Review of Benefits and Limitations of Coir Fiber Filler Material in Composites

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Abstract: **The applications of coir fiber reinforced composites have witnessed rapid growth in industrial applications as well as in fundamental research, due to their improved physical and mechanical characteristics. The paper started with the definitions of fiber and composites, before it provided a brief history of coir fiber starting from when it was observed from the Ramayana era around the third century B.C. The nature of coir fiber, it's processing and extraction, as well as its chemical properties, and physical and mechanical compositions were discussed in detail. Apart from being abundant in nature, cost effective, non-toxic, renewable, lowest thermal conductivity, and bulk density, the research pointed out that coir fiber is more durable than other natural fibers because of its high lignin content. Despite the remarkable properties of coir fiber, it was noted that untreated coir fiber composites have unwanted features such as dimensional instability and flammability which makes it unsuitable for high temperature applications. After explaining that the extremely hydrophilic character of coir, along with the hydrophobic nature of the polymers employed for matrix production makes the manufacture of coir polymer composites difficult, resulting in mechanical property loss following moisture uptake, the paper concluded that in order to reduce or eliminate the rate of moisture absorption, that coir fiber surface must be chemically modified.**

Keyword**: fiber, composite, coir fiber, coir fiber reinforced composite, lignin, cellulose, history of coir, limitations of coir fiber, benefits of coir fiber**

I.INTRODUCTION

A fiber is defined as a unit of matter distinguished by fineness, flexibility, and a high length-to-thickness ratio (Farnfield, 1975). The first fibers used by humans were natural fibers such as wool, sisal, cotton, silk, flax, and hemp, while the first synthetic fiber was most likely glass, (Grosberg and Dobb, 1991). In a nutshell, natural fibers are fibers that are not organic or man-made. They can be obtained from either plants or animals, (Ray and Rout, 2005). Natural fibers are multicellular in nature, comprised of a number of continuous, primarily cylindrical honeycomb cells with variable sizes, forms, and structures (Pothan et al., 2006).

The basic idea behind fiber composites is the use of fibers as reinforcement in a resin matrix. Fibers typically give the majority of the required strength, while resin provides binding to the fibers. This is because fibers cannot withstand actual loads on their own, and as a result, resin is utilized to bond and protect them.

Okpala, Chinwuko, and Ezeliora (2021), defined a composite as a material that comprise of two or more dissimilar constituents that when joined together are quite stronger than the individual components. They pointed out that a stronger material that is known as reinforcement is embedded in a weaker one known as matrix, to form a new material with enhanced properties like rigidity, long term durability, and improved strength. A composite material combines the most desired qualities of its parts while suppressing their least desirable properties, which in return gives better and unique mechanical and physical properties. Composites, plastics, and ceramics have been the dominating engineering materials during the past few decades.

Modern composite materials are made up of many different materials that are used in everyday life, as well as in sophisticated applications. While composites have already proven their worth as weight-saving materials, the current challenge is to make them durable enough to replace other materials while also remaining cost effective. This has led to the creation of several innovative procedures that are now in use in composite industry. At the moment, composite materials play an important part in the aerospace, car, and other technical applications due to their exceptional strength-to-weight and modulus-to-weight ratios (Haruna et al., 2014). Coir fiber composites are composite materials that are reinforced with fibers, particles, or platelets derived from coconut.

Composite material uses have expanded fast and have even found new markets, as numerous industries have utilized composites for diverse applications. Composite materials are divided into three types based on their matrix materials: polymer matrix composites, metal matrix composites, and ceramic matrix composites. Each form of these composites is appropriate for a variety of purposes. A matrix or binder material is the foundation material that binds or retains the filler material in structures, whereas filler material is present in the form of sheets, pieces, particles, fibers, or whiskers of natural or synthetic materials (Rajak et al., 2019).

II. HISTORY OF COIR FIBER

According to Coir Team (2021), coconuts are thought to have originally appeared in the Ramayana era about the third century B.C. they explained that a Greek sailor wrote in the first century A.D. about observing coco fibers from an East African hamlet being utilized in the construction of a boat, which was done by stitching together planks with twine spun from coir fibers. Mentions of coir characterization have also been discovered dating back to the 11th and 13th centuries A.D. In Sri Lanka, India, and the Persian Gulf, these fibers were utilized as building materials in place of nails.

The coir strands, sometimes referred to as lashings, were used by early Hawaiian settlers to bind their boats together. Maritime explorers have traditionally used coir rope as cables and rigging on their ships. Coir was also commercially sold in the United Kingdom in the mid-1800s, notably for use in carpets and fabrics used in flooring.

