the coconut endocarp pyrolysis and improved the ability of KOH and $Ca(NO_3)_2$ catalysts to produce biodiesel. In this sense, a detailed analysis of the catalyst functionalization, activation condition of the catalysts, and their application in transesterification to produce fatty acid methyl esters (FAMEs) was performed. Experiments were carried out at varying pyrolysis temperatures and dwell time, finding the best catalyst preparation via the pyrolysis of coconut endocarp at 600 °C for 1 h (FAME formation of 90.8%).

Gopal et al. [122] used mature coconut husk, tender (immature or green) coconut husk, coconut leaf petiole (central section that connects leaf blades), and coir pith (a sponge-like material found between the hard internal shell and the outer shell) as pyrolysis feedstocks for the production of biochar for remediating acidic soils. Due to the alkaline pH (>7.5), the produced biochar was considered ideal for neutralizing humid tropical soils, which are mostly acidic. At the same time, the high potassium content (>2.5%) makes them a valuable alternative organic K source for plants. Also, the suitability of coconut biochar for soil amendment was established through seed germination and earthworm avoidance tests.

4.3.5. Other Applications

Tang et al. [124] evaluated the use of six lignocellulosic residues, including coconut coir fibers, as a source of ferulic acid and phenolic compounds for bioconversion into vanillic acid. Before conversion, the samples of oil palm empty fruit bunch fiber (OPEFBF), coconut coir fiber (CCF), pineapple peel (PP), pineapple crown leaves (PCLs), kenaf (from *Malvaceae* family) bast fiber (KBF), and kenaf core fiber (KCF) were pre-treated with organosolv (NaOH-glycerol) and an alkaline treatment (NaOH). It was found that organosolv was superior for phenolic compound extraction, whereas the alkaline treatment enhanced the lignin extraction. Among the tested agricultural residues, it was found that PP was the best source of ferulic acid, yielding 5.72 mg/g (CCF 0.17 mg/g), whereas CCF was the best source of phenolic compounds, yielding 47.99 mg/g. However, vanillic acid production was only detected in fermentation with the PP and PCL liquors.

Luis-Zarate et al. [125] evaluated the efficiency of the removal of benzene, toluene, and naphthalene from water using coconut shells (endocarp), coconut fibers (mesocarp), and coconut shells with fibers (endocarp and mesocarp) as biosorbents and further evaluate the residues' saturated potential for energy generation by combustion. CF showed the highest adsorption capacities of 222 mg/g, 96 mg/g, and 5.85 mg/g for benzene, toluene, and naphthalene, respectively, which was justified by its morphologic characteristics and high concentration of phenolic groups due to the lignin structure. The combustion heat analysis showed an increase in heat capacity up to 657 cal/g, which is related to its characteristics of a high lignin and low ash content.

Oliveira et al. [123] proposed using coconut husk fibers as a photoprotective and antiglycation agent by determining their phenolic chemical composition and photoprotection capacity according to the sun protector factor of an ethanol extract of coconut husk fibers. Seven phenolic compounds were identified by high-performance liquid chromatography: quercetin, catechin, epicatechin, and vanillic, caffeic, 4-hydroxybenzoic, and chlorogenic acids. The prepared formulations showed photoprotective activity with a maximum SPF value of 15.94, equivalent to the standards for benzoquinone and quercetin. Therefore, using coconut byproduct can be considered as an efficient ingredient in sunscreen formulations, and is a low-cost alternative source of active ingredients for the cosmetics and pharmaceutical industries.

In their work, Lasmini et al. [126] proposed the use of coconut husks as a liquid organic fertilizer source to obtain the maximum shallot yield under dryland conditions. CH was combined with two different mulches made from silver–black plastic and rice straw and tested at four concentration levels. The applications of straw mulch with coconut husks waste at a dose of 1000 L/ha resulted in the highest plant height, number of leaves per plant, number of tillers, and bulb yield.

5. Discussion

5.1. Circular Economy

The circular economy is a sustainable and integrated approach that aims to support the regeneration and restoration of biological resources to produce value-added products while minimizing the negative impacts of waste from the industrial sector [132]. Ensuring the efficient use of resources has been recognized as one of the United Nations' Sustainable Development Goals (SDGs), confirming the importance of biological resources for achieving a sustainable future [133]. In particular, SDG12 was proposed to ensure sustainable consumption and production patterns by 2030, which is directly related to the concepts of residue reintegration and biorefineries [134].

