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A Review on Recent Developments on Waste Human Hair Composite and Its Hybrids

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ABSTRACT

Human hair (HH) is considered a waste material generated in salons and barbershops in most societies, especially highly populated cities, where it is produced in large quantities, thus rekindling the interests of academics. Several studies are ongoing on the possibility of utilizing it as a reinforcement in polymer composites, either in its raw form or as extracted keratin nanoparticles, due to its unique features and the current global emphasis on circular economy. The present review seeks to provide a synopsis of recent developments in the utilization of HH and keratin in polymer composites. Composites from different HH loading, length, and chemical treatments were made using hand lay-up and hot compression molding methods. HH has been investigated in diverse composite systems, encompassing HH/natural fiber composites, HH/synthetic fiber composites, and keratin-reinforced composites. Our study revealed that these innovative materials exhibit enhanced energy absorption capacity, mechanical strength, hardness, and thermal properties, positioning them as promising choices for a wide range of engineering applications. The review further revealed that keratin nano-particles can be extracted from waste HH using various methods such as reduction alkaline hydrolysis and can be used as reinforcement in polymer composites.

摘要

在大多数社会，尤其是人口稠密的城市，人的头发被认为是沙龙和理发店产生的废物，在那里大量生产，从而重新激发了学术界的兴趣. 由于其独特的特性和当前全球对循环经济的重视，目前正在对其作为聚合物复合材料增强材料的可能性进行几项研究，无论是以其原始形式还是作为提取的角蛋白纳米颗粒. 本综述旨在简要介绍HH和角蛋白在聚合物复合材料中的应用进展. 采用手工叠层和热压成型方法制备了不同HH载荷、长度和化学处理的复合材料. HH已在多种复合材料体系中进行了研究，包括HH/天然纤维复合材料、HH/合成纤维复合材料和角蛋白增强复合材料. 我们的研究表明，这些创新材料表现出增强的能量吸收能力、机械强度、硬度和热性能，使其成为广泛工程应用的有前途的选择. 综述进一步表明，角蛋白纳米粒子可以通过还原-碱水解等多种方法从废弃HH中提取，并可用于聚合物复合材料的增强.

KEYWORDS

Composite; nanofiller; keratin nanoparticle; hybrid composites; natural fibers; human hair fiber

关键词

混合成的; 纳米填料; 角蛋白纳米粒子; 混杂复合材料; 天然纤维; 人发纤维

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Introduction

In recent years, escalating concerns over global environmental pollution and high energy consumption have prompted the formulation of new environmental legislation and increased consumer demands (Sanjay et al. 2016). This, in turn, has further stimulated many researchers to seek sustainable materials capable of replacing non-biodegradable and environmentally unfriendly materials in reinforced composites and plastic products.

Natural fiber reinforcements seem to be good alternatives since they are bio-degradable, abundant, inexpensive, and have excellent physical and insulation characteristics and a high strength-to-weight ratio (Asdrubali, D'Alessandro, and Schiavoni 2015). Additionally, the cost of production and disposal at the end of their life cycle is considerably cheaper than those of conventional synthetic fibers (AL-Oqla and Salit 2017).

Human hair (HH), as one of the natural fiber reinforcements, has been explored by numerous researchers as an environmentally friendly material (Gupta 2014; Kathiresan and Meenakshisundaram 2022; Salih 2019; Verma, Studies, and Singh 2016).

According to Gupta (2014) and Shui-qing et al. (2017) human hair (HH) waste is defined as hair generated and discarded from salons and barbershops. HH waste has a slow rate of degradation and therefore improper utilization and disposal make its accumulation in large amounts in most dumping sites of major cities, posing health hazards, especially to the people living in the surrounding areas. Given its slow degradation and substantial volume, HH waste can persist in these areas for an extended period, potentially up to 2 years, occupying significant space. The prevalent disposal method in many of these sites involves burning, which releases hazardous gases, including nitriles, ammonia, hydrogen sulfides, carbonyl sulfides, phenols, pyridines, pyrroles, and sulfur dioxide, all of which pose environmental toxicity risks (Gupta 2014; Nanda and Satapathy 2019; Qian et al. 2014).

