

# Coir from Coconut Processing Waste as a Raw Material for Applications Beyond Traditional Uses

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The global production of coconut, mainly for food and oil production, exceeds 62 million tonnes per annum. Large quantities of coconut husk remain unutilized after industrial processing, giving rise to environmental problems. This fails to exploit the potential presented by the extraction of coir, which could have numerous applications. Traditional products such as textiles, mats, and brushes made from coir are increasingly being joined by new, high-value, non-traditional uses. This review article summarizes new fields of application for coir as reinforcing fibers in binderless fiberboards, natural fiber composites, construction materials, solid biofuels, and an absorbent for heavy metals and toxic materials. The use of coir in these new fields will reduce waste and increase sustainability.

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## INTRODUCTION

The coconut palm (*Cocos nucifera* L.) is a perennial, heterozygous, and solely seed-propagated crop (Arunachalam 2005).

**Table 1.** Major Coconut-Producing Countries and Global Coconut Production in 2019 (Food and Agriculture Organization of the United Nations 2021)

Country	Production Mt	Area (Mha)	Yield (t/ha)
Indonesia	17.1	2.80	6.12
Philippines	14.8	3.65	4.04
India	14.7	2.15	6.83
Sri Lanka	2.5	0.50	4.90
Brazil	2.3	0.19	12.47
Việt Nam	1.7	0.16	10.55
Mexico	1.3	0.20	6.31
Papua New Guinea	1.2	0.19	6.32
Thailand	0.8	0.12	6.48
Malaysia	0.5	0.08	6.99
Tanzania	0.4	0.66	0.65
<b>World</b>	<b>62.4</b>	<b>11.81</b>	<b>5.29</b>

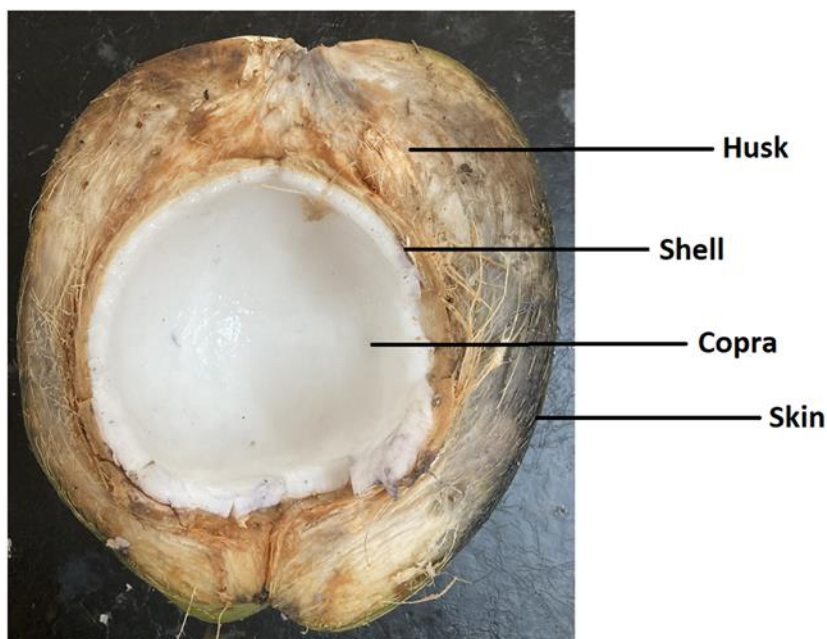
It grows along the coast and in the interior regions of almost all tropical countries. Its wide distribution has been favored by its usefulness and adaptability to different ecological conditions.

The fruit of the coconut palm, the coconut, is resistant to saltwater, biodegradation, and mechanical forces, allowing it to float in the sea for a long time, covering great distances, and to germinate on the coastal soils when washed ashore (Rethinam 2018).

The coconut has been used by humans for centuries as a source of food, drink, and oil, or for shelter and aesthetic purposes (Foale *et al.* 2020). Today, the coconut is grown, or occurs naturally, in 94 out of 284 countries and territories around the world (Food and Agriculture Organization of the United Nations 2021). The global production of coconuts and the major producing countries in Asia, the Americas, and Africa are listed in Table 1.

### Preparation of Fibers

Coconuts are primarily grown for the oil-rich copra and oil found inside the coconuts. The copra is surrounded by a shell and a thick husk comprised of coir and pith (Thampan 1981), as shown in Fig. 1.



**Fig. 1.** Exterior parts of a coconut (own photograph)

While fresh (green) coconuts are mainly used for nutritional purposes, *i.e.*, coconut water, the majority of the nuts grown commercially are processed after they have matured and dried out, indicated by them turning brown. The nuts are further processed into oil and fibers, forming the basis for a wide range of products.

Coconuts are harvested at different stages of maturation, depending on the intended use and industrial needs. Fibers from mature coconuts, indicated by a thick, brown, abrasion-resistant husk, are referred to as brown coir. The fibers extracted from immature nuts, also called white coir, have a lower mechanical strength compared to brown coir (Meenatchisunderam 1980).

There are many different mechanical, chemical and enzymatic processes to extract fibers from the coconut husk. The oldest and most common process is called ‘retting’ and

consists of a tedious mechanical and chemical process. The fibers are embedded in a matrix of pectin, polyphenols, and hemicelluloses that have to be degraded to release the fibers. In the first step, the husk absorbs water and the plant tissues swell. At the same time, a wide range of plant extracts and metabolites are washed out in a leaching step (Meenatchisunderam 1980). In the second step, the nuts are kept in the nutrient-rich leachate, enabling the growth of bacteria and fungi. These excrete enzymes that dissolve the bonds between the fibers, making them easier to separate. Different yeast species play an especially vital role in the degradation of pectic and phenolic substances in the outer shell (Nambudiri *et al.* 1972). To accelerate the process, chemicals such as lime, sodium sulphate, or sodium carbonate, supplemented with hot water and/or steam treatment, can replace the microbiological process (Jayasankar and Bhat 1964).

Additional mechanical pre-treatment such as splitting the husk into smaller pieces can further speed up the process. The fibers can also be treated with hydrochloric acid, acetic acid or UV prior to the mechanical defibrillation. The different treatments and their effects on the fiber strength are reviewed by Varma *et al.* (1984).

The retting process is followed by crushing and a mechanical defibrillation step. The husk is comprised of long fibers surrounded by a non-fibrous, lightweight, fluffy material referred to as coir pith. The pith makes up 50 to 70% of the fiber and is separated from the coir during the defibrillation process. Traditionally, workers beat the retted pulp with wooden mallets to separate the fibers from the pith and the outer skin, but this process has been replaced by motorized processes carried out in steel drums with beater arms that separate the fiber and the pith. The high lignin and cellulose content of coir pith results in a high level of recalcitrance, *i.e.*, the slow degradation of the fibers, which gives rise to environmental problems when disposing of the material in nature, as it can take decades to decompose (Nunes 2020).