Support policies and innovative technologies for advanced biorefineries represent a crucial point for developing a modern bioeconomy, especially in regions whose economic system is based on agricultural production. Biorefineries, focused on processing residue biomass, such as lignocellulosic materials, offer the potential for generating a wide variety of bioproducts with different chemical compositions [135]. Thus, besides aiding in adopting sustainable agricultural practices coupled with a circular economy approach, biorefineries can contribute to the generation of bio-based alternative fuels and chemicals for mitigating the effects of climate change [136].

The conversion of coconut agricultural residues into high-value bio-based low-carbon materials is an effective residue management strategy for applying the biorefinery concept in a cutting-edge circular economy, adding value to the whole supply and processing chain, increasing a company's competitiveness, and providing consumers with sustainable products and services. Based on the analyses of recent studies, the strategies for coconut lignocellulosic biomass valorization may include the improvement of recovery and processing techniques and the exploration of the uses for this biomass in sectors such as civil construction [108–111], manufacturing of adsorbent materials [112,113] and filters [114,117], ethanol production [19,26,118], bio-oils [22,119–121], biochar [122,125], and organic fertilizers [126].

However, it is important to highlight that inserting biomass as feedstock into the current industrial and economic model for an efficient transition to renewable generation requires more specific policies, collaborations, and investments [137].

5.2. Insights from Coconut Residue Value Chain

Regarding the large-scale management of coconut residues, the major strategy that has been adopted is direct disposal rather than recycling, recovery of energy potential, or any other reuse method [23]. Therefore, based on the current volume of coconut production and the expected exponential growth, the coconut residue value chain presents a huge potential for supporting green economic development [24,138].

The lack of advanced recycling techniques for coconut residues represents a challenge to achieving a circular economy and stimulating local low-carb economic development. This gap is due to the absence of specific policies to support a greener transition and disseminate knowledge regarding the benefits of recycling this waste. Promoting this change requires the active participation of small and large producers in the entire value chain [23,139].

Furthermore, investment in the research and development of innovative technologies for processing coconut residues can improve productivity and product quality and establish supplier–customer partnerships with industries, small companies, and potential sectors that can use coconut byproducts. This collaboration creates synergies and business opportunities, which can guarantee the viability of a circular economy and boost local economic development based on the "from waste to profit" approach [17,140].

Given this, the main aspects that have been identified regarding the recovery and reuse of coconut residue valorization are as follows:

(i) Value addition through product diversification and improvement of lignocellulosic chemical and functional properties in coconut residues;
(ii) Integration of the whole coconut value chain, from main coconut products to byproduct generation;
(iii) Strategic partnerships with other coconut industries or sectors;
(iv) Boosting investments in the research and development of innovative technologies for processing coconut residues;
(v) Identification and exploration of market opportunities for products derived from coconut waste at the national and international levels.

5.3. Coconut Industry: A Sustainable Pathway towards the 2030 Agenda Goals

Over the decades, the coconut industry has demonstrated its versatility and economic importance for several industrial sectors, from food and cosmetics to construction products and sustainable fuels. Although it also stands out for its ability to incorporate sustainable practices in the production and processing chain, the coconut industry still has the potential to open new pathways for exploring the different parts of the fruit, from its water to kernel and lignocellulosic residues, which offer a promising perspective for achieving the goals of the 2030 Agenda for Sustainable Development [140] (Figure 6).