The use of HH dates back some 3,000 years ago when ancient Egyptians mixed these biological waste fibers with clay and used the mixture to build walls of their houses. However, lately, researchers have been exploring the possibility of using HH as reinforcements in polymer composites simply because of their outstanding diverse properties and current environmental concerns, ecological risk, and the world energy crisis (Ali, Rohit, and Dixit 2023; Ansari, Dhakad, and Agarwal 2020). The unique properties of most biological fibers, such as their non-irritation properties, abundance in nature, nontoxic, non-corrosiveness, and lightweight, have attracted scientists to use them as alternative reinforcements to synthetic ones (Verma, Studies, and Singh 2016; Yu et al. 2017).

Furthermore, HH exhibits exceptional chemical composition, robust tensile strength, effective elastic recovery, insulation properties, a scaly surface, and unparalleled interactions with water and oil. Additionally, they demonstrate a slow rate of degradation. These features have made HH attractive and a potential raw material in polymer-reinforced composites (Gupta 2014; Naidu and Rao 2016).

Kotula et al. (2022) reported HH waste found in municipal solid waste and fashion industries to be about 8.6 and 2.5 million tons, respectively. This, therefore, calls for the need to utilize HH, which is considered useless in most societies, as a resource material for polymer composites. Polymer composites reinforced with natural fibers are environmentally friendly and therefore are more preferred in the construction and transport sectors, such as wall partitioning and automobiles, respectively (Ali, Rohit, and Dixit 2023; Hosseini 2017).

Unlike cellulosic fiber-reinforced polymer composites, HH-reinforced composites exhibit better fiber interfacial bonding because of their hydrophobic nature (Selvakumar and Omkumar 2021; Choudhry and Pandey 2013). However, some studies have shown that the incorporation of HH with other fibers and nanoparticles in polymer matrices results in improved mechanical properties and reduction of water-sorption properties (Ali, Rohit, and Dixit 2023; Hosseini 2017).

This review highlights possible utilization of HH waste as reinforcement materials in polymer composites, extraction of keratin nanoparticles from the waste, and the possibility of utilizing it as a prospect material for long-term and cost-effective material development. The findings will enable researchers to develop two different prospect polymer composite materials reinforced with either HH or keratin nanoparticles and further analyze its physical and mechanical properties.

This will not only address the environmental challenges posed by these wastes but also convert waste to wealth, thus creating jobs and increasing the living standards of the people.

Natural fiber reinforcements

Classification of natural fibers

Natural fibers are primarily obtained from either plants or animals, with cellulose and protein being their main components, respectively. Lately, natural fibers have received a lot of attention from scientists than synthetic fibers because of their availability and unique mechanical and physical properties (Atmakuri et al. 2020; Mbeche, Wambua, and Njuguna 2022; Verma, Studies, and Singh 2016).

Human hair fiber

Human hair (HH) is a vital component of humankind, representing a characteristic feature of mammals. Beyond providing protection to humans, it holds aesthetic significance. Regardless of the body part, HH undergoes three distinct phases of development: anagen (growth phase), catagen (transition phase), and telogen (rest phase), as illustrated in Figure 1 (Robbins 2012). The structure of HH is a distinctive hierarchical structure similar to other protein fibers such as feathers and wool (Verma, Studies, and Singh 2016; Yu et al. 2017). HH is primarily composed of 95% keratin, a fibrous structural protein. Keratin materials are broadly categorized into two types: α-keratin and β-keratin. The former, to which HH belongs, is characterized by a helical secondary structure. On the other hand, β-keratin, as observed in other materials, exhibits a sheet-shaped structure (Nakamura et al. 2002; Yu et al. 2017). Therefore, the primary component of HH is α-keratin protein which forms up to 65–95% (Rajbhar, Shahnawaz Alam, and Srivastava 2016; Shavandi et al. 2017). Further, a study by Chilakamarry et al. (2021) reported that the molecular weight of α-keratin is more than that of β-keratin which is 40 kDa and 10–22 kDa, respectively.