### **Waste Husk: Unutilized Potential for Coir Production and Environmental Problems**

The coconut husk makes up about 35% of the total weight of the coconut, and of that husk, about 30% is coir (Thampan 1981). In 2019, about 62 million tonnes of coconuts were produced on a global level (Food and Agriculture Organization of the United Nations 2021), creating about 20 million tonnes of husks and thus a theoretical potential of 6 million tonnes of coir.

The Food and Agriculture Organization of the United Nations estimated the production of coir in 2019 to be at about 1.26 million tonnes on a global level. Almost half (518,000 tonnes) was produced in India, making the country by far the leading coir producer in the world (Food and Agriculture Organization of the United Nations 2021). These figures show that large quantities of coir remain unutilized, since only a fraction of the available husks are processed in coir mills. While some are used for burning or charcoal production, large quantities of husks are unused and dumped as waste instead of being processed into valuable products.

As a result, it is common to see large heaps and landfills of coconut husks (Fig. 2) around coconut processing facilities. The biological degradation of this waste can take several years due to the high recalcitrance of the husks.



**Fig. 2.** Discarded waste coconut husks (own photograph)

Waste from the coconut-processing industries gives rise to numerous environmental problems. Waterlogged shells are reported to be breeding sites for mosquitoes, which can lead to epidemics of dengue fever or malaria in nearby communities (Dumasari *et al.* 2020). Other effects reported as reducing the life quality of the surrounding population include unpleasant smells and greenhouse gas emissions due to bacterial degradation of the coconut processing waste, a lack of storage space for the landfill sites, the clogging of natural watercourses and the destruction of the natural environment (Dumasari *et al.* 2020).

Gopal *et al.* (2001) have studied waste from coconut processing in detail, and have reported fire hazards and ground water contamination due to the release of phenolic compounds from coconut waste landfills. Another problem is that the remaining husks serve as breeding sites for the rhinoceros beetle (*Orcytes rhinoceros*), which is a major pest for coconut production. The beetles visits the landfills for oviposition, and the eggs hatch into grubs and later into beetles that fly to the surrounding palm trees, causing severe damage to oil palms and their nuts. This damage to the nuts leads to secondary fungal infections that cause further damage and economic loss. Nunes *et al.* (2020) concluded in their study that significant amounts of methane, a potent greenhouse gas, could be saved from uncontrolled release into the atmosphere by collecting and utilizing coconut shells instead of letting them rot away on landfills, and that it would be economical to collect and use them.



## CHEMICAL AND PHYSICAL FEATURES OF COIR

Understanding the chemical and physical features of coir is fundamental for developing new uses. This includes the structural, mechanical, chemical and thermal properties of the fibers.

### Structure of the Fibers

Satyanarayana *et al.* (1981) were the first to review the literature on the structure and properties of coir in great detail. Like any other plant fiber, coir is comprised of cells with different layers in the cell walls and a lumen in the center. The structure of the cell wall consists of several concentric layers that can be divided into an outer primary wall (S1), a central secondary wall (S2), and an inner secondary wall (S3). All the layers are fibrillar in nature, with variations in the composition, thickness and orientation of the cellulosic microfibrils. The degree of crystallinity and the orientation of the fibrils play a vital role in the fibers' mechanical properties, which differ depending on the species and stage of maturation (McLaughlin and Tait 1980).

The morphology of the coconut husk and coir has been studied in great detail by van Dam *et al.* (2006). They report that within the husk, coir acts as reinforcing fibers embedded in a matrix of spongy pith. The thin-walled pith cells are attached to the coir surface. The pith cells adhere to the coir, resulting in the formation of a natural composite. The coir itself is characterized by a gradually pitched helical structure with the cell wall composed of microfibrils oriented at an angle of approximately 45 degrees, explaining the high resilience of the fiber.

### Mechanical Properties of the Fibers

Biswas *et al.* (2013) studied the mechanical properties of mature (brown) and immature (white) coir in detail, determined the tensile strength of brown and white coir. They measured the tensile strength of brown coir as 165 to 222 MPa, and that of white coir as slightly higher at 185 to 237 MPa. Young's modulus was about 3.8 GPa for brown and 4 GPa for white coir, while the elongation at break was about 40% in both cases. Their data on coir was in accordance with data reported in the literature. The lower strength compared to jute and bamboo fibers was explained by the high degree of porosity.

### Chemical Composition and Thermal Properties

The chemical composition of coir has been widely studied and reported in the literature. Although there are differences depending on the species, location, and degree of maturation of the nuts, coir mainly stands out from other plant fibers due to its high lignin content. The cellulose content varies between 27 and 36 wt%, hemicelluloses between 17 and 23 wt%, and lignin between 37 and 42 wt% (Hill *et al.* 1998; Muensri *et al.* 2011; Stelte *et al.* 2019). The ash content was between 1.8 and 2.5 wt% (Stelte *et al.* 2019).

The chemical composition of the coir surface was studied by means of infrared spectroscopy. The data indicate the presence of surface waxes from the plant cuticle on the fiber surface (Stelte *et al.* 2019) which is an important parameter influencing the fibers' compatibility with a given polymer matrix when coir is used as a filler in a composite material.

A number of studies have been carried out looking on the thermogravimetric properties of coir. After initial moisture elimination peaking at about 323 K, organic components, namely hemicelluloses, cellulose, and lignin, decompose in the range of 523

to 643 K (Mothé and Miranda 2009). The derived weight loss reveals a superposition of two parallel processes, indicating that the cell wall polymers undergo decomposition at different temperatures.

## TRADITIONAL USE AND MARKET FOR COIR

Historically, Sri Lanka has been the world's largest exporter of various fiber grades, mainly mattress fiber, bristle fiber, and twisted fiber. India traditionally focused on the production of value-added products such as yarn, mats, ropes and rugs made from coir. Traditionally, coir was produced for the home market; however, large quantities of the fibers and value-added products are produced for export today. The biggest export market for coir today is China, which makes up 90% of the export volume (Rethinam 2018).

The global annual production of coir, including coir pith, has increased over the last decade at rate of 3.6 percent per annum. Production reached 995,000 tonnes in 2017 and is projected to reach 1,170,000 tonnes by 2027. The main production and export country is India, which accounts for more than 50% of all export shipments (Food and Agriculture Organization of the United Nations, 2019). The global trade value for value-added coir fiber products today is about 140 million USD per year, with India and Sri Lanka accounting for about 70 and 60 million USD, respectively (Food and Agricultural Organization of the United Nations 2021).