Figure 1: Coconut tree and fruits

Coconut fiber ropes and cordage have been used since prehistoric times, as coconut was also referred to as "Indian Nut" by explorer Marco Polo (Deccan Herald, 2020). Polynesian coir, also known as sennit, was once again utilized as a building material to weave together boats, houses, swords, and tools. Coir was used as a ship's cable by Indian navigators who crossed the seas to Malaya, Java, China, and the Gulf of Arabia centuries ago.

Coir was widely used as a ship's cable, fenders, and rigging by Arab authors in the 11th century AD. There was a coir industry in the United Kingdom prior to the second part of the nineteenth century. Captain Widely formed the well-known carpet businesses of Treloar and Sons in Ludgate Hill, England, in 1840, in collaboration with Captain Logan and Mr. Thomas Treloar, for the manufacturing of coir into different textiles suited for floor coverings.

Coir as a reinforcing fiber is gaining prominence in the composite research and industry due to its versatile character, as well as its high biodegradability and availability. They have a number of potential advantages, particularly in terms of environmental performance; this is because when natural fiber composite trash is burned, no net carbon dioxide emissions are released into the environment.

The history of natural fiber reinforced composites began in the last 20 years, when there was a lot of interest in using natural fibers to make polymer bound composites. They are environmentally friendly materials that can compete with glass/polyester in terms of strength, performance, and cost. The combination of natural fiber reinforced polyester composites has been shown to be an effective approach for designing materials that meet a variety of criteria (Idicula et al., 2006).

(Brahmakumar et al., 2005), shown that coir fibers may be effectively reinforced and bonded in a polyester matrix. Coconut is widely cultivated in several tropical Asian nations. Indonesia, the Philippines, and India account for 73 percent of global coconut output, with Indonesia being the greatest producer, the Philippines second, and India third. Brazil is the fourth biggest producer of coconut, which is used to make a broad range of floor furnishing materials including mats, yarn, and ropes. Despite all of these applications for coir fiber, just a small portion of the fiber produced is used. As a result, numerous studies have been conducted to investigate the use of coir as reinforcement in composites, (Geethamma et al., 2005; S. Mahzan et al., 2010).

III. ATURE OF COIR FIBER

Coir, often known as coconut fiber, is a hard structural commercial product derived from the coconut husk. Coir is an excellent replacement for cypress mulch or peat moss, since unlike peat and cypress, it is a renewable resource. Its harvest does not harm the environment in the same way as peat mining does, and it does not contain disease organisms that may be transmitted to plants.

Individual coir fiber measures 0.3–1.0 mm in length, 0.01–0.0.2 mm in diameter, and has an aspect ratio of 35. It features a medium - to large-sized lumen that is polytonally rounded or elliptically formed. The vascular bundle is collateral and is encased in a thick sclerenchymatous sheath. With increasing fiber age, lignin and hemicelluloses, which comprise the cementing elements of fiber cells, increase, whereas pectin declines.

The husk includes coir fiber as well as a corky tissue known as pith, according to (Shandilya et al., 2016). Due to its high lignin concentration, the husk is composed of water, fibers, and small quantities of soluble solids, and it has a higher biodegradability than most natural fibers. The lignin makes coir fiber excellent for applications in cars, biomedical, railway coaches, maritime, and other long-lasting uses (Kakou et al., 2015). Coir is relatively resistant to salinity and microbial degradation, and its current study as a polymer matrix reinforcement has shown promising results (Mohanty et al., 2005). Coir fiber polymer composite material is a viable alternative to other natural fiber polymer composites due to their exceptional performance in a wide variety of applications. Differences in coir fiber characteristics might be related to the source of the coconut plant from which the fibers were extracted or to the technique of extraction utilized.

Processing

The term coir is derived from the Malayalam word kayar, which means cord or rope (traditionally a kind of rope is made from the coconut fiber). Coir has been hand-processed throughout its history, initially by climbing the palms to get the coconuts and then by gathering them from the ground. Palm climbers discovered that utilizing a knife tied to a bamboo pole was the most effective method, allowing them to collect fruit from up to 250 trees each day.