Morphological structure and properties of human hair. HH has a typical radius of 25–50 μm and is composed of three sections, including the cuticle, cortex, and medulla as shown in Figures 2 and 3. The

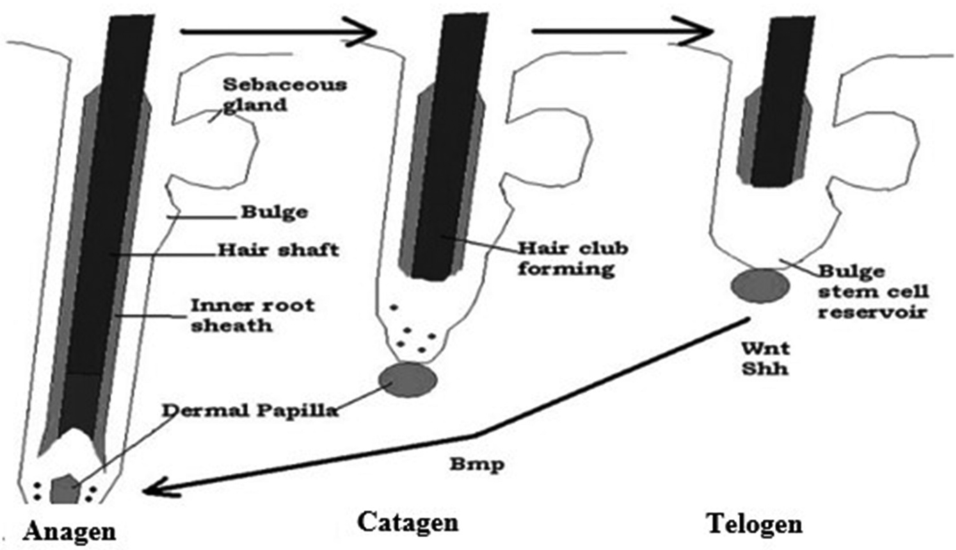

Figure 1. Schematic illustrating the three stages of growth of human hair fibers. Adopted from Robbins (2012).

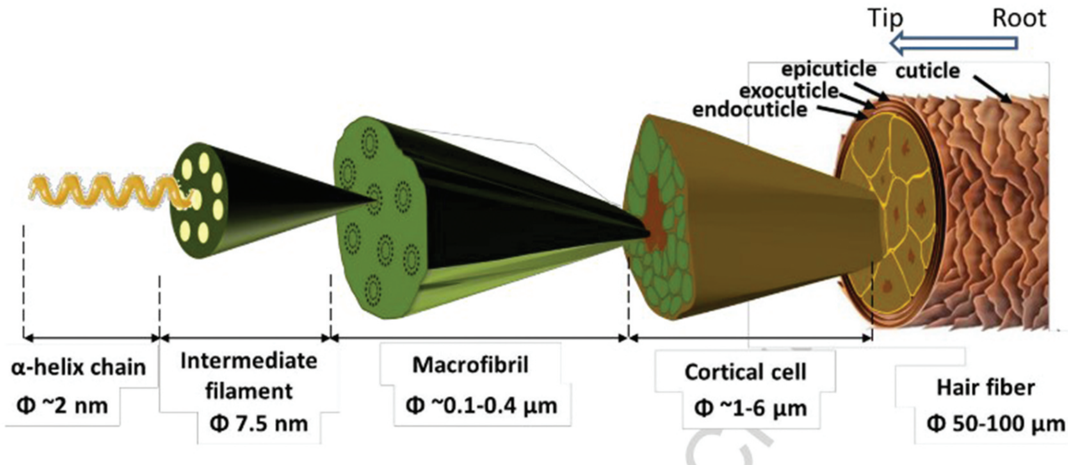

Figure 2. Schematic representation of hierarchical structure in human hair starting α-helix chains and progressing to the entire section. Adopted from Bhoyar et al. (2020); Yu et al. (2017).