**Table 2.** Export Volume (MT) of Coir Products from India, 2017-2021 (April-March) (International Coconut Community 2021)

Products	2016/17	2017/18	2018/19	2019/20	2020/21
Coir pith	490552	548479	566661	579980	680898
Tufted mats	51718	54279	54131	58131	81799
Coir fibers	370357	374320	299279	308457	354123
Handloom mats	20144	18277	19367	16910	20527
Geotextiles	6219	5845	7674	8068	8583
Coir yarn	4426	3328	3408	3028	3849
Curled coir	10356	8800	10768	11290	9381
Handloom matting	1273	1117	1071	1177	1418
Rubberized coir	888	900	807	578	982
Coir rugs and carpets	205	254	195	367	327
Coir other sorts	256	306	183	298	744
Coir rope	484	491	486	512	505
Powerloom mats	166	37	8	26	65
Powerloom matting	0	131	7	5	11
<b>Total</b>	<b>957044</b>	<b>1016564</b>	<b>964045</b>	<b>988827</b>	<b>1163212</b>

The International Coconut Community (2021) regularly publishes market figures for the key export countries. They report that amid the economic challenges caused by the COVID-19 pandemic, the global market for coir products showed an impressive performance. The main producing countries such as India, Sri Lanka and Indonesia enjoyed an increase in their exports of coir products. Table 2 shows the market development for India from 2017 to 2021, indicating that the market for coir products is relatively stable.

## USES BEYOND TRADITIONAL APPLICATIONS

The uses covered in this article that go beyond traditional applications fall into different fields with a significant volume and potential on the market. These are the production of binderless boards, composite materials, construction materials, environmental remediation materials, and biofuels.

### Binderless Fiberboards

Binderless boards are pressed without adding adhesives and are held together only by the natural adhesives present in the biomass fibers (Pintiaux *et al.* 2015). At present, most commercial fiberboards or particleboards rely on the use of synthetic adhesives to provide acceptable bonding and moisture resistance in the final board products. These adhesives, such as urea formaldehyde, are produced from petrochemical sources, and therefore pose both environmental and health concerns (Łebkowska *et al.* 2017; Duong *et al.* 2011). The finished boards or panels slowly emit formaldehyde into the surroundings, causing environmental pollution (Molhave *et al.* 1995). This may also negatively affect human health, causing irritation or worse effects such as cancer (Sheehan *et al.* 2018). In addition, significant production costs are associated with the use of synthetic adhesives as a component in boards or panels. These concerns have motivated the search for more sustainable adhesive-free alternatives for these products.

#### *Bond formation in binderless fiberboards*

The science behind the bonding in binderless boards in lignocellulosics is complex; a comprehensive review of this has been written by Hubbe *et al.* (2017). They state that lignin, mainly together with cellulose and hemicelluloses, is an integral molecular component that makes up the chemical constitution of plant-based fibers or particles used for commercial boards or panels. Thus, it is already present in the raw materials and has been reported as the main factor responsible for auto-adhesion by wood particles without the addition of synthetic adhesives (Avella and Delhoneux 1984). Lignin is a complex phenolic polymer that is biosynthesized from three different phenolic precursor units, *i.e.*, *p*-hydroxyphenyl, coniferyl, and syringyl alcohol. When polymerized, these give rise to H, G and S units, respectively. Several bond types exist between these units, which adds to the high complexity of lignin (Vanholme *et al.* 2010).

As shown in the review by Hubbe *et al.* (2017), the mechanism responsible for the adhesion is a combination of two main factors: (A) lignin within the inter-fiber or particle bonding zone responds to the elevated temperature and pressure according to its physical and chemical properties, described by its glass transition temperature  $T_g$ , flow properties, *etc.* and (B) lignin—in this case, particularly its phenolic parts—undergoes a range of highly complex chemical reactions, including free radical reactions that likely also involve the atmospheric oxygen present in the bonding zone. A proper understanding of the auto-adhesion mechanism must account for both of these factors. Other chemical components such as waxes can also be present in the bonding zone. These are found to produce a relatively weak adhesion, presumably due to the fact that weaker Van der Waals interactions dominate, and the formation of stronger inter-particle covalent bonds or hydrogen bonds play a secondary role (Stelte *et al.* 2011).

Several studies have shown that good adhesion is correlated with pressing conditions that allow a degree of molecular mobility in the surface lignin. This enables the establishment of good surface-to-surface inter-particle contact and bonding. This takes

place when the temperature is sufficiently high relative to the lignin  $T_g$ . Due to the chemical nature of lignin, the glass transition temperature,  $T_g$ , is not narrow; it is best described as a broad temperature region that depends on the lignin structure. Thus, syringyl lignin (lignin rich in -OMe substitution) tends to be a polymer with a more linear backbone, whereas guaiacyl lignin (lignin with an intermediate level of -OMe substitution) permits branching of the backbone, and a larger number of accessible linkage types within the lignin polymer. Differences of this kind in the lignin structure, that distinguish different types of fibers from one another, give rise to different  $T_g$  and flow behaviors.

The other factor mentioned above, (B), comes into play when sufficient inter-particle contact can be established due to the lignin polymer having a larger-scale flow or greater mobility. This may lead to the interlocking of polymer segments, which contributes to the overall adhesion. On the molecular level, this may be caused by Van der Waals or charge-transfer interactions between aromatic rings. Much stronger interactions may arise from covalent bond formation between lignin segments within the bonding zone.

At low temperature conditions, lignin has previously been shown to stabilize free radicals in the form of very stable lignin phenoxyl radicals that are immobilized within the lignin matrix (Barsberg and Thygesen 1999; Barsberg 2002; Barsberg *et al.* 2006). When surface lignin is subjected to conditions that promote the production of free radicals, *i.e.*, elevated temperature, it may act as a radical “sink” from which radical-radical reactions lead to the formation of new covalent bonds between lignin segments (Barsberg and Thygesen 1999; Barsberg 2002). The presence of atmospheric oxygen can enhance this process by causing the formation of lignin peroxy-radicals that can abstract hydrogen atoms from lignin and lead to a chain reaction by radicals. Covalent bond formation can end a chain reaction of this type. From the chemistry of phenolic antioxidants, it is well known that electron-donating groups (in a coarse description of their effect) enhance the antioxidant activity and radical-stabilizing ability of a phenolic structure. Thus, guaiacyl and syringyl (or single and double -OMe substituted) phenolic end-groups in lignin could be expected to act as ‘catalysts’ for the free radical mechanism described above due to their ability to stabilize free radicals (Barsberg *et al.* 2006).

The overall auto-adhesion is caused by a combination of many different complex mechanisms. Apart from lignin, other cell wall components may also contribute, such as hemicelluloses. These are flexible polysaccharides with relatively low  $T_g$ , and they possess many hydrogen-bond-forming hydroxyl groups that may be spatially organized to enhance the adhesion. Cellulose occurs in crystalline strands (microfibrils) whose surfaces are rich in hydroxyl groups. However, these are ordered surfaces with little flexibility to optimize hydrogen bonding that is not internal to the crystalline structure. One important difference compared to lignin-dominated adhesion is that polysaccharide hydrogen bonding is moisture-sensitive. Thus, given the right conditions, an increase in the amount of lignin on the surface of fibers or particles is expected to make the auto-adhesion of the resulting boards relatively moisture-resistant.