The optimal period to gather coir was believed to be 10 months, during which harvesters husked the coconuts and soaked them for a year to yield the coir, because extracting the coir from the shell needs soaking (known as retting). Depending on the availability of water source, harvesters soaked coconut husks in either salt or fresh water. Soaking the coir in salt water resulted in stronger coir. The results varied, but once the coir was further processed by rolling the fibers from three to ten nuts, depending on their size, the material was claimed to create roughly one pound of yarn. Mechanical processing was introduced by industrialization in 1950, it has led to modern-day dehusking machines that process around 200 coconuts per hour.

Extraction

Coir fiber is divided into two types: brown fiber from mature coconuts and finer white fiber from immature coconuts. Green coconuts, which are collected after six to twelve months from the palm, have flexible white fibers, while brown fiber is acquired by collecting completely ripe coconuts at the point when the nutritive layer surrounding the seed is ready to be processed into copra and dried coconut. During the coir fiber extraction process, a large amount of coir residue is generated.

To extract white fiber, retted husks are taken from the retting enclosure, washed to remove any clinging slime, dirt, or sand, and the exocarp is easily peeled off. The husks are pounded with wooden mallets on tree trunks or stones to separate the fibers. The fibers are washed, dried, and stacked together. The wet husks are put through spiked breaker drums to remove the fragile fiber, while the drums are pushed at high speeds in opposing directions to separate the long and short fibers. The brittle fibers that pass between the drums are gathered and cleaned by running them through another pair of drums with closer nails, followed by washing and drying.

Figure 2: Extracted and Un-Extracted Coir Fiber.

Source: Okpala, Onukwuli, and Ezeanyim (2021)

Chemical Properties of Coir Fiber

Many studies have investigated the chemical composition of coir fiber; Table 1 summarizes their findings. According to (Carlos -Brazil - et al., 2000), water is the most important chemical component of a living tree, but on a dry weight basis, all plant cell walls are primarily composed of sugar-based polymers (carbohydrates) combined with lignin, with minor amounts of extractives, protein, starch, and inorganics.

Cellulose has a strong crystalline structure and is resistant to hydrolysis, nevertheless, acid hydrolyzes it rapidly. Hemicellulose has a random, amorphous, and hydrophilic structure that serves as a cellulose support matrix. It has a low specific gravity, is equally soluble in alkali, and may be hydrolyzed in acid (John and Thomas, 2008). Lignin is an amorphous hydrophobic complex polymer (a thermoplastic) that gives plants stiffness and is not hydrolysable in acid, but is soluble in hot alkali, whereas pectin is a structured heteropolysaccharide that offers plants flexibility (John and Thomas, 2008).

Table 1: Chemical Composition of Coir

Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Source
36-43	0.2	41-45	1.8	(Yan et al., 2016)
45-50	-	30	-	(Roy et al., 2012)
37	-	42	-	(Verma et al., 2013)
43.4	0.25	45.8	3	(Verma and Gope, 2015)
36-43	0.15-0.25	41-45	3-4	(Zhang and Hu, 2014)
42.14	15-17	35.25	-	(Siakeng et al., 2018)
32-43	0.15-0.25	40-45	-	(Yusoff et al., 2016)
38-46	10-15	37-41	-	(Pérez-Fonseca et al., 2016)
42.44	0.25	45.4	3	(A. Khan and Mehra, 2014)
32-43	0.15-0.25	40-45	-	(Zainudin et al., 2014)
45.67	0.12-0.25	41-45	-	(Sudhakara et al., 2013)
39.3	-	29.8	-	(Chollakup et al., 2013)
43.44	0.25	45.84	3	(Haque et al., 2009)

Physical and Mechanical Composition of Coir Fiber

The diameter, density and weight gain by water absorption of a material are referred to as its physical characteristics, whereas it's mechanical properties include its tensile, flexural, and impact strengths. It also relies on the cellulose type and the shape of the basic cell. The cellulosic chains are arranged parallel to one another, forming bundles that each contain cellulosic macromolecules linked by hydrogen bonds, and the cellulosic chains confer stiffness to fibers called micro fibrils via links with amorphous hemicelluloses and lignin (Omrani et al., 2016).

Table 2 summarizes the physical and mechanical characteristics of coir fiber.

