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# Advancements in sustainable material development: A Comprehensive review of coir fiber and its composites

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This article contributes to:
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
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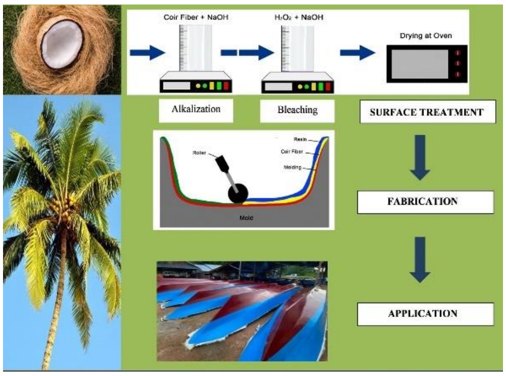


**Highlights:**

- Coir fiber supports SDGs with eco-friendly solutions, poverty reduction, food security, and economic growth.
- Treatments and techniques improve coir composites' strength, stability, and water resistance.
- Coir fiber is abundant, affordable, sustainable, and widely used in various industries.

## Abstract

Derived from coir coconut waste, coir fiber offers an environmentally friendly response to ecological challenges in various industries. Its application aligns with achieving Sustainable Development Goals (SDGs), such as eliminating extreme poverty, ensuring food security, and promoting decent employment and economic expansion. It also fosters environmentally friendly consumption and production, mitigates global warming, and conserves biodiversity. The study involves a comprehensive review of current literature, examining the methodologies including extraction techniques, surface modifications, and manufacturing processes like hand layup, casting, compression molding, hot pressing, and injection molding. The analysis identifies key improvements in mechanical, thermal, and physical properties of coir fiber composites, particularly enhanced tensile strength, thermal stability, and reduced water absorption due to chemical treatments. This confirms previous findings and contributes toward enhancing our understanding that coir fiber is extensively utilized in multiple industries, including housing, construction, transportation, biomedical, wrapping, electrical power, communication technology, biofuel, and bioenergy due to their natural abundance, affordability, ease of shaping, superior durability, and eco-friendly characteristics. Another crucial practical implication is that coir fiber and its composites offer numerous advantages that have significant consequences for the development of coir fiber in various fields.

**Keywords:** Coir fiber; Natural fiber composite; Industy; Sustainable development goals

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# 1. Introduction

Polymer Matrix Composite (PMC) is a composite material in which a polymer resin serves as the structure of the matrix or bridging material. PMC is recognized for being lightweight, cost-effective, environmentally sustainable, and having good properties [1]. This makes it suitable for various applications in aircraft, military, space, automobiles, sports, marine, and infrastructure materials [2],[3]. The polymer matrix offers support and adheres to reinforcing elements like fibers and particles. Fiber can be categorized into synthetic fibers and natural fibers based on the source material. Natural fiber offers exceptional properties, wide availability, and easy decomposition upon disposal. Notably, natural fiber plays a crucial role in promoting the development of eco-friendly and sustainable products [4]. The inherent strength of the fiber is determined by its composition of layers, including cellulose, hemicellulose, lignin, and other impurity elements [5]. Natural fibers deteriorate readily in acidic environments, including Hydrogen Chloride (HCl), Sulfuric Acid ($H_2SO_4$), Nitric Acid ($HNO_3$), and Phosphoric Acid ($H_3PO_4$) [6]. Surface contaminants can hinder matrix-fiber bonding, significantly affecting composite adhesive strength. Thus, comprehensive knowledge of the characteristics of natural fibers and their handling is crucial for enhancing the efficiency of natural fiber-based composite materials.

Coir fiber is a natural fiber that can be mixed with polymers to create a composite material. In 2020, global coir fiber production reached a total of 1,276,624 metric tons as can be seen in **Figure 1** [7]. White coir fiber is predominantly manufactured in India, specifically in the coastal area of Kerala state. Note that India produces 60% of the world's supply. Sri Lanka produces 36% of the world's brown fiber. More than half of the annual global coir fiber production is consumed in the countries where it originated, mostly in India. In 2020, India and Sri Lanka collectively produced 59% of the world's coir [8]. Note that Sri Lanka is the world's largest exporter of coir fiber and products produced from it, which remain the country's main exports.

Coir fiber, obtained from coconut husk, is a natural fiber that has garnered considerable interest recently due to its diverse applications in composite materials. Natural fibers may be classified based on sustainable sources into plants and animals. Thus, studying coir fiber composite is significant since it enables the investigation of environmentally benign and biodegradable materials. In addition, coir fiber is a promising soundproof material due to its absorption coefficient index, which ranges from 0.75 to 0.94 [9]. Surface treatments, including chemical and biological methods, enhance the fiber-matrix bonding, resulting in improved thermal stability, complex modulus, damping factors, and resistance [10],[11]. Furthermore, processing parameters and filler reinforcement influence wear behavior, where lower filler loading may enhance wear resistance [12]. Coir fiber can also be combined with kenaf fiber in epoxy composites for insulation due to its favorable thermal conductivity [13] while a combination of 50% jute and 50% coir fiber results in a ductile material. Notably, increasing the proportion of jute fiber leads to higher tensile strength [14]. Two types of fibers in a composite significantly affect the distribution of fibers and the contact between binder and fiber. This phenomenon impacts the physical and mechanical properties.

A large and growing body of literature has investigated the possibility of mixing coir fiber-reinforced polymer matrix composite with various filler materials. This includes Titanium Carbide (TiC) [15], waste powder [16], silicon carbide powder [17], nano clay [18], graphite [19], aluminum, and copper [20]. Incorporating fillers like rice husks, eggshells, and Calcium Carbonate ($CaCO_3$) has been shown to enhance the tensile, flexural, impact, and dynamic mechanical properties of hybrid coir fiber composites [21]-[23]. The evidence presented that filler material in the space between the matrix and fiber decreases the time to failure while the composite is under load. At the same time, enhanced comprehension of the function of filler materials can contribute to the creation of more robust and long-lasting composite for various applications.

Therefore, the purpose of this review is to provide a comprehensive understanding of coir fiber and its composite, focusing on the role of various filler materials and treatment methods in enhancing the physical and mechanical properties of the

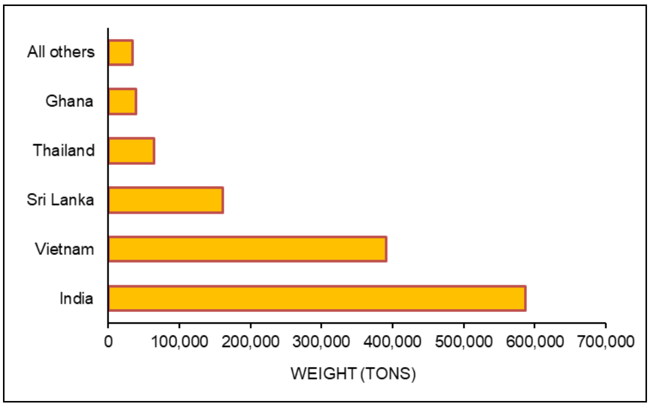


**Figure 1.** Coir production all over the world in 2020 [7]

composite. This review also aims to address existing gaps in the literature, particularly the limited discussion on how the size, shape, and orientation of coir fibers impact composite performance. Morever, to investigate the positive impact on the Sustainable Development Goals (SDGs).

## 2. Natural Fiber

Natural fiber is classified into three categories based on its origin: plant, animal, and mineral. Plant-based reinforcement composite is a major focus in various industries, including engineering, transportation [24], building materials [25], sports equipment, and electromagnetic interference shielding enclosures, to name a few [26]. Notably, plant fiber is a reinforcing material under ongoing study and development in the research and industrial sectors [27]. Natural fibers can diminish the effects of carbon footprint and greenhouse gas emission [28] and serve as substitutes for traditional composite [29]. Aside from conducting tests, the analysis and assessment of composite composed of natural fibers can be achieved using simulation software like ANSYS [30]. The simulation's goal is to enhance composite performance by optimizing parameters and selecting manufacturing techniques. In addition, multiple species of plants, such as banana [31], coir [31], coconut leaf stalk [32], jute [33], wool, flax, hemp, sisal, and palmyra [34],[35], can be explored and utilized as natural fibers for the development of products.

Previous research has examined and published the physical and mechanical characteristics of several natural fibers, as displayed in **Table 1**. Note that identifying the characteristics of natural fibers is crucial when creating a product from composite materials. Researchers and industry analyze properties such as density, elongation at break, tensile strength, and young's modulus of natural fibers to select the appropriate fiber for composite-based products. Lightweight composite refers to composite material with a lower density. The composite material's tensile strength is high due to its ability to stretch significantly before fracturing when subjected to an external load. Furthermore, the tensile strength and elastic modulus of natural fibers directly impact the strength and stiffness of composite. The thermal behavior of natural fibers is vital as low density might decrease thermal conductivity. Moreover, these mechanical characteristics impact the fibers' behavior in the production process, with fibers with high tensile strength offering improved structural stability. This indicates a need to understand that selecting natural fibers with suitable qualities is essential to guaranteeing the composite meets the required quality and performs optimally for the intended purpose, as we can observe in **Table 1** [36]-[38].