#### *Processing of binderless fiberboards*

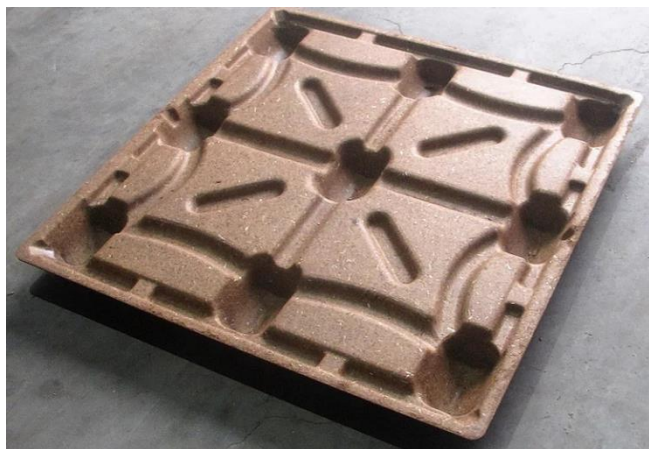
The production of high-density fiberboards from coir has been studied in great detail by van Dam *et al.* (2004a,b, 2006). They studied the composition and thermomechanical properties of coir and concluded that it is an excellent raw material for the production of high-density fiberboards. The lignin content of the fibers was shown to be about 31.9 wt%, and irreversible softening was found at temperatures above 140 °C, indicating a thermosetting behavior that may be used to develop a process for producing



binderless boards (van Dam *et al.* 2004a). They speculated that the irreversible changes are due to condensation reactions, *i.e.*, dehydration and crosslinking of lignin and lignin-like components. Furthermore, they pointed out that pre-treatment processes for the isolation of coir, *i.e.*, steam explosion and thermomechanical refining, should be carried out at temperatures below 120 °C to avoid irreversible changes to the lignin that almost certainly lead to a reduction in its self-adhesive properties (van Dam *et al.* 2004).

The fibers and chemical composition vary slightly depending on the variety and degree of maturation. Van Dam *et al.* (2006) studied six different varieties with different degrees of maturity to assess their suitability as a raw material for producing high-density fiberboard. They concluded that the varietal differences between the fibers were minor and did not affect the fiberboard production process. However, the effect of maturing on the chemical composition of the husks was more pronounced, with an increase in the glucose content. A study by Stelte *et al.* (2019) compared the lignin content of brown (mature) and white (immature) coir, finding that the lignin content increases with the degree of maturity.

A simple, efficient process was developed to produce high-strength, high-density fiberboards. Van Dam *et al.* (2004) studied extrusion, steam explosion, and milling as pre-treatment processes to isolate coir prior to hot-pressing into high-density fiberboards and three-dimensional molded parts. All three fiber-opening processes were deemed suitable for pre-treatment, and the mechanical properties of the boards and molded products were evaluated and compared to commercial MDF and particleboard. The binderless coir boards and molded products exhibited an excellent performance, suggesting that coir is an excellent raw material for fiberboards and molded parts. Cocopallet, a company from the Netherlands, recently developed a shipping pallet made from binderless coir (Fig. 3) that has real economic potential. The company indicates that millions of trees can be saved by using the ‘waste’ coir for the pallets if enough is produced (Cocopallet 2022).



**Fig. 3.** Binderless coir pallet. Figure provided by Cocopallet 2022 (<https://www.cocopallet.com/>)

### Composites Reinforced with Coir

Coir is an excellent filler for the production of composite materials. It can reinforce both synthetic and natural polymer matrices.

#### *Coir as a reinforcement for synthetic matrix polymers*

Coir has predominantly been combined with polypropylene, as well as polyethylene, epoxy, and poly(lactic acid), and made into composites. The amount of fiber

used as reinforcement, the addition of coupling agents, hybridization with other fibers and physical and chemical treatments have all been adjusted to obtain coir-based composites with the desired properties.

**Table 3.** Mechanical Properties of Coir-reinforced Synthetic Polymer Composites

Composite	Fiber content (%)	Impact strength (J/m)	Flexural strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Coir-PP	20	-	-	26.5	1.59	-
Coir-PP	15	-	16	35	1.50	-
Coir-Epoxy	22	-	34.6	20.2	2.7	-
Coir-PP	30	-	-	11.6	3.3	-
Coir-PP	20	52	47	26	2.4	6.2
Coir-Polyester	15	-	-	19.7	-	0.7
Coir-PLA	20	-	25	5	1.5	3.4
Coir-PLA	30	-	20	8	0.5	-
Coir-PP	30	24.6	50.3	26.6	1.96	-
Coir-epoxy	4	-	-	28.61	0.032	-
Coir-PP	20	43	21	18	1.6	-
Coir-PP	15	21.99	42.67	26.14	2.21	-
Coir-PP	20	65	33	-	3	-
Coir-PP	25	50	49	25	2.8	4.6
Coir-Polyester	10	-	-	21.4	0.46	-
Coir-PP	-	-	-	29.73	0.59	-
Coir-PP	20	51	48	26.5	2.65	-
Coir-PP	35	42	47	22	-	1.1
Coir-epoxy	30	111	-	28.7	3.18	-
Coir-epoxy	-	11.9	31.08	17.86	-	-

Note: References to original works can be found in Adeniyi *et al.* (2019)

Some of the properties of coir-reinforced synthetic polymer-based composites have been reviewed recently (Adeniyi *et al.* 2019) and are given in Table 3. These coir-based composites have been suggested as a useful means of developing tails, wings, and propellers for aeronautics, boat hulls, storage tanks, various sporting goods applications and packaging materials (Adeniyi *et al.* 2019; Hasan *et al.* 2021). Being inherently hydrophilic, coir will have limited compatibility with hydrophobic matrices. Hence, several approaches have been used, such as the alkalization of the fibers to remove hydrophilic substances and improve the fiber surface, or the use of compatibilizers and emulsions. Treated coir has shown an ability to substantially increase composites' properties and make them suitable for various applications. The properties of coir-reinforced composites also depend on the type of processing used. Open molding, extrusion, injection molding, resin transfer molding, and compression molding have all been used to develop coir-based composites. While access to the facilities required to prepare the composites determines the methods used for research-based studies, economical factors should be considered when coir-based composites are processed on a larger scale. Similarly, the size of composites also influences the choice of the method used for processing. Resin transfer molding (RTM) and compression molding are more commonly used, and RTM is preferable when larger composites need to be fabricated (Adeniyi *et al.* 2019). Reinforcing polypropylene with coir increased the flame resistance (LOI) from about 17-18% to as much as 21.5% when 70% coir was used. Increasing the

coir content also increased the tensile strength and water resistance due to the increase in the lignin content. The flexural and tensile strength of the composites increased by 26 and 35%, respectively, when the coir content was increased from 40 to 60% and maleated polypropylene (MAPP, 3%) was used as the compatibilizer. It was suggested that the composites formed met the specifications required for non-structural components such as automobile door panels (Ayrilmis *et al.* 2011).