Table 2: Physical and Mechanical Composition of Coir Fiber

Average diameter (mm)	Water Absorption (%)	Density (g/cm3)	Young Modulus (GPa)	Tensile Strength (MPa)	Elongation at break (%)	Source
0.025	-	1.2	2.74	286	20.8	(Yan et al., 2015)
0.4	130-180	1.2	4-6	175	30	(Anupama et al., 2014)
0.01-0.46	-	1.15-1.46	2.2-6	95-230	15-51.4	(Yan et al., 2016)
0.25	-	1.2	2.74	286	20.8	(Yan et al., 2015)
0.1-0.45	10	1.3-1.5	4-6	105-175	17-47	(Sanjay et al., 2018)
0.38		1.2	2	144	4.5	(Yusoff et al., 2016)
-	-	-	3.23	165.2	39.45	(Andiç-Çakir et al., 2014)
-	-	-	4-6	144	15-40	(Zainudin et al., 2014)
0.1-0.4	-	1.15	4-6	108-252	15-40	(Sanjay et al., 2018)
-	-	1.37	3.19-3.23	158-165	39-41	(Yan et al., 2015)
-	-	-	4-5	250	20-40	(Tran et al., 2013)
0.1-0.45	-	-	3-6	106-175	47 (max)	(Yan et al., 2015)
-	-	-	4-6	131-175	47.2	(Sudhakara et al., 2013)
0.2	-	1.3	3.11	144.6	32.3	(Saw et al., 2012)
-	93	1.17	8	95-118	-	(Sen and Reddy, 2011)
-	-	1.2	4-6	593	30	(Ku et al., 2011)

IV. BENEFITS OF COIR FIBER AS FILLER MATERIAL IN COMPOSITES

Many researchers have reported the benefits of coir fibers, including the fact that they are abundant in nature, non-toxic, renewable, and cost-effective, as well as providing the necessary bonding with the cement-based matrix for significant improvements in material properties such as ductility, toughness, flexural capacity, and impact resistance (Ardanuy et al., 2011).

Coir fiber is more durable than other natural fibers because of its lignin content, it also has the lowest thermal conductivity and bulk density. The inclusion of coconut coir decreased the heat conductivity of the composite specimens resulting in a lighter product. The development of composite materials for buildings based on natural fibers such as coconut coir with low heat conductivity is an intriguing option that would address environmental and energy concerns. (Asasutjarit et al., 2005; Khedari et al., 2001)

With a growing emphasis on fuel efficiency, natural fibers such as coir-based composites are finding more usage in vehicles, railway coaches, and buses for public transportation. Coir fiber reinforced composites are also used to create seat cushions for Mercedes vehicles (Naveen and Yasaswi, 2013). There is a great possibility to fabricate coir-based composites for a wide range of applications in building and construction, such as boards and blocks.

Other benefits of coir fiber include:

- Tough and durable
- Provides excellent insulation against sound
- Easy to clean
- Not easily combustible
- Flame retardant
- Totally static free

The impact of lignin as a compatibilizer on the physical characteristics of coconut fiber-polypropylene composites was investigated by (Bledzki et al., 2010). The coconut fiber polypropylene composites using lignin as a compatibilizer were shown to have greater flexural characteristics than the control composites. It is used to make a broad range of floor furnishing materials, yarn, rope, and other products due to its hard-wearing qualities, durability, and other benefits.(Satyanarayana et al., 1982).

The damping characteristics of randomly oriented coir fiber-reinforced polypropylene composites are superior to those of synthetic fiber-reinforced composites. This is because a greater resin content has better damping characteristics, therefore, a lower fiber loading results in more energy absorption. The highest damping ratio of 0.4736 was found in coir composite at 10% fiber content, while increasing fiber content to 30% increased natural frequency of material to 20.92 Hz (Munde et al., 2018).

By utilizing 70% fiber content and 28% epoxy in the casting (Natsa et al., 2015), created military helmets out of coir fiber reinforced polymer composite. The study used several fiber compositions in epoxy resin to generate a variety of specimen. The manufactured helmet's physical characteristics were measured and compared to those of other helmets. The manufactured helmet weighs less than both the Chinese and British helmets. However, it weighs only a little more than a US Ballistic helmet.

V. LIMITATIONS OF COIR FIBER AS FILLER MATERIAL IN COMPOSITES

Despite its favorable characteristics, untreated coir fiber composites have certain unwanted features such as dimensional instability, flammability that makes it unsuitable for high temperature applications, UV radiation, acids, and bases (Izzuddin Zaman et al., 2010). The majority of research on coir fiber composites show that a variety of factors such as fiber volume fraction, fiber length, fiber aspect ratio, fiber-matrix adhesion, fiber orientation, and stress transmission at the interface have a substantial impact on their mechanical properties. A variety of studies on coir fibers have been conducted to investigate the influence of various fiber characteristics on the mechanical properties of composite materials.