**Table 1.** Physical and mechanical properties of natural fiber

| Types of Fiber | Density ($g/cm^3$) | Elongation at break (%) | Young's modulus (GPa) | Tensile strength (MPa) | Authors |
|---|---|---|---|---|---|
| Flax | 1.5 | 3.2 | 26.5 | 900 | [35] |
| Hemp | 1.48 | 1.60 | 70 | 690 | [37] |
| Corn stalks | - | 1.90-2.30 | 4.10-4.50 | 33.40-34.80 | [35] |
| Jute | 1.3 | 1.8 | 26.5 | 400 | [35]-[37] |
| Abaca | 1.50 | 3-10 | 12 | 400 | [37] |
| Banana | 1.35 | 5.90 | 12 | 500 | [37] |
| Kapok | - | 1.20-1.75 | 4.56-5.12 | 80.3-111.5 | [35] |
| Rice straw | - | 2.11-2.25 | 24.67-26.33 | 435-450 | [35] |
| Sisal | 1.5 | 3 | 9.4 | 700 | [37] |
| Bagasse | - | 6.20-8.2 | 15-18 | 257.3-290.5 | [37] |
| Kenaf | 1.45 | 1.6 | 36.5 | 930 | [37] |
| Bamboo | - | 4.0-7.0 | 22.2-54.2 | 360.5-590.3 | [37] |
| Pineapple | 0.60-1.60 | 14.50 | 400-627 | 144 | [37] |
| Coir | 1.2 | 30 | 6 | 175 | [37] |
| Cotton fiber | 1.5 | 8 | 13 | 400 | [37] |
| Calotropis fiber | 1.3 | 680 | 3.4 | 25.1 | [36] |
| Human hair fiber | 1.1 | 150-270 | 3.4 | 4.1 | [35] |
| Ramie | 150 | 2.50 | 24.50 | 565 | [37] |
| Alfa | 0.89 | 5.80 | 22 | 350 | [37] |

# 3. Extraction and Treatment of Coir Fiber

The coconut tree, scientifically known as cocos nucifera (L.) (Arecaceae), is a common fruit-bearing plant found worldwide [39]. The typical length of coir fiber varies between 0.25 and 0.35 meters. The cross-section of coir fiber displays a multicellular structure with a varying number of cells, ranging from 30 to over 300. There are two different types of coir fiber: white coir and brown coir. Empirical studies have proven that dark coir demonstrates greater strength than white coir. White coir fiber has a density of 1.01 ± 0.05 g/cm$^3$, while brown coir fiber has a density of 1.29 ± 0.07 g/cm$^3$. Furthermore, the study discovered that adding coir fibers up to 30 mm in length to a composite material improved its mechanical properties compared to composite with shorter fibers [40].

Natural fiber typically includes coir fiber, which is constructed from multiple layers of components like lignin, hemicellulose, cellulose, and other substances. This includes protein, pectin, and ash. At the same time, coir fiber's irregular surface texture makes it ideal for being embedded in a matrix to enhance the bonding strength. To achieve a strong binding, the material layer on the fiber's surface must be eliminated since it may impede bonding between the matrix and coir fiber [41]. Various treatment approaches, such as chemical, physical, biological, and combination, have been used to improve the matrix and coir fiber interface. Moreover, by subjecting structural components covering the outer layer of cellulose, namely hemicellulose, and lignin, to a series of treatments, including the processes of surface treatment, rinsing, and drying, it is possible to produce a rougher surface and increasing the percentage of cellulose in the fiber. This, ultimately, leads to an enhancement in the mechanical and physical attributes of composite [42].

Modification of coir fiber surface structure became a fundamental stage in composite fabrication to eliminate several material contents, such as impurities and extraneous substances that prevent the bonding strength among matrix and coir fibers [43]. Sodium hydroxide (NaOH), oxalic acid ($H_2C_2O_4$), sodium bicarbonate ($NaHCO_3$), and potassium permanganate ($KMnO_4$) were included as a type of soluble medium in the surface layer modification of fiber coir by some previous researchers [44],[45]. In another major study, Rahayu et al. [46] experimented with different NaOH concentrations of 0.5 M, 1 M, and 5 M, immersion temperatures of 60 °C, 70 °C, and 80 °C, and soaking times of 1 hour, 1.5 hours, and 2 hours. The greatest cellulose content was achieved by utilizing coir particles sized at 100 mesh, a NaOH concentration of 1.5 M, and a temperature of 80 °C for 1.5 hours. The cellulose content obtained was measured to be 69.82%. Treating coir fiber with alkali solutions enhance surface roughness, which improves bonding strength in composite materials [47] and decrease fiber diameter [48]. In the study by Nasidi et al. [49] variations in NaOH concentrations of 0%, 1%, 2%, and 3% were examined. The Scanning Electron Microscopy (SEM) analysis revealed that pores in the fiber structure started to emerge at a concentration of 3%. As a result of surface treatment, the density can drop from 1.4 g/cm$^3$ to 1.0 g/cm$^3$. It can also absorb more oil, have more pigment and filler, and have particles that are 99.5 g/100 g, 47.7 µm, 15.2 ± 21.9 µm, or 40.9 g/100 g of average size [50]. However, alkali content must be considered while altering the surface structure of coir. As a result, surface roughness and pore development enhance the interlocking between the matrix and coir.

Varying the duration of coir fiber soaking in the medium can result in varying quantities of cellulose, hemicellulose, and lignin due to factors such as soaking time, temperature, and the composition of the soaking medium [44],[51],[64]. In 2020, Kumaran et al. [65] submerged the fiber in NaOH, glacial acetic acid, and benzoyl chloride solution at varying durations of 30, 60, 90, 120, and 150 minutes. Fourier Transform Infrared Spectroscopy (FTIR) analysis can identify alterations in cellulose, hemicellulose, and lignin concentration. Notably, an increase in the intensity of the peak at 3,312 cm$^{-1}$ suggests higher amounts of cellulose. In addition, in fibers without treatment, a peak was observed at 2,916-2,852 cm$^{-1}$ and decreased after treatment, indicating a reduction in the amount of hemicellulose. Meanwhile, changes in the peak intensity of lignin at 1,642 cm$^{-1}$ indicated a reduction in the amount of lignin. Furthermore, alkaline treatment degrades the branching and amorphous structures of coir by attacking the hydroxyl group (-OH), which then combines with water molecules (H-OH) [66]. To produce clean fiber, the fiber separated from the black liquor is then bleached and purified with the help of various chemical and physical processes, including bleaching with Hydrogen Peroxide ($H_2O_2$). Note that increasing the bleaching process time can significantly impact the functional properties of coir cellulose and carboxymethyl cellulose [67]. The effects of the coir fiber surface treatment can be observed using SEM. In addition, there is strong evidence that extended immersion of coir fibers can lead to structural damage and deterioration, resulting in a loss in composite strength [68].

The highest concentration of NaOH used among researchers is the one with a 5% content, as indicated in **Table 2**. NaOH is an alkaline agent that removes contaminants and dirt from fiber structures. It acts as an interconnecting blocker between the fiber and the matrix. A possible explanation might be that using a 5% concentration to alter the surface of fiber coir includes its efficient modification, cost-effectiveness, performance, validity, and ease of regulating the modification procedure. At the same time, Raj et al. discovered that the hydrophobic characteristics of fibers were enhanced by treating them with 5% NaOH. This treatment boosted the bonding between the fibers and the epoxy matrix, resulting in increased tensile strength, flexural strength, impact strength, hardness, and reduced water penetration [69]. Meanwhile, Ali et al. discovered that alkaline treatment of coir fibers in coir/polypropylene composites reduced water absorption and significantly improved both tensile and impact strengths [70]. The appropriate concentration required can differ based on the modification method, chemical type, reaction conditions, and intended alteration outcome. Hence, a thorough assessment is necessary to verify that the chosen percentage can achieve the desired outcomes without sacrificing the financial effectiveness or material excellence of the changed outputs [71]. It is apparent from **Table 2** that the significant variables in the coir fiber treatment process include immersion time duration, media, temperature, and drying time. Recommended soaking times are anticipated to alter the surface structure of the fiber to generate voids, therefore restoring the mechanical link between the matrix and coir fibers. The last step in the fitting procedure is drying the fiber coir. Notably, the high-water content in the fiber might hinder the incorporation of fibers through the matrix and reduce the strength needed to support the composite construction. Another crucial finding was that drying processes have a significant role in the last phases of the treatment procedure; hence, some past research utilized different parameters.

In addition to its constituent elements, another characteristic of the fiber coir to be considered as reinforcement material by a compound material-based product is its mechanical properties, as observed in **Table 3**. By recognizing and improving these characteristics, a composite

**Table 2.**
Treatment of coir fiber

| Media | Contain (%) | Immersing Time (Hours) | Drying Time (Hours) | Drying Media and Temperature | Authors |
|---|---|---|---|---|---|
| NaOH | 5 | 24 | 48 | Sunlight | [72] |
| NaOH | 8 | 24 | 168 | Oven 40 °C | [73] |
| NaOH | 5 | 24 | 4 | Oven 60 °C | [74] |
| NaOH | 5 | 1 and 2 | 4 | Oven 60 °C | [44] |
| $H_2C_2O_4$ | 5 | 1 and 2 | 4 | Oven 60 °C | [44] |
| $NaHCO_3$ | 10 | 120 and 168 | 4 | Oven 60 °C | [44] |
| NaOH | 5- 20 | 3 | 5 | Oven 90 °C | [75] |
| $KMnO_4$ | 0.25- 1 | 3 | 5 | Oven 90 °C | [75] |
| NaOH | 2-12 | 2.5 | 5 | Oven 60 °C | [54] |
| NaOH | 5 | 4 | 48 | Sunlight | [76] |
| NaOH | 5 | 2 | - | Oven 70 °C | [77] |
| NaOH | 5 and 10 | 6 | 2-3 | Electric Oven | [78] |
| NaOH | 10 | 3 | 12 | Oven 70-75 °C | [79] |
| NaOH | 2 | 3 | 3 | Oven 60 °C | [80] |
| NaOH | 1-8 | 2 | 0.5 | Oven 110 ± 5 °C | [48] |
| NaOH | 5 | 1-48 | 24 | Room Temperature | [81] |
| NaOH | 5 | 24 | 48 | Room Temperature | [82] |
| NaOH | 5 | 10 | 24 | Room Temperature | [83] |
| NaOH | 5 | 4 | 168 | Sunlight | [84] |
| NaOH | 5 | 24 | 24 | Sunlight | [85] |
| NaOH | 5 | 2 | 3 | Room Temperature | [86] |
| NaOH | 6 | 3 | 48 | Room Temperature | [87] |