Through twin screw extrusion and injection molding, coir has been combined with other natural and synthetic fibers to develop hybrid composites with polypropylene (PP) as the matrix. The tensile and flexural strength decreased as the amount of coir increased – but the moisture sorption increased. Natural fibers, coir and banana fibers have distinct properties, particularly in terms of fineness and lignin content. Care should be taken to blend the fibers uniformly in order to obtain consistent properties and utilize the advantages of each fiber (Bujjibabu *et al.* 2018). Proper coupling agents/compatibilizers such as maleic anhydride grafted PP (MAPP) need to be used to improve the strength when combined with PP.

Various modifications have been made to improve the interaction between the coir and the synthetic matrices. Treating coir with alkali, stearic acid, or potassium permanganate provided increased mechanical properties and electrical performance. A decrease in the dielectric constant and an increase in the flexural modulus and strength were noticed due to improved adhesion and enhanced polar interactions (Lai *et al.* 2005). Extrusion and injection molding of coir treated with benzene diazonium salt with polypropylene as the matrix provided an increase in the tensile strength of about 15% compared to neat polypropylene (Haque *et al.* 2009, 2010). In another study, fibers cut to 1 to 3 mm in length were immersed in a 5% NaOH solution, to which O-hydroxybenzene diazonium salt was added and the fibers were dried. The treated fibers were combined with 10 to 25% polypropylene granules, and the mixture was extruded into pellets. These were later injection-molded into composites of the desired shape and size. Composites containing the treated fibers had a higher tensile strength compared to neat PP. The flexural strength, flexural modulus, and hardness of chemically treated coir-reinforced PP composites were higher compared to the untreated composites. A considerable decrease in the hydrophilicity, an increase in interfacial bonding and better filler matrix interactions had occurred, leading to improved properties (Islam *et al.* 2010). However, the extent of treatment of the coir should also be limited, since excessive treatment is detrimental to the properties of the fibers and hence the composites. Coir treated with 2 to 8% alkali improved the properties of polypropylene composites, whereas those treated with 10% alkali decreased the fiber strength and hence the tensile properties of the composites (Gu 2009).

Coir in the form of loose fibers and pressed mats was used as a reinforcement with unsaturated orthophthalic polyester resin and 1% methyl-ethyl-ketone as the catalyst. Composites were developed through a solution-casting process, and the amount of fibers, compression pressure, time and temperature were varied. Flexural strength ranged from 0.9 to 25.7 and 1.0 to 31.2 MPa when the pressure was increased from 2.6 to 5.2 MPa. The tangled mass of fibers with a random orientation provided better properties than the pressed fiber mats (Monteiro *et al.* (2008). Polyester is highly hydrophilic, resulting in poor fiber matrix dispersion, the wetting of fibers, and consequently lower composite properties. Acetylation of coir or using silanes or titanates was believed to improve the compatibility between the coir and polyester. The chemical modifications improved the interfacial shear strength between the fibers and the matrix and led to an increase in the tensile strength and modulus due to the change in the fiber properties, particularly the increased hydrophobicity

on the surface. Acetylation was found to enhance properties better compared to silane or titanate coupling (Hill and Khalil 2000). Coir was treated with alkali or bleached to remove lignin and later grafted with acrylonitrile to improve compatibility with polyester and composite properties. Treated coir was made into non-woven mats and used to reinforce polyester composites developed using the resin transfer molding approach. Modifications to the fibers improved the mechanical properties; acrylonitrile grafting increased the tensile strength and flexural strength by 14 and 15%, respectively. Bleaching and alkali treatment also decreased the moisture sorption of the fibers but did not provide composites with properties similar to that of glass-fiber-reinforced polyester due to the relatively weak properties of coir compared to glass fibers (Rout *et al.* 2001).

Fibers treated with alkali (5% NaOH, 20 °C, 30 minutes) were used to reinforce epoxy and plain concrete. The treated fibers were made into composites using hand lay-up and the resin transfer molding approach. Alkali treatment caused substantial changes to the surface morphology and the mechanical properties of the fibers. Substances such as lignin, wax and oils were removed and the surface became irregular and rougher, which enhances the fiber matrix adhesion. Treatment with alkali also causes the ionization of hydroxyl groups, which also makes the fibers more compatible with the epoxy matrices. Due to such changes, a 17.8% increase in tensile strength, a 6.9% increase in tensile modulus, a 16.7% increase in flexural strength, and a 7.4% increase in flexural modulus was possible, but a decrease in tensile and flexural strain also occurred (Yan *et al.* 2016). In another study, it was proposed that fiber lengths affect the properties of epoxy composites, but poor interfacial adhesion affects the tensile and flexural strength and modulus (Biswas *et al.* 2011). Changes in fiber length also caused variations in the void content, the amount of moisture sorption, and the density of the composites, which also affected other properties. An optimum fiber content was necessary to obtain composites with an increased tensile strength and modulus without affecting other properties (Das and Biswas 2016). Treating coir with sodium carbonate also removed external components, exposed crystalline cellulosic fibers and increased the internal structure and swelling. This improved the tensile and flexural modulus when used as a reinforcement for epoxy or polyester. However, the properties of the coir-reinforced epoxy were lower than those of neat polyester or epoxy due to the limitations in the orientation of the fibers in the composites (dos Santos *et al.* 2018).

In another study, short fiber hybrid composites were developed by combining with epoxy and Portland cement particles with sizes between 37 and 44  $\mu\text{m}$ . The fibers were treated with 10% alkali (sodium hydroxide) at room temperature for 15 hours. Composites were fabricated using the hand lay-up and resin transfer molding techniques. Alkali treatment substantially increased the interfacial adhesion, reduced the porosity, and improved the tensile and flexural properties. The addition of cement particles did not produce any major improvement in the properties, and it was suggested that it was not possible to obtain enhanced mechanical and physical properties simultaneously (Oliveira *et al.* 2018). Fibers with lengths ranging from 3 to 15 mm were combined with epoxy (70 to 85%) and 10%  $\text{Al}_2\text{O}_3$  as particulates and made into composites. Increasing the fiber content to 15% and fiber length to 12 mm increased the strength, with a maximum tensile strength of 25.7 MPa, a flexural strength of 29.8 MPa, and an impact strength of 14.8  $\text{kJ/m}^2$ . Composites with a higher fiber content had an increased moisture sorption but good matrix-fiber adhesion (Das and Biswas 2016). Blending coir with glass fibers and developing epoxy-based hybrid composites also showed similar results, with a maximum flexural strength of 63 MPa and a hardness value of 21.3 Hv (Bhagat *et al.* 2014). Coir- and jute-

fiber-reinforced hybrid epoxy (Novolac) composites have also been developed using hand lay-up techniques. Fibers cut to 1 cm in length were made into mats and laid in different configurations with a 3:1 ratio of coir to jute. Hybridization was found to improve the dimensional stability and mechanical properties of the composites and jute provided higher moisture resistance compared to coir (Saw *et al.* 2014). Coir-jute composites were also found to have better properties than pure coir-epoxy composites (Singh *et al.* 2021).