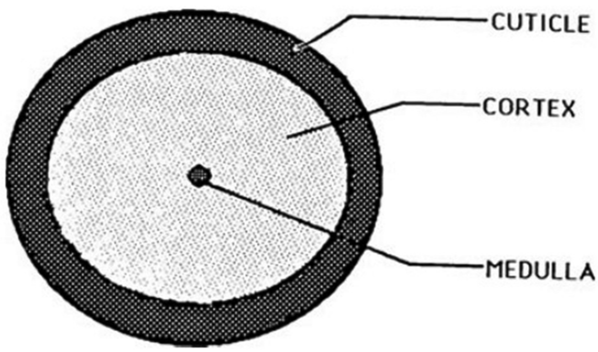

Figure 3. Schematic diagram of a cross section of a human hair fiber. Adopted from Robbins (2012).

cuticle, which is the outer part, is described as roof shingles containing several flat layers of thin scales overlapping one another. The average length and thickness of each scale are about 60 μm and 0.5 μm, respectively. The cortex, which is the inner section, is made of rough rod-like cell structures measuring ~100 μm long and 1–6 μm thick. These cells called keratin form the largest part of the hair. Chemically, the primary component of HH is α-keratin protein, which forms up to 65–95%. And like any other protein fiber such as wool, it is this main component that largely defines the unique properties of HH, including its high strength, stability, and insolubility in water and organic solvents (Nanda and Satapathy 2017; Shavandi et al. 2017; Verma, Studies, and Singh 2016; Wolfram 2003; Yu et al. 2017). This is why damaging the cuticle does not affect the original tensile properties of the original HH fiber (Yu et al. 2017). The properties of HH are summarized in Table 1. Finally, the medulla is a loosely packed porous area at the center of the hair fiber (Robbins 2012).

Chemical properties of human hair. According to Qian et al. (2014) and Rao et al. (2018), HH has been reported to contain several raw elements and amino acids, as illustrated in Figure 4. Therefore, when it is thrown into the environment, it decomposes slowly over the years and returns these constituent raw elements to the environment (Gupta 2014).

Table 1. Properties of human hair. Adapted from Ali, Rohit, and Dixit (2023), Kathiresan and Meenakshisundaram (2022), Rao, Kiran, and Prasad (2018), Selvakumar and Meenakshisundaram (2019), and Selvan (2014).

Properties	Value
Length of hair fiber (mm)	12–65
Diameter of hair (μm)	17–180
Aspect ratio	110–680
Tensile (MPa)	200–400
Tensile Strength Strain	4.5%
Density (g/cm^3)	1.32–1.34
Specific gravity	2.57
Young's Modulus (GPa)	1.74–4.39
Elongation at break (%)	216.94
Poisson's ratio	0.37
Flexural Strength (MPa)	25–30
Elongation	1.5 times its dry weight
Cross-section	Circular
Chemical reaction	Depends on hair surface porosity. About 80% of human hair is made of protein-keratin
Absorption	Depends on the physical process of surface tension
Friction	Depends on the cuticle geometry and its physical-chemical status

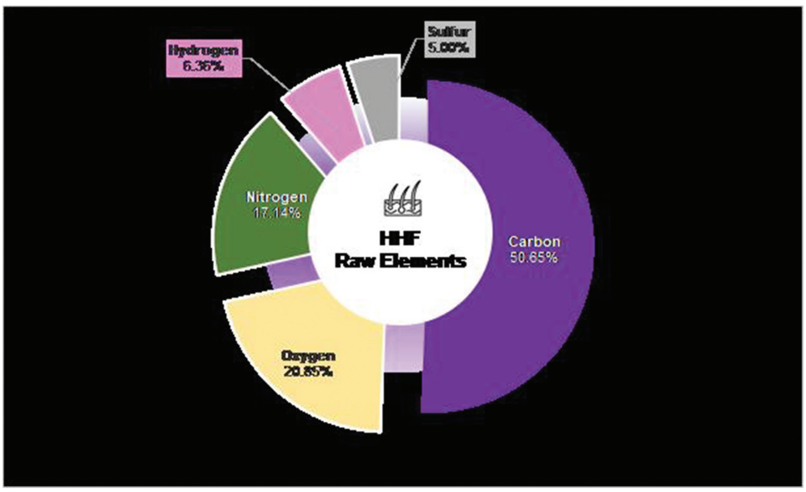

Figure 4. Raw elements contained in the hair fiber. Adapted from Rao et al. (2018) and Gupta (2014).