product can be created with maximum strength, durability, and rigidity suitable for the intended use. Accordingly, a higher tensile strength of the coir fiber results in a stronger composite. A coir fiber enhances structural support for the polymer matrix, boosting the composite's strength. In addition, surface modifications can enhance the strength of coir fibers. Utilizing white rot fungi can enhance tensile strength by decreasing lignin content, hence boosting bonding strength [88]. Note that extended treatment significantly impacts tensile strength, breaking force, Young's modulus, and particularly elongation at break [81]. Furthermore, an increase in elongation and a decrease in young modulus can occur due to the breaking of hydrogen bonds in the crosslinked network of cellulose and lignin structures. Therefore, experimental designs play a crucial role in evaluating the impact of natural fiber pretreatment on the mechanical properties of composite. In addition, the alkali treatment of 6-cm-long fibers for coir fiber-reinforced composite significantly contributes to flexure and dynamic mechanical properties [89]. Pavalaydon et al. [90] utilized the taghuci design of experiment (DoE) to optimize experimental variables in the treatment of alkaline coir fiber for reinforcing polyvinyl alcohol (PVA) composite. This includes NaOH concentration, treatment time, and treatment temperature. The results revealed that a NaOH concentration of 2 wt%, a treatment time of 16 hours, and a treatment temperature of 90 °C could increase tensile strength. These findings enhance our understanding that the DoE is crucial for creating high-quality materials to ensure efficient manufacturing processes and achieve optimal mechanical properties while keeping costs low. Ru et al. [91] utilized analysis of variance (ANOVA) to enhance the mechanical characteristics of coir fiber by optimizing NaOH concentration, treatment time, and treatment temperature. This statistical method is widely available and has been employed in many investigational studies. NaOH concentrations range from 2.6 to 10%, treatment periods vary from 2 to 22 hours, and treatment temperatures range from 20 to 60 °C. Meanwhile, the ideal parameters determined for NaOH concentration, treatment duration, and treatment temperature using analysis software are 4.12%, 15.08 hours, and 34.21 °C.

A two-way ANOVA revealed that optimizing parameters in the treatment of coir fiber provides a highly efficient, economic, and high-performance production process. Surface modification can be performed using the silane process in addition to the alkaline procedure. In 2022, Jayachitra et al. conducted a comparison of three coupling agents: amino silane (KH550), epoxy silane (KH560), and methyl silane (KH570). Remarkably, silane modification enhances the bonding between the fiber and matrix, leading to a more uniform stress distribution from the matrix to the fiber when under load. This results in increased tensile strength, tensile modulus, flexural strength, and flexural modulus of coconut inflorescence/glass fibril-fortified hybrid epoxy composite [96]. Khuntia and Biswas [97] immersed coir fiber in Diammonium Phosphate (DAP) solutions with concentrations of 10% and 20%. The coir is cut into 4 to 6-mm lengths and mixed with PP. Note that the reduction in flexural strength at 10% and 20% reinforcement with the introduction of DAP may result from the smoothing impact on the fiber surface caused by DAP treatment. This diminishes the efficiency of load transfer between the fiber and the matrix. The interaction between DAP and the matrix can affect flexural strength by potentially reducing the interfacial strength between the fiber and the matrix in a complex manner.

**Table 3.** Mechanical test of coir fiber

| Tensile strength (MPa) | Modulus of elasticity (GPa) | Elongation (%) | Refs |
|---|---|---|---|
| 51.98 ± 12.06 – 89.58 ± 14.46 | 4.00 ± 0.99 – 5.20 ± 1.66 | 12.18 ± 7.42–20.24 ± 5.24 | [44] |
| 17.96 ± 0.61 – 100.76 ± 10.18 | 1.15 ± 0.11 – 6.33 ± 0.64 | 1.18 ± 0.11– 2.98 ± 0.30 | [51] |
| 131-175 | 4-6 | 15-40 | [55] |
| 105.81 ± 36.51 | 1.51 ± 0.42 | 30.79 ± 11.48 | [92] |
| 175 | 3.79 | 30 | [93] |
| 209.15-240.60 | 3.407-5.352 | 7.05-14.95 | [78] |
| 152.3 | 3101.2 | 35.5 ± 0.2 | [64] |
| 132-230 | 4.2-6.1 | 16-41 | [60] |
| 140-600 | 3-6 | 15-35 | [94] |
| 95-175 | 4-6 | 17.51.4 | [95] |

# 4. Composite Based on Coir Fiber

Composite reinforced with coir fiber are versatile engineering materials extensively utilized in industries like automotive, construction, furniture, shipping, and sound absorption [98] due to their superior strength, lightweight, affordability, and malleability [99]. Composite consists of a matrix, reinforcing materials, and other supplementary components, categorized into polymer matrix composite, metal matrix composite, ceramic matrix composite, and hybrid composite material [100]. At the same time, polymers are crucial for binding fibers, distributing loads in all directions when the composite is under stress, and preserving the structure of the composite. Presently, polymer matrix composites are widely used in various applications and have emerged as a significant advancement in the industrial sector. In addition, researchers have made significant breakthroughs in integrating matrices with natural fibers to fulfill eco-friendly development goals and utilize plentiful waste fibers discovered in nature [101].

Commonly utilized matrix polymers for composite include thermoset, thermoplastic, and biodegradable matrices. The choice of polymer for a coir-reinforcement composite will be based on achieving a balance between desired material qualities, application requirements, environmental issues, and economic considerations. Furthermore, it is widely held that material testing and assessment are crucial to verifying that the polymer and coir fiber blend fits the specific criteria for a given application. Composite matrix polymers incorporating natural fibers from agricultural waste like a banana [102], passiflora foetida [103], sisal [104], kenaf [105], jute [106], palm oil [107], palmyra sprout [108], date palm [109], bamboo [110], and coir [37] have been extensively studied. Moreover, they are emerging as sustainable options in research and industry. Coir fiber, a component of the coconut fruit, is a promising composite material [111] due to its green [112], sustainable [113], inexpensive, and biodegradable properties [14].

## 4.1. The Process of Manufacturing Coir Fiber Composite

Various procedures in composite manufacturing are tailored to the specific product being produced. In most recent studies, coir fiber composite has been fabricated using various methods. Composite manufacturing designs can use statistical analysis, namely ANOVA, to estimate the optimal combination of constituent elements. This includes fiber size, density, and matrix content to achieve the highest product quality [78],[79]. Another study improved the extraction process and increased the composite's ability to absorb water by treating coir fiber with an alkaline solution and heating it in a microwave prior to making the composite [116]. Maglalang et al. [117] developed a composite filament suitable for Three-Dimensional (3D) printing. It consists of a mixture of Polylactic Acid (PLA) and coir fiber in the form of particles with a size of 74 µm, produced using a filament maker and a fused deposition modeling printer. In addition, commonly utilized processes in industry and research include hand layup, casting, compression, hot press [118], and injection molding [119]. **Figure 2** displays the manufacturing flow of coir-fiber-reinforced composite. The extraction procedure and manufacturing parameters are essential factors in manu-

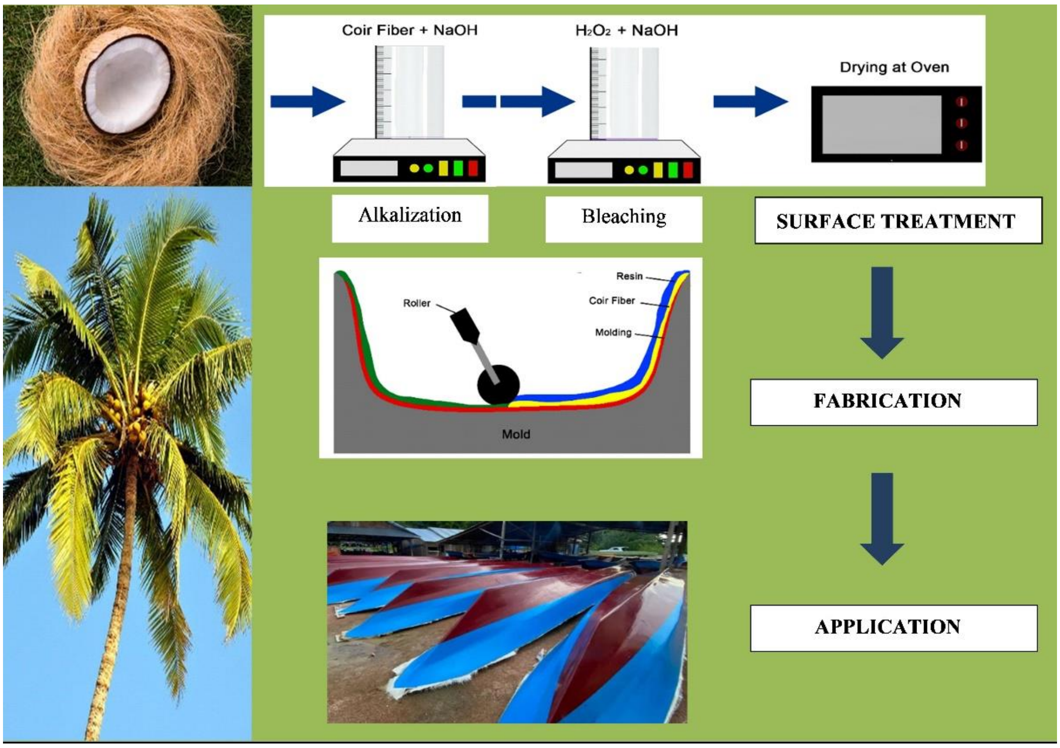


**Figure 2.** Fabrication flow of coir-reinforced composite

facturing products of superior quality. Notably, the discarded coir fiber is transformed into an item of goods through a multi-stage manufacturing technique. The initial procedure involves removing the coir fiber from the coconut with mechanical equipment. Consequently, the following step involves manipulating the surface with an agent of treatment, such as a chemical alkali solution. This procedure alters the composition of cellulose, hemicellulose, lignin, and other oxidizing components to generate pores on the fiber's surface, improving the cohesiveness between fiber and matrix throughout production. The final stage involves a customized manufacturing process designed to suit the particular purpose and its benefits.