#### *Completely biodegradable coir composites*

Composites using coir have been developed using synthetic polymers such as polyester, polypropylene, or epoxy as resins. Since these composites contain synthetic polymers, they can only be considered to be partially degradable. Efforts have been made to develop completely biodegradable coir composites using natural and synthetic biodegradable resins (matrices) such as poly(lactic acid). Starch is one of the most widely used and inexpensive biopolymers but is non-thermoplastic. Chemical modifications have been made to starch to make it thermoplastic, utilize the modified starch as a matrix, and develop completely biodegradable composites. Fibers (5 to 30% by weight) were cut to 10 mm lengths and combined with cassava starch and 30% glycerol in an industrial mixer. Later, the mixture was cast into steel molds and compression-molded at 160 °C for 50 minutes. The composites obtained were thermally treated at 60 °C for 12 hours to improve their performance properties. Instead of using synthetic biopolymers, completely biodegradable coir-based composites have been developed using proteins (notably wheat gluten) as a binder with and without chemical modifications. Coir fibers were treated with sodium hydroxide or (3-triethoxysilylpropyl)-t-butylcarbamate (carbamate silane) to improve the interfacial interaction and mechanical properties. A 25% increase in stress at failure and an 80% increase in maximum stress was observed when the modified fibers were used as reinforcement due to improved fiber-matrix interactions (Hemsri *et al.* 2012). In another approach, wheat gluten was toughened using thiolated poly(vinyl alcohol) (PVOH) by esterifying PVOH with 3-mercaptopropionic acid. Modified PVOH (20%) was combined with acetic acid, freeze-dried and later made into powder for use as a matrix. Coir fibers were also treated with silane and alkali, blended with wheat gluten, and compression-molded into bars at 150 °C for 10 minutes at a pressure of  $1.1 \times 10^8$  N/m<sup>2</sup>. The first-ply failure strength of composites containing modified wheat gluten was 20% higher than that of composites containing unmodified gluten. Similarly, the maximum stress was higher by up to 26%. It was suggested that the composites obtained could be suitable for applications such as furniture, construction boards and packaging (Diao *et al.* 2014).

### **Construction Materials**

Coir fibers can be used as reinforcement in traditional building materials such as concrete and gypsum, providing the building material with additional stability.

#### *Coir fibers as reinforcement in concrete*

Unlike most other natural cellulose fibers, coir has been used as a reinforcement and/or additive to concrete to prevent cracking, improve resistance to environmental conditions, *etc.*

In one study, 0.125 to 0.75% coir was combined with cement, lime and sand in a ratio of 1:2:8, to which the coir fibers were added. The compressive strength of the cement blocks increased substantially and the residual strength, toughness, and ductility also increased up to a fiber content of 0.5%. However, resistance to acid and alkali decreased

due to the addition of coir (Sathiparan *et al.* 2017). Additives such as dispersing agents, defoamers, and wetting agents were included to improve the properties of coir-reinforced concrete. In addition, chemical and physical modifications were made to both the matrix and fibers. Coir fibers with a length of 2 and 4 cm were treated with alkali and used as additives for concrete along with the dispersant, defoamer and wetting agent in various proportions and cast into composites. Increases of 12% in flexural strength, 340 to 940% in toughness, and 860 to 1280% in ductility were possible. Alkali-treated fibers exhibited better interaction and composite properties (Li *et al.* 2006). The addition of 0.4 to 0.75% untreated coir and alkali-treated coir improved the workability of the mortar and decreased the water absorption capacity. With increasing fiber content, the flexural and compressive strength and toughness of the mortar improved due to the addition of coir, with the alkali-treated fibers exhibiting greater strength than the raw fibers (Andiç-Çakir *et al.* 2014).

#### *Coir reinforcement in gypsum*

In addition to cement, coir has been used as a reinforcement for gypsum to improve its resistance to environmental degradation and its mechanical properties. Coir fibers (0.5 to 2%) were added to a bentonite-lime mix, which increased the unconfined compressive strength by 4% depending on the curing time. An enhanced post-peak region was observed. The product was suggested to be suitable for building temporary roads (Dutta and Mohanty 2015). Coir fibers were combined with feathers and used to reinforce gypsum and potentially replace false ceiling tiles used in interior applications (Guna *et al.* 2021). Gypsum tiles containing up to 30% fibers were manufactured; the addition of coir increased the mechanical properties. Good resistance to moisture and high flame resistance similar to that of commercial gypsum boards was obtained. The product was said to be useful for promoting green building initiatives.

#### **Acoustic Panels Made from Coir**

Coir fibers were combined with PVOH and made into samples to determine their acoustic properties. The noise reduction coefficient of the composites depended on the thickness of the samples and the number of air gaps.

Experimental data obtained in an impedance tube closely followed various models used to predict the acoustic sorption of natural fiber materials (Table 4) (Taban *et al.* 2019). The acoustic properties of coir are also related to the age of the fibers and the frequency of testing. Fresh coir had an average absorption coefficient of 0.8 at 1360 Hz and a thickness of 20 mm. Increasing the thickness increased the sound absorption, particularly at lower frequencies. Including perforated plates and increasing the number of air gaps was also found to improve acoustical properties (Fouladi *et al.* 2011). The sound absorption panels were lightweight and biodegradable, and found to be suitable to replace glass fiber and mineral fiber-based acoustic panels. Based on the ISO 354 standard, an absorption coefficient between 0.7 and 0.85 was obtained for frequencies between 1000 and 1800 Hz, similar to that of simulation values (Zulkifli *et al.* 2008). In another study, various models were used to predict the acoustic performance of coir-reinforced composites. The results obtained from the modeling studies were comparable to the experimental data. Coir composites had an acoustic absorption of 0.81 at frequencies between 1000 and 3000 Hz and 0.84 at 2000 Hz with a thickness of 40 mm (Taban *et al.* 2020). A substantial increase in the acoustic absorption of coir was also reported when the coir fibers were compressed. The sound absorption of fibers compressed to a thickness of 60 mm was about 66% higher than the same amount of fibers compressed to 100 mm. By contrast, increasing the number



of air gaps between the fiber layers was reported to improve the sound absorption at low frequencies. A suitable arrangement of air gaps and fiber layers and the addition of a perforated plate were suggested to improve the acoustic absorption of coir-based composites (Fouladi *et al.* 2010; 2012). Coir fibers made into samples with a thickness between 7 and 35 mm, a density of 110 and 220 kg/m<sup>3</sup> and an airflow resistivity of N.S.m<sup>-4</sup> were studied for their acoustic behavior in the frequency range between 100 Hz and 5000 Hz in an impedance tube as per ISO10534-2 and ASTM E1050-98 standards (Bhingare and Prakash 2021). The sound absorption properties varied considerably with the density and thickness of the samples. A sound absorption coefficient between 0.5 and 0.84 at frequencies between 2700 and 3100 Hz was obtained for samples with a thickness between 21 and 35 mm and a density of 220 kg/m<sup>3</sup>. In terms of sound transmission loss, samples that were 35 mm thick had a loss of 11.3 dBA, suggesting that they are suitable for acoustic applications.