The effect of fiber content on the mechanical characteristics of coir fiber reinforced composites was studied by (Izzuddin Zaman et al., 2010). The coir fiber volume in the composite was varied from 5% to 15% in the research. The results demonstrate that when the fiber volume percentage increases, the tensile strength and Young's Modulus drop. The decrease is caused by inadequate interfacial adhesion between the fibers and the matrix. The decrease is caused by inadequate interfacial adhesion between the fibers and the matrix. Brittleness of the fibers also led to low mechanical strength since stronger fibers have more potential to withstand larger loads. When the fiber volume fraction is raised, the failure strain increases. (Izzuddin Zaman et al., 2010).

When submerged in water, coir fiber reinforced composites and polymer-based composites absorb moisture in humid environments. In general, moisture diffusion in composites is affected by variables such as fiber volume fraction, void volume, additives, humidity, and temperature. (Errajhi et al., 2005; Weitsman, 2006). Moisture diffusion in polymer composites has been demonstrated to be controlled by three distinct processes. The first involves water molecules diffusing into the tiny gaps between the polymer strands.

The second method includes capillary transport through the gaps and faults at the fiber-matrix contacts. The third includes the movement of tiny fractures in the matrix caused by fiber swelling. (Dhakal et al., 2007; Thwe and Liao, 2002), investigated the mechanical performance of coir fiber/polyester composites, the mechanical behavior of coir fiber/polyester composites with ineffective coir fiber reinforcement is related to their low modulus of elasticity when compared to bare polyester resin. (Harish et al). Because of their ability to absorb moisture from the environment and their poor interfacial interaction with the hydrophobic polymer matrix, untreated coir fibers are limited in their usage in industrial applications. (Sudhakara et al., 2013).

(Asasutjarit et al., 2005), investigated the optimal treatment conditions and fiber length for producing coconut coir fiber-based cement board from portland cement and coir fiber. He observed that a composite made using 1-13cm lengths of raw coir fiber did not conform appropriately due to the spring back effect and the difficulty of performing measurements. As a result, the composite failed to meet the standard specification required for testing samples. Moisture can cause the leaching of water-soluble components and/or the breakdown of fibers or particles into low molecular weight degradation products in natural fiber reinforced cement board samples. As a result, the bonding of fibers and cement in composites may be disrupted.

(Balea et al., 2019; Naveen and Yasaswi, 2013), studied the effect of fiber length on coir fiber reinforced composites, he discovered that the mechanical properties of the composites such as tensile strength, flexural strength, impact strength, and so on are also greatly influenced by the fiber lengths, and the micro-hardness decreases with the increase in fiber length up to 20 mm.

Small changes in the physical nature of fibers for a given volume content of fibers can cause significant variations in the overall mechanical characteristics of composites. These composite materials sometimes depart from their designed condition as some defects, such as manufacturing defects, cause them to digress from the expected improvement in mechanical properties. These manufacturing flaws include fiber displacement, waviness, and occasionally breakage, fiber/matrix de-bonding, decortication, and the creation of voids in a composite material's matrix. 1% increase in void content in composites results in a drop in tensile strength (10–

20%), flexural strength (10%), and inter-laminar shear strength (5–10%), correspondingly (Mehdikhani et al., 2018).

(Bhaskar and Singh, 2013), investigated the water absorption and compressive characteristics of a coconut shell particle reinforced epoxy composite. It was determined that the water absorption capacity of coconut shell particles was limited to a maximum of 30%. Coir fiber is made from lingo cellulose and has highly polarized hydroxyl groups. As a result, they tend to be hydrophilic (Harish et al., 2009). The extremely hydrophilic character of coir, along with the hydrophobic nature of the polymers employed for matrix production, makes the manufacture of coir polymer composites difficult, resulting in mechanical property loss following moisture uptake. Because of the poor compatibility, the coir fiber surface must be treated chemically to make it less hydrophilic and enhance the interface contact between the fiber and the matrix. (Khan et al., 2006; Tajvidi and Ebrahimi, 2003).

VI. CONCLUSION

This paper demonstrates that coir fiber can be utilized as reinforcement in composites, as it has the benefits of being lightweight, having a high strength-to-weight ratio, inexpensive, and being widely available. However, the primary drawbacks are its relative moisture and fiber volume content, as well as other limits due to length and fiber orientation, which are common to natural fibers. To minimize or eliminate the rate of moisture absorption, the coir fiber surface must be chemically modified.

More study is required for the modification of the chemical properties of coir which will thus eliminate or decrease the limitations of coir fiber. This is important for broadening the application of coir fiber composites.

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