Composite products are comprised of a variety of materials. Every substance likely possesses unique features and behaviors. Thus, selecting the appropriate fabrication method is crucial for producing high-quality products tailored to specific applications. The lay-up method involves the manual or automated placement of layers of coir fiber into a mold, followed by the injection of a resin binder. Correspondingly, the layers are compressed to generate a compact and consistent composite substance. This technology has been utilized to create sandwich composite from polyester polymer composite. The coir fiber is aligned longitudinally with a volume proportion of 20%, while the resin occupies 80% of the volume. This procedure includes positioning wooden core boards, applying top and bottom composite skins, combining resin with hardener, rolling, pressing, and allowing them to dry at room temperature [120]. The size, length, and orientation of the coir fiber, along with the material composition, influence the distribution and cohesiveness between the matrix and the fiber. Interestingly, this correlation is related to impacting the qualities of the composite [121]. Furthermore, PP and coir fiber are capable of being combined as a composite and utilized in automobile parts and building materials by compression molding. At the same time, the machine controls pressure and heat to create high-density and precise products [122], making it an attractive option for various applications. This includes partitions, roof tiles, windows, door frames made of coir fiber and Low-Density Polyethylene (LDPE) [123], and automotive insulating materials using coir/jute fiber and polyurethane foam [124].

Coir fiber is a plant-based material that may be easily converted into various products, including composite laminates, using hand layup and compression molding techniques. Venkatesan et al. [125] created two epoxy and nano-silica blends, which were subsequently applied to the coir fiber mat surface. The material's constitution was adjusted by altering heavyweight portions, whereas pressure, time, and temperature were kept steady. When subjected to pressure and heat, the interaction of epoxy, fiber, and silica nanoparticles exhibits varied behavior. Therefore, optimal weighted percentage composition ensures uniform dispersion of coir fiber and silica nanoparticles, leading to enhanced mechanical qualities. It is essential to note that the presence of improper material composition can lead to the production of clusters and aggregates. This can act as focal points for stress concentration and reduce the mechanical properties of the material. In addition, research variables are crucial in creating high-quality composites. The DoEs use the Taguchi design method to discover and optimize factors in research, such as pressure and temperature [62]. Hence, alteration of fiber surface structure, material content, and compression machine parameters influences the qualities of composite with excellent characteristics, as indicated by other studies [126].

To produce composite using the casting method, cellulose nanocrystals from coir fiber go through a dissolving mechanism with a composition of 2% (w/w) coir cellulose nanocrystal, 1% (w/w) oxalic acid, and 10% PVA solution (w/w). To ensure that the material is well dispersed, mix using a magnetic stirrer for 2 hours. Subsequently, the solution is poured into the mold and dried for 24 hours at room temperature. The final stage is heating at a temperature of 120 °C with a duration of 2 hours to produce a composite in the form of a thin film [127]. The mixture utilizes magnetic and mechanical stirring to evenly distribute coir fiber throughout the matrix, reducing voids and enhancing the structure of composite. It also improves the strength of association between coir fibers and the matrix, resulting in stronger mechanical and physical features [128].

The injection molding method is one of the more practical ways of shaping coir fiber-reinforced composite into various shapes based on their intended applications. The process commences by sealing the mold and injecting the molten plastic material into it under high pressure. Thus, accurate regulation of pressure and temperature is crucial for obtaining optimal outcomes. The plastic material is immediately cooled after being injected to solidify. Notably, coir fiber-reinforced polyprophylene, and polyethylene composite can be manufactured using injection molding as a substitute for synthetic plastic, producing sturdy packaging [129],[130]. This machine is also utilized to make hybrid composite polyester reinforced with banana and coir fiber [119]. A Nylon 6 composite was created by reinforcing it with coir fiber using a twin-screw extruder operating at 75 rpm and a temperature range of 210 °C to 280 °C. The granular material undergoes injection molding at a pressure of 90 bar to create a composite suitable for use in automobiles. Aside from pressure and temperature, the mechanical properties of hybrid composite are most significantly affected by changes in weight fraction composition, fiber orientation, and fiber distribution [131].

## 4.2. Performance of Coir Fiber-Reinforced Composite

The physical and mechanical properties of coir-fiber-reinforced composite can be used to evaluate their performance. Composite used in various products must adhere to test criteria tailored to the specific load and environmental circumstances they will encounter during application. Furthermore, composite materials intended for automotive applications must undergo testing for density, water absorption, hardness, tensile strength, flexural strength, and impact resistance according to the American Society for Testing and Materials (ASTM). ASTM D792 - standard test methods for density and specific gravity (relative density) of plastics by displacement, ASTM D570 - standard test method for water absorption of plastics, ASTM D2240 - Standard test method for rubber property—durometer hardness, ASTM D638 - standard test method for tensile properties of plastics, ASTM D3039 - standard test method for tensile properties of polymer matrix composite materials, ASTM D790-standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials, and ASTM D256 - standard test methods for determining the Izod pendulum impact resistance of plastics [132][133]. The ASTM is a global standards organization that creates and releases voluntary consensus technical standards for a wide range of materials, products, systems, and services. Meanwhile, the level of hardness of automatic motorcycle clutch pads can be assessed using the International Standardization Organization (ISO) 6507 [20]. Prior studies have noted the significance of standardization. Therefore, it is a crucial aspect of ensuring consistency in the quality of a product, beginning with overseeing the selection of material categories, fabrication techniques, and requirements.

In recent years, epoxy and polyester resins have become popular polymers as matrices in coir-reinforced composite. The tensile and impact strength evaluation results for composites using epoxy and polyester polymers reported by several researchers can be observed in in **Figure 3** and **Figure 4**. Each of the two polymers offers advantages, whereas polyester offers economical costs, quite good strength and stiffness, ease of processing, compatibility with glass fiber, fast drying time, fire resistance, resistance to water, and corrosion. On the other hand, polyester polymers offer advantages such as high mechanical strength, stiffness, lack of moisture, good surface quality, chemical resistance, and modifiability. Based on the results of previous studies, in **Figure 3** and **Figure 4** illustrate that the tensile and impact strength of coir-reinforced composite for the use of epoxy and polyester matrices are indeed influenced by various factors. This includes the type of matrix and reinforcement used, composition ratio, fiber surface modification, and fabrication process. Note that every type of material possesses distinct qualities that, when combined, result in varied responses and behaviors in the making process. The constituents, when present in adequate amounts and arranged correctly, work together to create an extremely strong connection between the matrix and fibers. Moreover, they additionally assist with properly transporting stress throughout the matrix toward the coir and filler when the material is loaded, as observed in **Figure 3** and **Figure 4** [63],[68], [120], [134]-[158].

## 4.3. Effect Size, Shape, and Orientation of Coir on the Composite Properties

Fibers have a significant influence on the physical and mechanical properties of composite. When added to the matrix, fiber has a function as reinforcement to inhibit the failure process of a product when it receives external loads. Several researchers have paid significant attention to evaluating the effect of fibers on the performance of composite. Most researchers evaluated the effect of different weight fractions of coir fiber [125],[159]-[161]. Meanwhile, other researchers have selected other variations of coir fiber for the physical and mechanical properties of composite [162]. Rajamurugan et al. reported the results of their research on coir fiber-reinforced polyester composite in 2022. Coir fiber is made in chope shape with varying fiber lengths of 15-20 cm and fiber angle orientations of 0, 22.5, 45, 67.5, and 90° to become a laminated composite. This research uses ANOVA to optimize drilling variables such as spindle speed (V), tool feed rate (f),

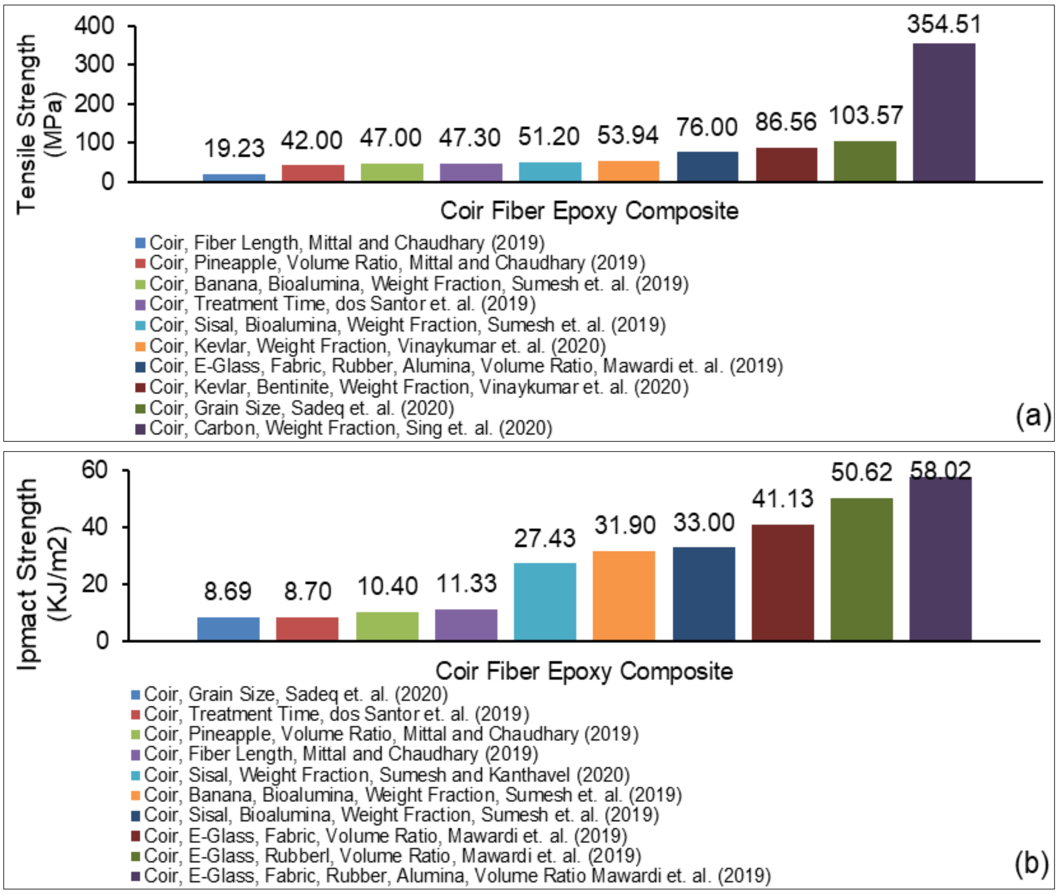


**Figure 3.** (a) Tensile strength of coir fiber-reinforced polyester composite, and (b) Impact strength of coir fiber-reinforced epoxy composite