Historical uses and new research areas of human hair. Studies by Gupta (2014) and Verma et al. (2016) highlighted the unique properties of HH, making it attract a wide range of applications, such as in the fields of medicine, agriculture, engineering, and fashion. HH has also been historically used across the globe, and recently, many countries are researching its new potential uses as illustrated in Tables 2 and 3. However, these uses depend on the properties of HH, which can vary among cultures, care treatments, and ethnicities. These factors can equally affect its length, straightness, damage, contaminations, and even color.

Kotula et al. (2022) summarized some of the current proposed applications of HH waste, such as in electrode materials for solar cells, electrochemical sensors, electrocatalysis, supercapacitors, and gas adsorption, with the main aim of minimizing hazardous contaminations of HH in the environment (Kotula, Kubiak, and Pajewska-Szmyt 2022).

Surface modification of human hair. Human hair (HH) surface treatment has been investigated by many scientists to improve its properties. In the recent times, researchers have explored the mechanical, morphological, and degradation properties of surface-modified HH.

Table 2. Historical uses of HH and key attributes. Adapted from Gupta (2014).

Country of production	Use	The kind of hair required	Potential users/markets
India, China, Korea, Tunisia, Italy, Russia, Bangladesh, and Pakistan	Wigs, hair extensions, eyebrows, beard	Long, undamaged	Fashion-conscious individuals, patients suffering hair loss
China, India, and the USA	Fertilizer	Any kind, without toxic contamination	Farmers, gardeners, and households having garden/potted plants
Pest repellent	India, USA, and Mauritius	Any kind	Farmers, gardeners, and households having garden/potted plants
India, Bangladesh, Syria, and Europe	Clay/Concrete reinforcement	Any kind	Households, architects, designers, and construction workers
USA, Philippines	Oil-water separation	Any kind, except very small (<1 inch)	The petroleum industry, oil refineries, sewage treatment, and water supply departments
India, the USA, Hawaii, and a few European countries	Stuffing toys, furniture, mattresses, and so forth	Any kind, except very small ones (<1 inch)	Furniture makers, toy makers, artists, and so forth
China, India	Fabric making	Any kind except small ones (<2 inch)	Coat tailors, garment enterprises, artists, and producers of mats
Past: China, England, USA, Prussia, France, Italy, and Scandinavian countries Present: China, USA	Artwork	Any kind	
USA, Europe	Hydrolyzed protein (HHKP)	Any kind	Hair care industry
India, China, Korea, and Europe	Extracting amino acids	Any kind except contaminated and chemically treated hair	Agriculture, food processing, and pharmaceutical industries
China, India	Ethnomedicinal uses		
Europe, India, China, and Turkey	Suturing material		
Europe, USA	Testing material for hair care products	All kinds	Hair care industry
India, USA	Cosmetic brushes	Undamaged hair	Fashion conscious people (mostly women), theater personnel
India, China, the USA, and Romania	Hygroscope	Long, undamaged hair (>12 inches)	Meteorologists, Scientific institutions
USA, Europe	Nesting material for birds	Any kind but ~3 inch or smaller	Environmentalists, horticulturists, and gardeners
America, Japan	Ropes	Any kind except small ones (<2 inch)	Anyone
Philippines	Musical instrument		
China, Europe	Oil filter		

Table 3. Countries carrying out new research in HH. Adapted from Gupta (2014).

New uses/areas of research	Countries where research is undergoing
Liquid fertilizers	India, USA, Korea, Bangladesh Canada,
Concrete reinforcement	Canada, India
Pollution control	Canada, Singapore, India, Iran, Korea, Egypt, and Jordan
Molded furniture and objects	UK
Engineering polymers	Singapore, China, Japan, and India
Follicle cell cultures/tissue regeneration	Switzerland, the UK, Korea, and France
Composites for superconducting systems	India, Greece, and The Netherlands
Flexible microelectrodes	China