**Table 4.** Noise Reduction Coefficient of Coir Fiber-PVOH Composites of Different Thickness Compared with Experimental Models (Taban 2019)

Thickness	Backing conditions	Noise Reduction Coefficient (NRC)			
		Experiment	D-B model	Miki model	J-C-A model
25	Rigid backing	0.27	0.32	0.29	0.27
	10mm	0.33	0.42	0.39	0.35
	20mm	0.31	0.44	0.40	0.37
	30mm	0.34	0.46	0.42	0.40
35	Rigid backing	0.37	0.42	0.39	0.37
	10mm	0.41	0.50	0.47	0.44
	20mm	0.44	0.53	0.50	0.47
	30mm	0.45	0.56	0.52	0.49
45	Rigid backing	0.54	0.51	0.48	0.54
	10mm	0.51	0.59	0.55	0.52
	20mm	0.56	0.62	0.59	0.57
	30mm	0.58	0.67	0.61	0.60

### Coir Fibers Used for Environmental Remediation

Coir's ready availability, low cost, relatively prolonged degradation, and unique structure makes it a preferred fiber for the sorption of various pollutants. After carbonization and other physical and chemical modifications, coir has been used in fibrous form for environmental remediation. Coir fibers were pyrolyzed at 600 °C for 4 hours and later treated with 0.1 M HCl to demineralize the surface. Acid treatment increased the pore size and porosity, facilitating higher sorption. The specific surface area of the modified coir sorbent was 403 m<sup>2</sup>/g and the total pore volume was 0.151 cm<sup>3</sup>/g, with micropores of <2 nm contributing to about 17.4% and mesopores (2 to 20 nm), accounting for 69%. When used for the sorption of two drugs, dichlorvos and pymetrozine, a sorption of up to 19 mg/g was possible, with acidic pHs providing higher absorption (Binh and Prakash 2019). Waste cooking oil is an ideal feedstock for the production of biodiesel, but contains high amounts of free fatty acid (FFA) which hinder conversion. The possibility of using activated carbon from coir for the sorption of FFA was studied in a fixed-bed adsorption column. The activated biochar was able to reduce the amount of FFA by 93% at a waste cooking oil flow rate of 3 mL/min and also had a high sorption ability (1646 mg/g) for methylene blue (Oktavian *et al.* 2020). Studies have shown that coir can sorb considerable amounts of dyes.

However, the role that the various components of coir play in the sorption of dyes was not clear. In a recent study, it has been shown that removing lignin decreased the sorption of acid and reactive dyes but increased the sorption of basic dyes. Removing hemicellulose and increasing the  $\alpha$ -cellulose content also increased the sorption of basic dyes. The amount of lignin affected the removal of acid dyes due to the reduction in the carboxyl content. Hence, appropriate pre-treatments are required before coir fibers are used for specific dye removal (Samanta *et al.* 2018). In addition, several modifications have been made to increase the efficiency of coir when sorbing various dyes (Table 5). Treating coir with sulfuric acid at 60 °C for 3 hours resulted in a net negative charge on the fibers and hence the higher absorption of the cationic dye methylene blue with a sorption capacity of 121 mg/g compared to 10 mg/g for the anionic dye acid orange 7 (Ong *et al.* 2013). Treating coir fibers with the cationic surfactant hexadecyltrimethylammonium bromide instead of acid was helpful in considerably increasing the sorption of acidic dye (direct red 12B): 76.3 mg/g was sorbed compared to 14.9 mg/g with the basic dye (Rhodamine B) through chemisorption (Sureshkumar and Namasivayam 2008).

**Table 5.** Form of Coir used for Sorption of Various Dyes and the Sorption Capacity

Form of Coir	Type of Dye	Adsorption Capacity (mg/g)
Coir pith	Congo red	6.72
Coir pith	Acid violet Acid brilliant blue Rhodamine B	1.65 16.67 203.25
Coir pith	Rhodamine B Acid violet	2.56 8.06
Coir pith	Procion orange	2.6
Coir pith	Congo red Methylene blue Acid brilliant blue Procion orange	6.72 5.87 15.24 2.60
Surfactant-modified coir pith	Acid brilliant blue Procion orange	159 89
Cationic surfactant-modified coir pith	Direct red 12B Rhodamine B	76.3 14.9
Thermally activated coir pith	Acid brilliant blue	15.24
Thermally activated coir pith (carbon prepared from coconut husk)	Methylene blue	5.87

Note: References to original works can be found in Chowdhury (2016)

Purified coir was obtained by treatment with sulfuric acid followed by alkali and later bleaching with 10% sodium hypochlorite at 50 °C for 1 hour. The purified coir was used to sorb dyes from wastewater using a down-flow hanging sponge reactor. The sorption of the dye followed the Langmuir isotherm model, with a maximum sorption of 303 pt/Co/g at 30 °C, suggesting that the purified coir is suitable for the industrial-scale removal of dyes in dye effluents (Nguyet *et al.* 2020).

Similar to the approach used with the dyes, various modifications (Table 5) have been made to improve the sorption of metal ions from polluted water using coir pith. Sorption capacities between 8.6 and 263 mg/g have been reported for lead, chromium, nickel, and other metal ions (Chowdhury and Konica 2016). Selective chemical modification such as treatment with nitric acid (thiolation) provided coir fibers with a specific surface area and charge density of  $1.186 \times 10^{25} \text{ m}^2/\text{g}$  and  $5.39 \times 10^{24} \text{ meq/m}^2$ ; the highest sorption level was observed for Pb(II) followed by Hg (II) and As (III) (Igwe *et al.* 2008). Not only common metals, but even rare metals such as gallium have been successfully recovered (70.5%) using oxidized coir fibers. Oxidation increases the surface area and facilitates higher sorption through ion exchange (19.42 mg/g). High desorption was also possible after treatment with 0.5 M HCl (Suryavanshi and Shukla 2009). The sorption of metals by coir also depends strongly on the initial dosage, the metal concentration and the pH. It was possible to triple the sorption of Cu(II), Pb(II), Ni(II) and Fe(II) after treating coir with alkali (18%) and when the pH was between 4.5 and 5. The sorbed metals were easily desorbed and the coir fibers recycled up to 3 times without any major loss in the adsorption capacity (Shukla and Shukla 2013). Functionalizing coir fiber with the thiophosphoryl (P=S) group formed stable complexes ( $\text{Cl}_3\text{P}=\text{S}$ ) and high binding capacities (0.2 to 5 mmol/g) for  $\text{Cd}^{2+}$  (de Sousa *et al.* 2010). Coir has been activated using various chemicals and subsequent carbonization to improve its porosity and pore size and hence its ability to remove various sorbents. Activating coir dust with zinc chloride and carbonizing at 800 °C resulted in carbon with a pore diameter of 2-4 nm and a surface area of 1884  $\text{m}^2/\text{g}$ . This carbon provided high sorption for methylene blue and Remazol yellow though pseudo-second-order kinetics and intraparticle diffusion.