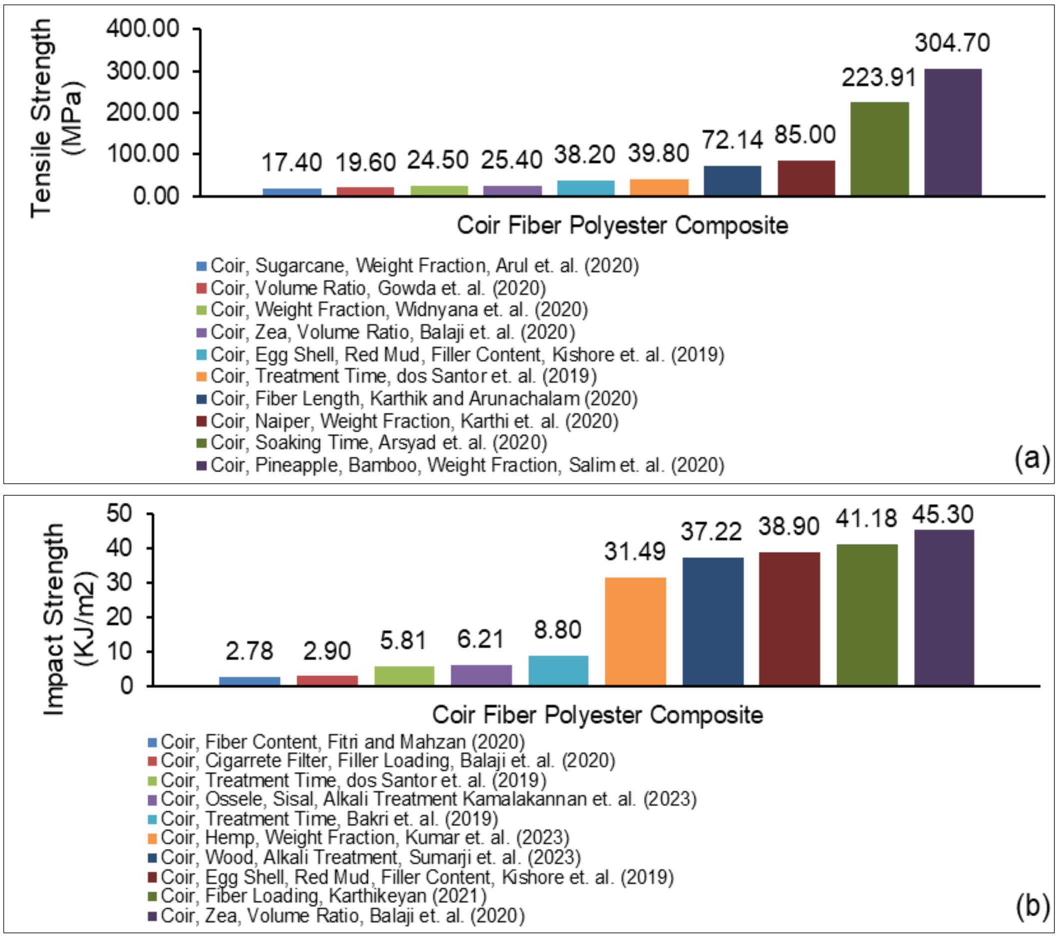


**Figure 4.** (a) Tensile strength of coir fiber-reinforced polyester composite, and (b) Impact strength of coir fiber-reinforced polyester composite

drill diameter (d), and fiber orientation angle (θ) when making products using the drilling method. The research results reveal that the parameters V = 1625 rpm, f = 237.5 mm/min, d = 6 mm, and θ = 22.5° provide drilling results with a smooth surface without any delimitation phenomena. This result may be explained by the fact that delamination occurs when the cutting force applied to the composite material exceeds the durability or bond strength between the laminates. This causes the composite layers to separate [163].

In their excellent investigation, Karthikeyan and Kalpana [164] discovered that an increase in fiber length led to improvements in water absorption, tensile strength, tensile modulus, flexural strength, impact strength, and hardness of the coir fiber-reinforced epoxy composite. Note that longer fibers can enhance the contact area between the fiber and the matrix, potentially improving the load transmission between them. Additionally, longer fibers typically result in a more organized and uniform structure, leading to improved mechanical and physical characteristics of the composite material. Meanwhile, improper length increases in fibers can enhance their water absorption capacity, which is vital to consider in situations where moisture resistance is needed [94],[165],[166]. The ability to absorb water is mostly influenced by the coir content rather than the coir length due to the higher presence of hydroxyl (OH) and other polar functional groups. Gopalan et al. [167] used vinyl ester and isophthalic thermosetting polymers. The size of the coir fiber varied by 1, 0.5, and 0.001 mm, and the fly ash weight fraction varied by 5, 10, and 15%. The research was conducted using a DoE, where there were nine sample combinations in Taguchi's L9 array. The research results suggest that the coir fiber size of 0.001 mm contributes to improving tensile behavior and flexural modulus.

In 2021, Vignesh et al. applied statistical analysis to generate coir diameters of 0.2, 0.5, and 0.8 mm, along with coir lengths of 30, 50, and 70 mm, in their experiment design. Further statistical tests revealed that composite containing coir fibers with a diameter of 0.8 mm and a length of 30 mm have improved tensile strength, measuring 27.90 MPa, and higher compressive strength of 68.98 MPa. Furthermore, increased fiber diameter and decreased fiber length enhance interlocking with the composite matrix, leading to improved mechanical properties [168]. Optimizing fiber weight and length for polyprophylene polymer composite can be achieved using statistical software like Minitab. In addition, analysis results indicate that weight percentage and length ratios of 25.67% and 34.85 mm, respectively, will offer optimal performance in automotive applications [169]. Note that the grain size of coir particles significantly impacts the mechanical characteristics of epoxy composite particles containing coir. The enhancement in strength due to the size of microscopic particles is linked to the neutrality of the sample, leading to the composite losing its elastic and plastic capabilities. Moreover, the high strength value signifies strong adhesion between the fiber and the matrix, reducing the creation of cavities and pores surrounding the fiber. Large particle sizes enhance pressure strength by absorbing stress concentration, while small particles may not offer a strong enough barrier against pressure loads due to the stress concentration around them, resulting in quick failure. Additionally, composite with smaller particles is more likely to rupture and fail structurally more quickly than composite with larger particles since the smaller particles can be compressed and released between each other [80].

Mishra et al. [170] observed a positive correlation between coir fiber and the mechanical characteristics of SiC-filled epoxy composite using three distinct fiber configurations: unidirectional, woven at ± 45° orientation, and chopped fiber. Studies reveal that fiber-reinforced compounds exhibit superior mechanical capabilities in most aspects when compared to clamp-based composite, except for sliding strength. At the same time, fiber-reinforced weaving composites demonstrate improved performance in all mechanical parameters examined, including tensile, flexural, and compressive strength. Furthermore, the incorporation of silicon carbide has contributed to the enhancement of this characteristic. Fiber coir can be aligned in longitudinal and transverse orientations within a composite rubber matrix. Arrohman et al. [171] discovered that the fiber's composition and direction significantly impacted the tensile strength, modulus of elasticity, and strain by influencing the bonding strength between the matrix and the fiber. Consequently, it affects the composite's performance [172].

## 4.4. Thermoset Polymer Composite

A thermoset polymer is a polymer that undergoes permanent hardening through heating or chemical reaction. The polymers possess a robust three-dimensional cell structure and are incapable of melting after they go through the act of hardening. The thermosetting polymer types diglycidyl 1,2-cyclohexanedicaboxylate (DCN) and branched Polyethylenimine (PEI) can be combined with hybrid fiber types of coir and glass to form a laminated structural composite [173]. Composite laminated constructions utilize polymer thermosets due to their beneficial properties, such as high strength, thermal resistance, consistency in dimension, and stiffness [174]. Previous studies utilized a coir fiber-reinforced polyester composite. Nasution et al. [175] discovered that post-curing at high temperatures can decrease voids, enhance crosslinking, and thus enhance impact strength. The technique known as Taguchi can be utilized to optimize the manufacturing parameters. Meanwhile, Karuppiah et al. [176] studied the impact of speed, the load being applied, and distance during sliding on the friction and wear characteristics of jute/coir fiber-reinforced polyester composite alongside eggshell powder/nanoclay filler hybrid. Their findings indicated that speed was the most significant factor, accounting for 64.1% of the composite accomplishments.

Several researchers have extensively studied the use of thermoset polymers in reinforcing coir fiber composite for various applications. **Figure 5** is a map that illustrates how common epoxy resins are in reinforced composite coir when examining polymer thermosets. Polymer thermosets can be classified as epoxy, polyester, phenolic, and vulcanized rubber based on prior research. Notably, epoxy polymers have significant benefits over others in coir fiber-strengthened composite due to their exceptional resistance to coir fiber. The robust interaction between epoxy and coir fiber strengthens the composite material's mechanical characteristics and longevity. Furthermore, epoxy polymers provide excellent resistance to moisture, chemicals, and the deterioration of the environment, resulting in a more advantageous option for composite reinforced coir fiber in many applications. Note that epoxy resin may harden at lower temperatures, allowing for improved control of the curing process in manufacturing. The primary polymer thermosets are commonly utilized as raw materials in industrial processes, particularly through the hand layup method. Thus, it has commonly been assumed that this method is favored for its design flexibility, cost-effectiveness, rapid production, precise fiber control, and suitability for massive parts, as observed in **Figure 5** [13], [14], [17], [21], [26], [31], [34], [55], [60], [61], [78], [80], [82], [94], [96], [120], [121], [125], [128], [158], [160], [162], [164], [166], [168], [170], [174], [175], [177]-[247].