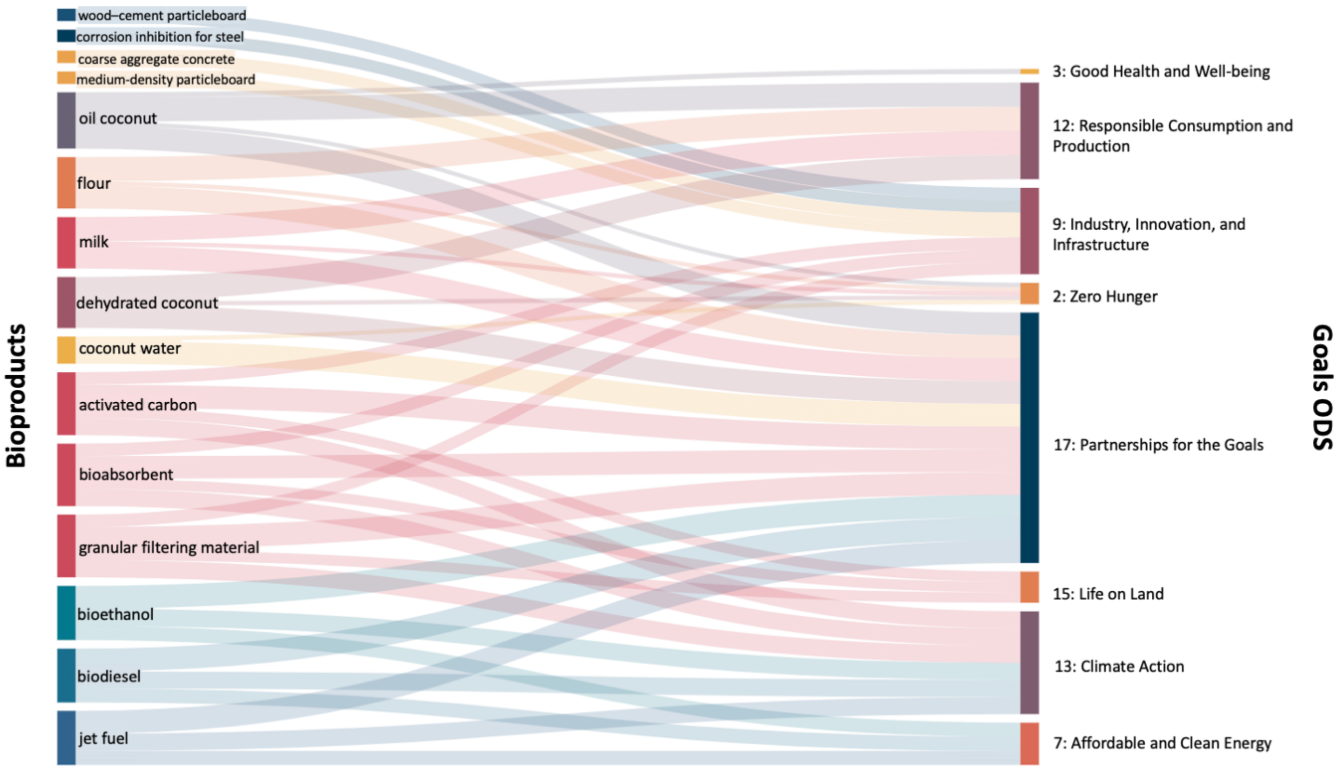

Figure 6. Interlinking coconut-derived products with the objectives of the 2030 agenda for sustainable development.

a. Goal 2: Zero Hunger

Indicator: Utilization of coconut kernel products such as coconut oil in food industries as an alternative cooking fat.

b. Goal 3: Good Health and Well-being

Indicator: Coconut oil's incorporation into cosmetics for hair products and body moisturizers, enhancing skin barrier function and performing anti-inflammatory functions.

c. Goal 7: Affordable and Clean Energy

Indicator: Production of bioethanol from green coconut husk fibers, providing a renewable energy source.

d. Goal 9: Industry, Innovation, and Infrastructure

Indicator: Use of coconut residues in civil construction, producing materials like particleboards and wood–cement particleboards.

e. Goal 12: Responsible Consumption and Production

Indicator: Development of sustainable alternatives, such as coconut flour, milk, and desiccated coconut, contributing to responsible consumption practices.

f. Goal 13: Climate Action

Indicator: Pyrolysis of coconut shells for bio-oil production, offering potential biofuels and chemical products, aligning with climate-friendly initiatives.

g. Goal 15: Life on Land

Indicator: Utilization of coconut biochar for remediating acidic soils, supporting sustainable land use and ecological health.

h. Goal 17: Partnerships for the Goals

Indicator: International trade of coconut products contributes to economic partnerships and global commerce.

The applications of coconut residues, from civil construction to filtering materials and adsorbents, align with the need for sustainable alternatives, waste management, and the development of eco-friendly technologies, promoting circular economy principles. The comprehensive utilization of coconut products contributes to addressing multiple dimensions of sustainability, fostering economic growth, and supporting environmental conservation.

6. Challenges and Future Perspectives

Given the increasing popularity of coconut products, mostly coconut oil and water, coconut has significantly increased its relevance in agribusiness and the demand for its primary derivatives is expected to grow exponentially in the following years. Thus, new technologies and strategies are being investigated to enhance the whole coconut sector and its supply and value chain by improving management, commercialization, and the quality of the cultivation system, and innovating the processing industries and techniques [141].

Consequently, coconut crop production is leading to the generation of large amounts of lignocellulosic residues and environmental pollution since such wastes are commonly considered of low value and are incorrectly disposed of [142]. Therefore, there is also a need to develop knowledge and encourage scientific investigations toward exploiting the potential of such residues for generating renewable and high-value-added products.