**Table 6.** Various Types of Coir and Their Ability to Sorb Phenols from Water

Adsorbent Type	Adsorbate	Adsorption Capacity
Coconut husk	2,4,6-trichlorophenol	716.10 mg/g
Coconut-shell-based activated carbon	Phenol	205.8 mg/g
Coconut husk	2,4,6-trichlorophenol	191.73 mg/g
Acid-treated coconut shells	Phenol	0.53 mmol/g
	2,4-dichlorophenol	0.31 mmol/g
Thermally activated coconut shells	Phenol	0.36 mmol/g
	2,4-dichlorophenol	0.20 mmol/g
Palm pith carbon	2,4-dichlorophenol	19.16 mg/g
ZnCl <sub>2</sub> activated coir pith carbon	Phenol	92.58 mg/g
Carbonized coconut coir pith	2,4-dichlorophenol	19 mg/g
Activated carbons developed from coconut shell	$\alpha$ -, $\beta$ -, and $\gamma$ -picoline	25.06-400.0 mg/g
Activated carbon developed from coconut shell fibers	$\alpha$ -, $\beta$ -, and $\gamma$ -picoline	36.90-400.0 mg/g
H <sub>3</sub> PO <sub>4</sub> activated coir pith	Phenol, p-chlorophenol and p-nitrophenol	0.46, 0.49 and 0.52 mmol/g

Note: References to original works can be found in Bhatnagar *et al.* (2010)

It was suggested that the activated carbon was suitable for large-scale industrial applications due to the short equilibrium times and lower cost (Macedo *et al.* 2006). Not only coir but nanocellulose extracted from coir and further modified through acetylation has been used to remove vanadium (V) and chromium (III) in waste water with removal efficiencies of 94 and 85%, and sorption capacities of 33 and 114 mg/g, respectively (Daniel *et al.* 2021). Recent studies have suggested that raw coir is more suitable for sorption of heavy metals compared and relatively high sorption capacity of processed coir considering cost and life cycle analysis. Highest absorption efficiencies between 21 to 24% were reported for Cd, Ni and Pb (Dilshani *et al.* 2022). A comprehensive review on the sorption of metal ions using coir in various forms have been published by James and Yadav (2021).

As with dyes and metals, coir fibers have also been found suitable to sorb and remove various phenols and radionuclides in water. Activated carbon from coir, treatment with acid, H<sub>3</sub>PO<sub>4</sub>, *etc.* helped achieve high phenolic removal with an adsorption capacity ranging from 0.20 mmol/g to 716 mg/g (Table 6) (Bhatnagar *et al.* 2010). This does not only apply to water: coir pith activated using phosphoric acid was able to remove phenol, p-chlorophenol, and p-nitrophenol from petroleum industry effluents, with optimum removal at pH 6 and applying the Freundlich isotherm (Anirudhan *et al.* 2009). Further, the sorbed phenols were recovered after treatment with 0.1 M NaOH.

### **Fuel Pellets and Briquettes Made from Coir**

Few studies have been published on the production of biofuel pellets (Forero-Nunez *et al.* 2012, Stelte *et al.* 2019, Dos Santos *et al.* 2021) and briquettes (Saha *et al.* 2016; Brunerová *et al.* 2017) from coconut fibers. Most studies used either shredded shells or coir pith as a raw material and only one study looked specifically into the pelletization of coir fibers (Stelte *et al.* 2019).

Fuel pellets are an internationally traded commodity. They are certified according to international standards that grade fuel pellets based on their mechanical properties, heating value, and inorganic (ash) content. Coir has been shown to have a high lignin content correlated to a high calorific value. Combined with the excellent bonding properties of these fibers when exposed to heat and pressure, coir has been shown to be an excellent raw material for fuel pellet production (Stelte 2019). One key advantage of using coir fibers instead of shredded husks or pith material is that large amounts of inorganic salts are removed during the processing of the fibers, increasing the pellet fuel properties.

## **CONCLUSIONS AND FUTURE CONSIDERATIONS**

It can be concluded from the literature studied for this review that the potential amount of coir that can be obtained from coconut processing waste exceeds the volume used for traditional coir products by far. About 20 million tons of husk occur as a by-product in the coconut processing industry per annum. A large fraction is discarded as waste due to lacking applications and market for these husks. Finding new applications for coir extracted from these husks, is adding value to the industry and coconut producing farmers.

Coir is a fiber of high strength and resilience and traditionally used for household products such as mats, ropes, and textiles. The unique combination of the fibers mechanical

properties and their naturally high lignin content makes coir an ideal raw material for a wide range of applications.

One important application of coir beyond traditional uses are binderless fiberboards. At present, most commercial fiberboards are manufactured using synthetic adhesives that give rise to health and environmental issues. Reviewing the science behind bond formation in fiberboards and identifying the importance of lignin, its molecular structure, and interaction with other wood polymers provides an understanding how and why coir is such a promising raw material for producing binderless fiberboards. The role of glass transition and irreversible thermosetting behavior of coir at elevated temperature are important aspects to consider when processing coir and key aspects to achieve high mechanical properties of the produced fiberboards. The use of waste coir in applications such as pallets could reduce the use of wood and composite pallets.

This knowledge is also of high relevance for the use of coir as reinforcing fiber in composite materials in combination with both fossil and biobased polymers. Literature indicates that coir can be an excellent reinforcement in combination with a wide range of matrix polymers. Surface treatment of the fibers to increase compatibility with the matrix polymer and choosing the right processing techniques are key factors to achieve good bonding and this high product strength. Coir fibers can also be used as reinforcement in concrete and gypsum, providing the building material with additional stability. The reviewed studies indicate that the fibers improve strength and the building materials resistance to environmental conditions and preventing of cracks. Acoustic panels have been identified as an important area of use for coir based materials and these have shown to have excellent noise dampening properties over a wide frequency bandwidth.

Using coir for absorbing colorants and pollutants from water is another promising field of application. Studies have shown that a wide range of dyes and phenol based pollutants can be absorbed and removed from water using coir. Last but not least, coir has a high heating value which makes it, in combination with its excellent bonding properties, a favorable raw material for fuel pellet and briquette production that can be used as cooking and heating fuel in local homes replacing firewood and fossil based fuels.

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