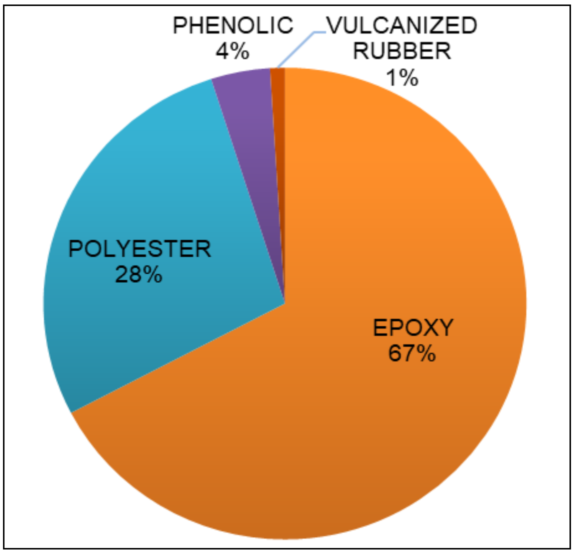


**Figure 5.** Mapping the utilization of polymer thermosets (previous studies)

## 4.5. Thermoplastic Polymer Composite

A thermoplastic polymer is a type of polymer that can undergo melting and reshaping upon exposure to heat. The weak connections between molecules facilitate modification of form and re-processing. Research has been conducted on composite that combines low density polyethylene (LDPE) and coir fibers using compression molding processes. Prior studies assessed the impact of treatment on the mechanical properties, morphology, and structure of the composite material. Utilizing 5% NaOH can enhance the cohesiveness between the fiber and matrix interface, leading to improved thermal resilience and strong mechanical qualities. A significant influence is an environmentally friendly solution to the waste issue [248]. Research also utilizes P-Polyvinyl Chloride (P-PVC) as a thermoplastic polymer for electronic instrument materials reinforced with coir fiber. Accordingly, adding 2 wt.% of coir fiber content can create strong resistance suitable for use in switches and cables [249]. In 2023, Tayfun et al. [250] utilized four treatment media to alter the surface of coconut fibers. The treatments included mercerization, amino-functional silane treatment, bio-based epoxy resin sizing, and isocyanate treatment of a polyurethane matrix composite. At the same time, SEM findings indicate that altering the fiber opening structure removes debris and forms pores, facilitating the binding of the matrix into the fiber. This finding seems consistent with other research, which discovered that improving the adhesion between the matrix and fiber enhances its thermomechanical characteristics.

Numerous prior studies have identified the key factors that enhance the overall performance of coir fiber-reinforced thermoplastic polymer composite. In 2023, Obada et al. [251] reported that acid exposure caused an increase in hardness in exposed samples, up to 31.5% after 81 days. In the strengthened sample, the increase in hardness was 17.3% after 54 days. After 54 days, X-ray diffraction (XRD) analysis revealed that the strengthened samples had increased crystallinity, indicating increased strength due to more significant intermolecular bonding in the crystalline phase. Environmental conditions, including acid exposure, play a crucial role in determining the physicochemical and mechanical characteristics of composite. In 2023, Santosh and colleagues discovered that including natural coal as a filler in coir fiber-reinforced composites led to notable enhancements in strength, noise absorption, and moisture resistance. Moreover, coal can be easily added as a filler without altering other qualities due to its widespread availability, affordability, and lack of requirement for chemical manipulation. The composite with 30% filler content exhibits a higher fire resistance rating compared to coir fiber and PP alone. This offers a chance to create a bio-based composite with a high coconut fiber concentration and characteristics that surpass composites produced from other biomaterials [252]. In addition, high-density polyethylene thermoplastic polymer composites can be analyzed using finite element estimates, as demonstrated by Agwu et al. [253]. The elastic characteristics of composite were assessed using a combination of elements and various fiber volume fractions. This study demonstrated that the fiber volume fraction significantly impacts the elastic properties of composite. Additionally, this work accurately modeled fiber geometry and produced results compatible with the confirmed analytical model by utilizing the element approach [253].

Several studies have identified different thermoplastic polymers suitable for use as a matrix in reinforced composite coir products, as illustrated in **Figure 6**. Thermoplastics like polyprophylene (PP) are favored for their simplicity of manufacturing, reuse, and recycling, long-term viability, resilience to impacts, toughness, adaptation, durability against chemicals, compact attributes, tailorable characteristics, and lower processing temperature. The use of PP typically reduces the density and pliability of the composite because of the limited adhesion between the fiber and the matrix. The thermal study indicated that higher breakdown temperatures up to 20 °C resulted in greater thermal stability. Meanwhile, the Differential Scanning Calorimetry (DSC) examination demonstrated a reduction in crystallinity with a higher PP content. The change in peak intensity observed in FTIR spectroscopy indicates a chemical interaction between PP and coir fibers. At the same time, an SEM study reveals alterations in surface structure due to the presence of PP, potentially impacting the material's porosity and particle dimensions. Significantly, chromatic tests revealed notable alterations in hue and color intensity with the addition of PP, suggesting visible changes in the biocomposite material [254].

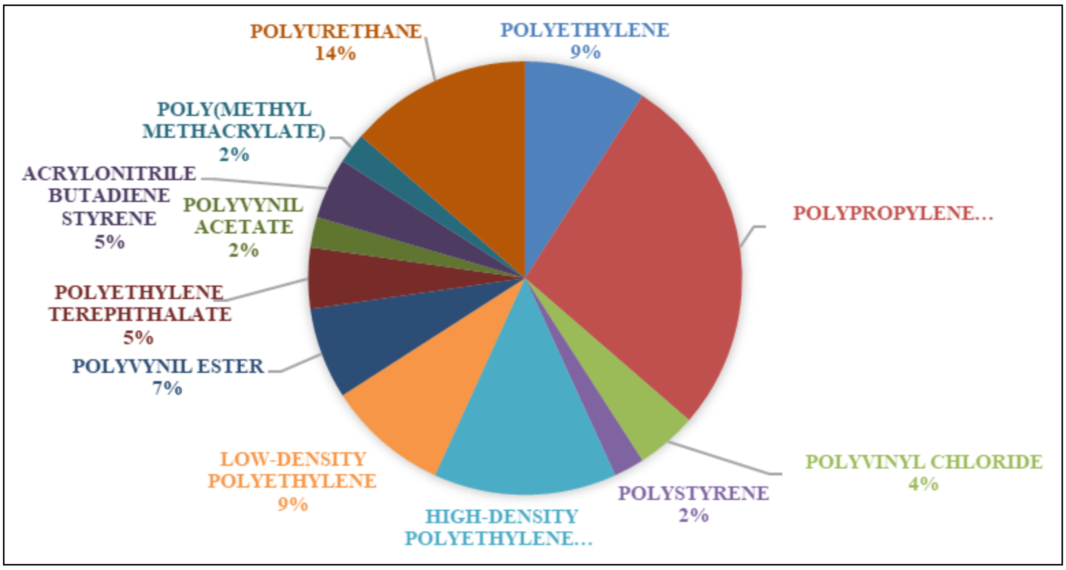


**Figure 6.** Illustrates the thermoplastic polymers commonly utilized in coir-reinforced composite [83], [97], [123], [124], [126], [129], [167], [252]-[290]

## 4.6. Hybrid Composite

Hybrid composite is created by combining two or more reinforcing components to achieve certain physical and mechanical qualities required for a product. Furthermore, key markers of hybrid composite behavior are biodegradability, cost-effectiveness, low density, and environmental friendliness [263]. Coir fiber is a natural fiber that has been thoroughly examined and proven highly appropriate for blending with other materials. Coir and hemp fiber serve as reinforcements, while polyester acts as a matrix. Hybrid composite can be manufactured by combining laminate techniques with variations in their composition. The combination of 15% coir fiber and 5% hemp fiber ($C1_5H_5$) results in superior qualities such as tensile strength, flexure stress, tensile modulus, flexural modulus, and impact strength when compared to other mixtures. Furthermore, the correct composition results in structured matrix bonding and even fiber distribution. In contrast, an improper relative composition can lead to reduced strength caused by inadequate hydrophilic fibers, weak polyester hydrophobic bonding, and low cellulose concentrations in coir fibers [55]. Notably, cellulose is the primary component of fiber that enhances the mechanical characteristics of composite. Hybrid composite can be evaluated as thermal insulators using python programming. The composite consists of an epoxy base material serving as a matrix and a blend of orange peel and coconut coir fiber acting as reinforcement. The tool applies both empirical data and theoretical frameworks to forecast the heat transfer characteristics of a material [191]. Another finding mentioned that the approach developed by Taguchi significantly contributes to optimizing parameter variation. This includes the composition of the material, alkaline treatment, pressure, and temperature throughout compression molding, as well as its mechanical attributes [59].

In the industry area, hybrid composite can serve as compact materials in applications like packaging and sports. One example is the coir/hemp/polyester hybrid composite, which provides a super-performance composite [156]. The epoxy/coir composite can be blended with various natural fibers, like jute, flax, cotton, human hair, sisal, and kenaf. It is almost certain that introducing different fibers can enhance the flexibility and durability of fibers. Remarkably, sisal fibers have the greatest bending strength because of their strong interfacial adhesion and high tensile strength [8]. Thus, merging two or more components in a hybrid composite may lead to the formation of a void within the matrix and the fiber. Additionally, research has identified natural particles as a composite material with potential applications in the automotive industry. Optimal performance in tensile, flexural, and impact strength is achieved with a mixture of natural particles, including 15% neem wood waste, 5% coir, and 5% sugarcane bagasse [190]. Moreover, the filler powder can decrease cracks and matrix breakages [193]. However, certain composite hybrids, such as E-glass fiber/aluminum powder/epoxy hybrid composite, may not improve mechanical qualities when added to coir fiber. Composites without the addition of coir fibers produce 20% better mechanical characteristics compared to the coir-fiber content, including impact, flexural, compressive, and tensile characteristics [189]. In addition, strength reduction may result from environmental factors such as filler clustering, empty spaces, microscopic cracks on surfaces, and inadequate adhesion between matrix and fibers [184].