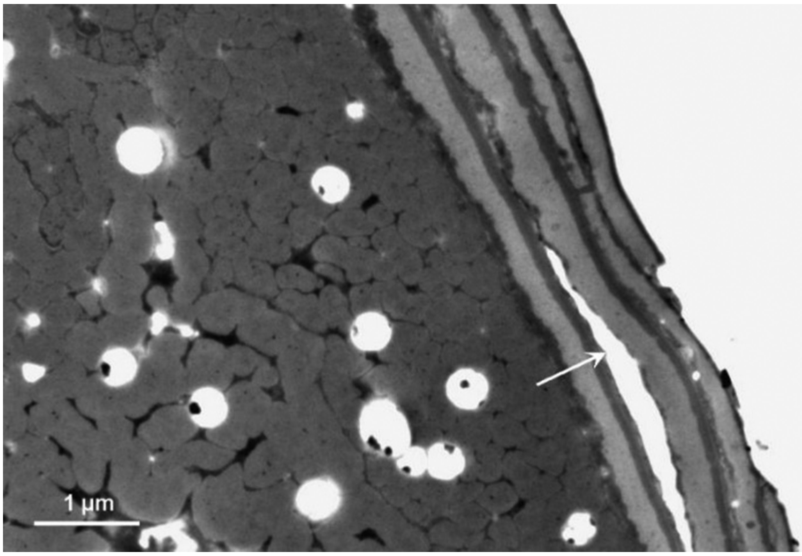

Figure 5. TEM image of hair cortex and cuticle from a 2× bleached hair. A region of severe endocuticle damage is indicated by the arrow. Note the degradation of the melanin granules (white circles) in the cortex. Source: Malinauskyte et al. (2020).

Malinauskyte et al. (2020) investigated the outcome of pH on the morphology and characteristics of bleached HH. They reported that varying pH values affect the properties of bleached HH. At pH levels of 10, they observed a reduction in cross-linking density, an increase in HH diameter, and water absorption, suggesting good active penetrations at pH levels above 10.

Another study by Grosvenor et al. (2018) on the effect of bleaching HH with peroxide revealed physical damage due to oxidation, such as degradation of the melanin granules and damage of the endocuticle at different locations, as shown in Figure 5.

Kathiresan and Meenakshisundaram (2022) carried out a study on the effect of 5% sodium hydroxide (NaOH) treatment of *Caryota obtusa*, *Delonix regia*, *Sterculia foetida*, and HH on the mechanical and physical properties for possible use in polymer composite materials. Using Fourier Transform Infra-red Spectroscopy (FTIR), scanning electron microscope (SEM) and a tensile testing machine, the four types of fibers were analyzed to ascertain the effect of NaOH treatment. FTIR analysis for NaOH-treated HH indicated additional peaks at 2918.73 cm^{-1} and 2850.27 cm^{-1} wave number, attributed to C-H stretching vibrations of CH_2 groups, leading to the creation of an absorption band (Figure 6). HH treated for 1 h reported the highest tensile strength of about 215 MPa as compared to other treated fibers. Conversely, untreated HH reported a high tensile strength (155–200 MPa) compared to the other fibers, as illustrated in Figure 7. This indicates that HH, like any other fibers, can be utilized as an alternative reinforcement material in polymer composites

Keratin (EKP) and keratin nanoparticle (KNP) extraction process. Keratin is a biopolymer abundant in various sources, including human hair, horns, wool, nails, claws, and feathers from birds. However, the most commonly explored sources of keratin include hair α-keratins, wool, and feather β-keratin, mainly due to their widespread availability as waste products from slaughterhouses, barber shops, poultry farms, and hair processing industries. Keratins obtained from these sources vary in amino acid composition, secondary protein structures, and molecular weight.

Recently, many authors have highlighted the possibility of extracting keratin from protein fibers such as wool, chicken feather, and HH as reinforcement in composite production.

Studies by Shavandi et al. (2017) and Chilakamarry et al. (2021) analyzed various keratin extraction techniques, including reduction, alkali hydrolysis, oxidation, sulfitolysis, enzymatic and microbial