Agro-industrial residues are grouped into two classes based on their economic value: the first refers to residues that already have consolidated value and the second are the residues that have fewer potential applications or are chiefly restricted to scientific research, although they have shown remarkable characteristics for numerous applications [143]. Therefore, using coconut waste as an alternative and renewable raw material to generate value-added products requires the redirection of this waste to the consumer market and to be part of a sustainable circular economy [144].

Some of the challenges identified by this review are presented in Table 3, which summarizes what improvements are needed to allow the use of coconut waste in different processes according to the applications found in the literature.

Table 3. Analysis and challenges of the different biotechnological uses of coconut residues (CRs).

Application	Highlights	Challenges
Civil construction	- CR properties have a corrosion inhibition effect for mild steel in sulfuric acid solutions. - The abundance phytochemicals (tannins, flavonoids, and phenolics) make residues suitable alternatives to coarse aggregate in concrete production and as raw materials to produce panels.	- Corrosion inhibition efficiency depends on the extractive solvents used and this ability is lost at high temperatures. - Physical and mechanical properties (water absorption, swelling in thickness, modulus of rupture, and modulus of elasticity) of construction materials decrease with an increase in the level of CR inclusion. - Building materials with CRs cannot be exposed to excessive humidity. - New strategies must be developed to improve the mechanical properties of CRs.
Adsorbent material	- CRs have a high adsorption capacity to remove dyes (rhodamine B, methylene blue, cibacron blue, and remazol red) and polycyclic aromatic hydrocarbons (PAHs) from aqueous solutions. - CRs have high adsorption capacities for benzene, toluene, and naphthalene. - CRs have filtering abilities to remove oil and fat from water contaminated with diesel and hydrocarbons. - The lignin content in CRs can improve the β-glucosidase performance of crystalline cellulose in enzymatic hydrolysis.	- Dye adsorption capacity is greatly reduced with the number of reuses. - Further research is needed to investigate the mechanisms and behaviors of the adsorption reactions between the sorbents and pollutant and to determine the leaching potential and performance of a sorbent under different hydrological conditions. - Research is still lacking for some aspects concerning the energy required and economic viability on a commercial scale.
Production of organic solvents	- CRs are strongly viable substrates for ethanol production via saccharification and fermentation with *Saccharomyces cerevisiae.* - Residues can be used as a carbon source for the production of rhamnolipids with interesting emulsifying properties.	- The efficiency in producing second-generation ethanol from coconut biomasses depends on the pre-treatment steps. - More studies need to be conducted to evaluate the viability of the process concerning the loss of sugars in the pre-treatment step. - The process for producing ethanol was conducted only on a laboratory scale, making it necessary to evaluate in a pilot/at the industrial scale to prove its efficiency and good cost–benefit ratio.
Feedstock for pyrolysis process	- CRs can produce high bio-oil yields containing a high content of hydrocarbon components. - CRs demonstrate a high potential for producing phenolic compounds and biofuels. - Derived bio-oils can be used as a green alternative component to enhance the physicomechanical properties of other materials, e.g., silica-filled styrene butadiene rubber compounds. - Derived biochar can be used as a catalyst to produce biodiesel and for remediating soils.	- Pyrolysis product distribution and composition is also influenced by the process' operation conditions. - Depending on the components of interest, it is necessary to employ some catalysts to improve the selectivity. - More studies must be performed at pilot and large scales.

7. Conclusions

Coconut palm and its fruit have been cultivated and consumed in several countries around the world, with production heavily concentrated in the Asia continent and the Pacific Region, mainly in Indonesia, the Philippines, and India. Due to the high demand for coconut derivatives, residues from the coconut sector are available in large quantities, and although they have not been appropriately used, they have an interesting and promising chemical composition with a high content of lignin, cellulose, and hemicelluloses that are favorable for generating high-value-added byproducts.

Among the applications where coconut waste has been proven to be an efficient raw material for generating byproducts are in civil construction, as an adsorbent material, and in the production of ethanol, bio-oil, and organic fertilizers. Furthermore, several research studies have identified coconut residues as a rich source of phenolic compounds that are useful as antioxidants and anti-inflammatories and have potential for use in the pharmaceutical industry. Its phenolic profile is attributed to its high lignin content.

While these applications are promising, several technological challenges hinder their widespread implementation. This review not only underscores the significance of coconut waste in promoting a circular economy and sustainability but also serves as a resource for researchers seeking to enhance its applicability. By addressing the technological drawbacks, this work encourages further research and innovations, fostering the advancement of coconut waste utilization in diverse fields. To provide a broader and more effective use of these natural resources, it is essential to face the highlighted challenges by investing in innovative technologies and integrating the entire coconut value chain, from coconut production to residue recovery and processing.

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