## 4.7. Biodegradable Composite

Biodegradable composite materials can naturally decompose when discarded in the environment. Products must possess biodegradable qualities to tackle environmental concerns. Coir fibers can serve as enhancers for biodegradable resin polymers, including Polyactic Acid (PLA), starch-based resin, Polycaprolactone (PCL), and Polybutylene Succinate (PBS) due to the inherent characteristics of coir fibers that are readily broken down by microorganisms in the surrounding environment. The coir fiber comes from the coconut fruit's skin, which contains lignin, cellulose, and hemicellulose. This makes it easily broken down by bacteria and fungi in soil or water, allowing the material to decompose organically and be environmentally beneficial [47],[104]. Moreover, this composite is well-suited for thermal insulation due to its excellent thermal resistance, low thermal conductivity, and superior resistance to weight loss when heated. Chemical treatment of coir fibers with alkoxysilanes and amylase enzymes can enhance fiber-matrix interlocking as well as improve thermal and mechanical qualities by increasing crystallinity [73],[74],[118]. Hence, surface treatment of fibers is crucial for enhancing the strength of PLA composite reinforced with coir fibers. The alkaline treatment effectively removes impurities like dirt, waxes, and lignin from the fiber surface, reducing voids and boosting the outer layer's rigid structure. At the same time, polar active groups lead to interlocking and chemical bonding, resulting in higher interfacial shear strength [295]. The pores, empty spaces, and hydroxyl groups facilitate water penetration, leading to an increase in the overall weight of the biocomposite [64].

Silvia and Ridwan [291] published a study in 2023 that suggested the high amounts of coir and chitosan in the composite PLA had a big effect on the properties of the material. The highest tensile strength is discovered when the weight ratio of 19% coir to 1.8% chitosan is just right. This indicates that the right mix of these two ingredients can improve the compound's traction strength. A composition of coir modification 20% (w/w) and chitosan 2% (w/w) has the highest thermal resilience, suggesting that a heavier fraction can potentially enhance heat stability. The coir fiber and chitosan create extra structures that hinder the motion of PLA molecules, consequently rendering it more resistant to decomposition at extremes of temperature. The distinct characteristics of coir fiber and PLA result in differing polarity behaviors, potentially leading to collapse upon stress receipt as PLA may not uniformly disperse stress to the coir fiber. In addition, the PLA-g-MA compatibilizer acts as an adhesive between coir fiber and PLA by utilizing hydroxyl groups to enhance the link between the two materials, resulting in composite with strong mechanical qualities [296]. Notably, plasma treatment is currently an approach used to enhance compatibility between matrices and fibers by increasing the hydrophilicity of the polymer. The result of this study indicates that this modification can improve the interaction between matrices and fibers, consequently enhancing the adhesion level and boosting the mechanical attributes of composite materials [297].

The blend of the mechanical benefits of natural fibers like coir fibers with the eco-friendly characteristics of biodegradable polymers creates an appealing and sought-after option in sustainable composite production. From the data in **Figure 7**, it is apparent that PLA is commonly used to produce reinforced composite coir due to its outstanding attributes. It can be derived from natural sources like pumpkin, corn, or ammonia and offers good tensile strength, stiffness, high resistance to heat, and adjustability of mechanical, thermal, and degradation properties. The key aspects of biodegradable material can be listed as follows: recyclable, biodegradable, and compatible with multiple manufacturing methods, which include injection molding, extrusion, and thermoforming, as observed in **Figure 7** [90], [117], [118], [291], [292], [293], [298]-[309].

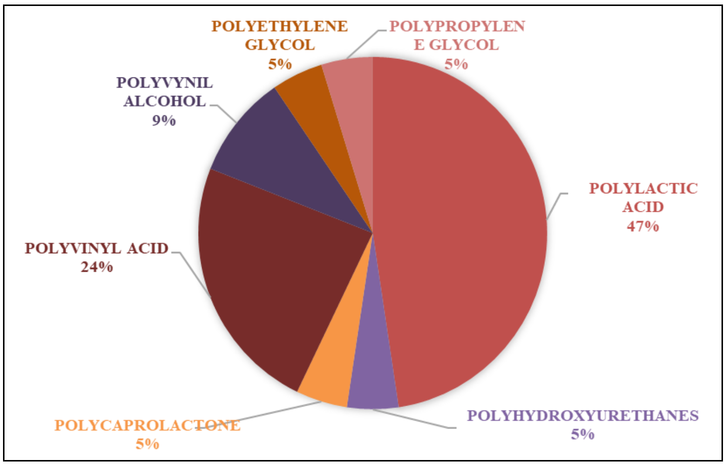


**Figure 7.** Classification of biodegradable polymers used to produce coir fiber-reinforced composite

## 4.8. Thermal Properties

Studying and improving the thermal characteristics of coir-fiber-reinforced composite polymers is crucial to guaranteeing their durability, performance, and applicability in various temperature environments and manufacturing sectors such as automobile construction, shipment, and electronics. Heating the composite causes it to decompose gradually due to the gas evaporating. Polyvinyl Alcohol (PVA) biofilms reinforced with cellulose coir exhibit greater stability compared to pure PVA due to the coir's contribution to high crystallinity [310]. Thermo-chemically treated and reduced filler content in coir fiber-reinforced polyhydroxybutyrate (PHB) polymer composite enhance crystallinity, fusion enthalpy, and melting temperature, resulting in greater thermal stability compared to untreated fiber [311]. Meanwhile, chemical treatment significantly enhances the thermal stability of the coir pith/nylon/epoxy hybrid composite by removing lignin [312]. Other researchers have focused on surface treatment as the primary factor in enhancing the thermal characteristics of coir-reinforced composites with poly-lactic acid polymer types [313]. The treatment process attempts to eliminate the constituent parts of fiber, such as lignin. Lignin is a component in fibers that can degrade readily. Notably, the absence of lignin might enhance the cohesion between the matrix and the coir fiber, leading to a decrease in gaps between the two components. This lowers the heat penetration into the composite material. Bhagwat et al. [314] studied the impact of adding coir fibers to reinforced PBS composite, discovering that the incorporation of coir fibers reduced the thermal deterioration of the product.

# 5. Potential Application of Coir Fiber Composite

The study and industry sectors are currently emphasizing the advancement of environmentally friendly materials. Natural fiber-enhanced composites are a viable alternative to synthetic fibers due to their advantageous physical, mechanical, and thermal attributes, sustainable sourcing, cost-effectiveness, ecological friendliness, and ease of manufacturing despite some limits [265]. Recent developments in the field of coir fiber have led to a renewed interest in the green industry. In 2022, Parashar and Chawla used finite element analysis with the ANSYS 15.0 program to examine differences in how coir fiber-enhanced green composite are used [315]. The ANSYS program provides crucial technical information prior to manufacturing. It contributes to enhancing the design process and performance of coir fiber-enhanced composite products, minimizing errors, and enhancing the efficiency of development and production. Composite reinforced coir fiber has applications in various industries, including construction, transportation, biomedical, packaging, and electrical. It is well known that coir fiber has great potential for widespread application in different industries due to its ability to promote the quality of goods [316], [317].

## 5.1. Housing, Construction, and Building Materials

A considerable amount of literature has been published on biocomposite material as a construction material to create extremely lightweight, eco-friendly, and cost-effective structures, enhancing strength, design, and aesthetics. Coir fibers possess certain qualities that are suitable for use in biocomposite. The most interesting finding was that this composite material is capable of chemical and biological degradation and is derived from naturally occurring and environmentally friendly sources. Notably, biocomposite materials made of PP and coir fiber have the potential to be used for household items and wall panels [254]. Furthermore, coir fiber enhances the effectiveness of gypsum and helps decrease its harmful effects on the environment. The 30% coir component can increase flexibility by 5.6 MPa, representing an 187% increase compared to pure gypsum. Furthermore, enhanced acoustic impedance, particularly in the range of 2,500 to 4,000 Hz, decreased moisture absorption, and exceptional heat resistance are attained [318]. Various buildings and constructions are designed to utilize composite reinforced coir fiber as a sound suppression board [256],[319]. In addition, wall panels can be constructed using composite panels composed of PP plastic waste, coir fiber, and mud sourced from the paper industry. The PP/fiber-coir/sludge mixture experiences a 0.104% lesser thickness change when submerged in water than the 0.508% fiber-PP/coir mixture. The number complies with European Standard EN 634-2, which specifies that the thickening value should not exceed 1.5% after being submerged for 24 hours. Due to how different materials are distributed and how they interact with each other, it is crucial to maintain their performance. The evidence from this study suggests that to make products with the best mechanical qualities, the manufacturing method must ensure consistent fiber distribution, effective fiber-matrix interaction, and void-free production [289].

## 5.2. Transportation

Metal materials have largely controlled car components in recent decades. It impacts the vehicle's dimensions and weight, costs of manufacturing, energy consumption, parts and accessory quantity, concerns regarding the environment, and selling prices. Coir and luffa can be mixed to create hybrid fiber epoxy composite laminates using hand-layup production techniques for vehicle parts [320]. Meanwhile, green composite, bonded with coir fiber, can decrease the weight of components for use as a wheeled bumper [183]. In addition, composite polymer Acrylonitrile Butadiene Styrene (ABS) and coir fiber are used as alternative helmet materials. Impact strength of 0.408 J/mm$^2$ and optimal flexibility were achieved from specimens with a 40% fiber volume fraction. In contrast, those with a 20% fiber volume fraction had a tensile strength of 52,785 MPa and an elastic modulus of 13,064 GPa [199]. Another substantial finding was the use of hybrid coir and glass fibers to reinforce LDPE composites for bumper applications. An increase in fiber content of up to 30% led to higher impact strengths ranging from 2 to 5 J and hardness between 4 and 13 HBR [282]. Hybrid cotton fleece, coir, and sugarcane are combined with green epoxy resin to create car body parts. An elevated fiber concentration leads to a rise in impact strength from 3.89 kJ/m$^2$ to 4.43 kJ/m$^2$ and a reduced thermal expansion coefficient compared to other fibers, ranging from $3.832 \times 10^{-5}$ /°C to $4.323 \times 10^{-5}$ /°C. Accordingly, there is a strong possibility that materials with a lower heat expansion factor experience little shrinkage when exposed to heat [321].

## 5.3. Biomedical

Medical devices must be composed of materials that are biocompatible, sturdy, long-lasting, chemically stable, biodegradable, and capable of maintaining their size and shape over time.

Cevanti et al. [322] stated that coir's cellulose fiber, including around 46% lignin, shows promise as a filling material for dental applications due to its ability to enhance tooth material strength. A hydrogel composite consisting of PVA and coir has favorable degrading characteristics for use in the biomedical and pharmaceutical industries. Nanocellulose, at a concentration of 20%, can retain water, enhance therapeutic efficacy in the human body, promote cell proliferation, and interact beneficially with biological tissues [323]. Another example of this study was conducted by Paul et al. [324] in coir fiber for extracting ferulate acid, a precursor of vanillin. Note that ferulic acid is isolated from the coconut region using the hydro-distillation extraction process. The separated ferulic acid is used by *Bacillus ariabhattai* NCIM 5503 to produce vanillin through submerged fermentation. The fermentation process is enhanced through the utilization of the Taguchi DoE software. Moreover, optimizing the process parameters leads to a 1.3-fold increase in vanillin yields, reaching a maximum vanillin yield of 640.96 ± 0.02 mg/L following optimization. Vanillin is a key ingredient in the food, pharmaceutical, and cosmetic sectors, and using lignocellulosic material from coir fiber contributes to the sustainability of these industries.

## 5.4. Packaging

Food items, beverages, and other types of products are enclosed in specialized materials designed to shield them from physical, chemical, and biological harm. The wrapping can preserve the product for an extended time. Various studies have indicated that composite materials suitable for food packaging include biofilms made from avocado seeds and coir fibers [325], PVA combined with coir fiber [326], and chitosan used as natural matrices with coir [327]. Interestingly, tensile strength and elongation at break are crucial factors for environmentally friendly packaging materials [304]. In addition, coir pulp with ginger dregs Oleoresin can serve as a packing material due to its ability to inhibit contamination and microbial growth in food products [328]. Nanocomposite like PVA and coir fiber cellulose nanofiber have the potential to substitute for synthetic plastic food packaging [302]. At the same time, PP-reinforced coir fiber composites provide the necessary flammability qualities and thermal stability for covering and packaging materials [122]. Another example is that coir fiber and groundnut shell are potential bio-composite for food packaging due to their superior antibacterial abilities, greater tensile strength, and elongation capabilities [79].

## 5.5. Electrical and Communication Industry

Composite materials are used to provide mechanical support to wires and offer electrical shielding to the power system network. Items like miniature switches, isolation rods, mobile/laptops, and computer protectors can be manufactured using biocomposite made of bisphenol-F epoxy and reinforced coir and bagasse fibers. Both types of fibers have increased electrical resistivity because of their lower fiber density and reduced fiber crystallinity [207]. The insulating panels can be made from a multilayer polymer of phenol formaldehyde clamp reinforced with short and long fibers. Formaldehyde phenols have strong thermal resistance and enhance the dimensional stability of composites under heat. Loose coir's structure significantly reduces thermal conductivity to values ranging from 0.0624 to 0.04628 W/m.K. The correct composition of these two materials suggests that the fiber is evenly distributed inside the matrix, resulting in strong internal bonding and favorable flexural capabilities for use as an insulating panel [239]. Furthermore, nanocellulose is utilized as a substrate for 5G antennas to enhance antenna performance in terms of efficiency, bandwidth, and frequency response. Nanocellulose possesses flexible and strong characteristics that result in the creation of lightweight and durable antennas. The findings indicate that the biodegradable nature of nanocellulose may have played a vital role in contributing to the continuous advancement of 5G technology and business sectors [329].

## 5.6. Biofuel and bioenergy

In the green energy sector, coir fiber could be utilized in the production of biofuels and bioenergy. Notably, coir fibers are well-suited for making fuel pellets due to their high lignin content and high heating capacity. These pellets can serve as an alternative to firewood and charcoal in regions with scarce resources, thereby decreasing the need for land clearance for cultivation. The authors conducted a dynamic mechanical-thermal investigation to ascertain the glass transition temperature of coir lignin. The softening process occurs at around 120 – 130 °C, a temperature commonly reached in an industrial-scale pellet mill [330]. Verma et al. [331] noted that the quantity of cellulose, hemicellulose, and lignin in coir impacts the bioethanol manufacturing capacity. Hemicellulose is a carbohydrate polymer that provides a carbon source in the production of bioethanol via the process of fermentation. The process of converting coir fiber into ethanol begins with alkali treatment so that cellulose and hemicellulose can be easily hydrolyzed. Next, enzymes are introduced to convert it into simple sugars such as glucose. The final stage involves Saccharomyces cerevisiae Hansen 2055 to decompose glucose and produce ethanol as the final product [332]. The concentration of glucose is crucial for the synthesis of ethanol as a fuel. Controlling hydrolysis factors such as time, pH, and temperature utilizing statistical calculations can achieve increased ethanol output [333]. Thus, this opportunity is further exemplified in studies using green power from coir fiber in diesel-fueled engines [334].

# 6. Sustainable Development Goals (SDGs)

The material evaluators in the manufacturing sector assess more than just the functionality of the item. The industry plays a role in the achievement of SDGs by considering the influence of initial material sources, the community, business purposes, and governance. The influence of coir fiber on SDGs might vary based on growing practices, processing methods, financial development, environmental impacts, and climate change. Therefore, it is crucial to incorporate sustainable practices in the manufacturing and use of coir fiber to enhance its beneficial effects on the SDGs. The production of coir fibers involves the use of by-products from coconut cultivation, where coir is one of the natural fibers of plants that have been identified since 1975 and has the potential to continue to increase its production by 2030 [335]. Implementing environmentally friendly coir fiber processes can aid in conserving land ecosystems by efficiently applying by-products and minimizing waste to achieve SDG 15. Coir fiber is biodegradable, serving as an eco-friendly substitute for synthetic products. Moreover, promoting sustainable coir fiber manufacturing can help save land resources and decrease erosion [336]. Stoddart [337] demonstrated quantitatively for the first time that the production of coir fiber coir reels increases the occupation of the riverside by water rats, rendering earlier observations immeasurable now. When coir and perlite are combined, they can help regulate the temperature around the roots of butterhead lettuce plants growing in tropical regions, promoting plant growth and flowering [338]. Goal 14 is accomplished by employing aquaponics technological devices, utilizing coir to preserve nutrients and water quantity for fishing and vegetable operations in metropolitan and residential regions, and offering solutions to mitigate harmful emissions.

In addition, it is essential to note that the coir fiber sector offers employment opportunities, particularly in regions with extensive coconut production. Encouraging responsible manufacturing of coconuts may accelerate economic growth [339], aligning with Goal 8 by increasing a country's quantity of exports and generating quality jobs in rural regions [340]. Furthermore, Goal 1 involves enhancing the quality of life for rural populations [341] and the implementation of governmental measures to safeguard the rights of employees [342]. Implementing eco-friendly methods and technologies will help coconut farmers appeal to consumers who value the environment and achieve a competitive advantage in the worldwide market. In recent decades, sustainable coir fiber production has significantly contributed to combating climate change by effectively absorbing $CO_2$ in natural settings [343]. Coir fiber supports target 13 by lowering the production of greenhouse gases due to its minimal carbon footprint. Another crucial factor to consider is utilizing coir fiber as an eco-friendly material, which contributes to reducing the consequences of global warming by conserving renewable resources and minimizing garbage. Additionally, it is renewable and has a minimal carbon footprint, making it an eco-friendly substitute for synthetic products [28].

# 7. Conclusion

This study highlights the great potential of using coir fiber as the main material in composite and various other products, which has positive implications for reducing factory waste, developing environmentally friendly resources, and encouraging economic development. Its use contributes significantly to achieving SDGs such as eliminating poverty, food security, employment opportunities, financial stability, environmentally responsible production and consumption, mitigating global warming, preserving marine life, and conserving terrestrial biodiversity. Furthermore, it is generally assumed that coir fiber has an unusual structure, consisting of many layers of cellulose, hemicellulose, lignin, and impurities, with pores and an uneven surface shape. Converting coir fibers into composite and other product necessitates first-order procedures, such as extraction and treatment. The current study has examined how surface treatment, such as mechanical, chemical, biological, and combined processes, affects the thermal, mechanical, and physical properties of coir fiber-reinforced polymer composite. The study extends our understanding that coir fiber can generally be combined with various polymers, including thermoset, thermoplastic, and biodegradable. In addition, the size, shape, and orientation of the coir fiber play a crucial role in the composite properties. Another vital implication for expanding our knowledge is that coir fiber could interact effectively with a variety of natural and synthetic fibers, as well as fillers. The most obvious result from this research is that coir fiber is becoming an increasingly popular choice due to its many benefits and ease of manufacture using various production methods such as hand layup, casting, compression, hot press, and injection molding. Moreover, it is employed in various industries, including housing, construction, transportation, biomedicine, packaging, electric power, information technology, biofuels, and bioenergy. Additionally, exploring hybrid composite formulations and the long-term durability of coir fiber composite under diverse environmental conditions offers significant potential for future research. Moreover, there is an opportunity to examine advanced fabrication techniques and their impact on the tribological and thermal behavior of the composite.

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# Authors' Declaration

**Author Contribution**
A.I.I: writing—original draft, formal analysis; J.P.S.: supervision, formal analysis; T.C.: Writing-review and editing, formal analysis; A.E.H: data curation, validation; M.S: writing- review and editing, formal analysis; M.R.M.R.: Writing- review and editing, validation; J.J.: validation, visualization; D.F.F.: formal analysis, data curation; R.D: visualization, Writing- review and editing. All authors have read and agreed to the published version of the manuscript.
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