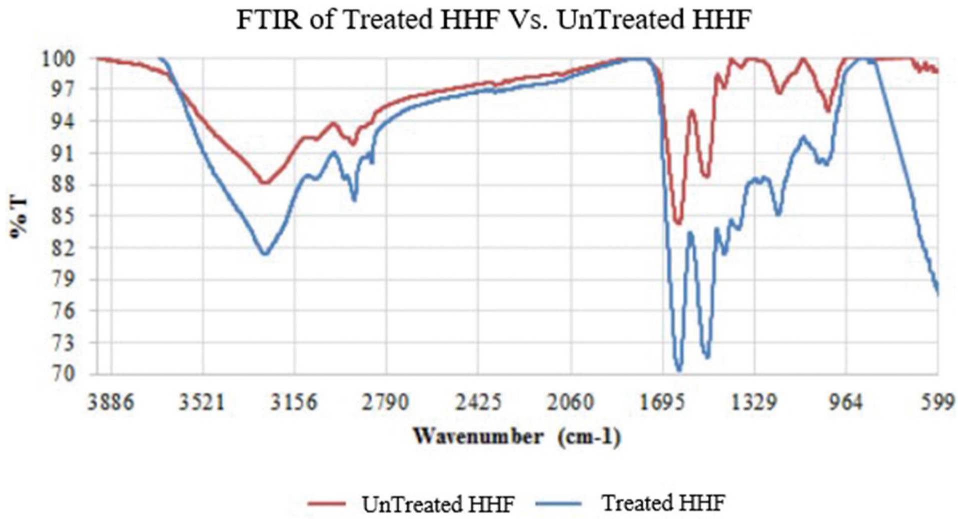

Figure 6. FTIR spectrum of untreated and treated human hair. Source: Kathiresan and Meenakshisundaram (2022).

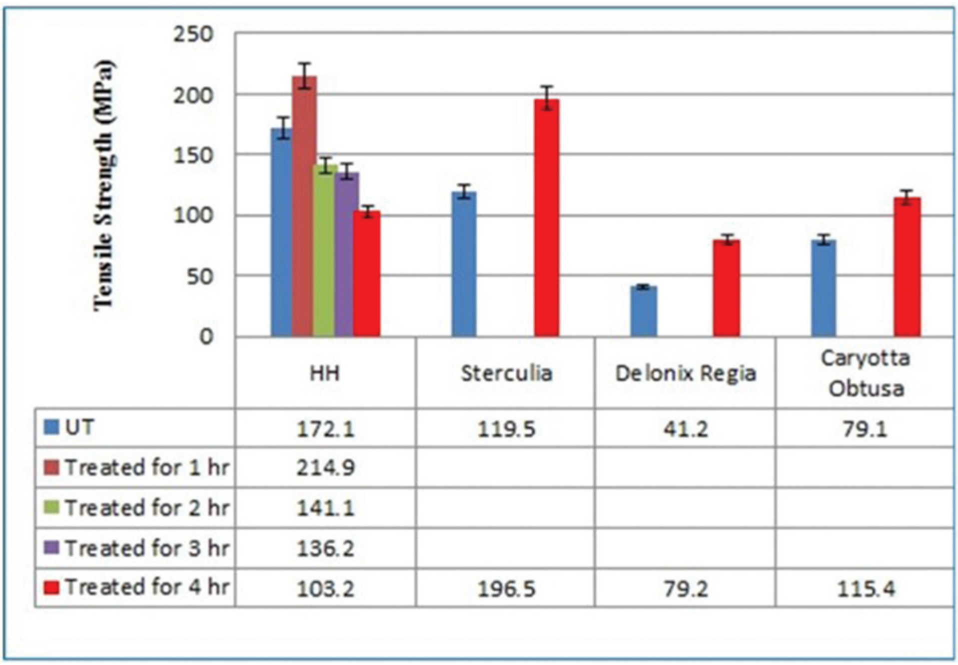

Figure 7. Tensile strength of untreated and treated natural fibers. Source: Kathiresan and Meenakshisundaram (2022).

treatment, and use of ionic liquids for extracting keratin from wool fibers for biopolymers. Shavandi et al. (2017) reported protein yields ranging from 6% to 95%, with the ionic liquid (IL) technique producing the highest yield of 95%, while the oxidation method produced the lowest yield of 6%. This finding was consistent with Ji et al. (2014) who obtained keratin from poultry feathers using the ionic liquid method. They cleaned feathers with water and reduced them to smaller pieces, added different ratios of IL, feathers, water, and Na_2SO_3 into glasses, heated the mixture to a set temperature while mixing, and noted that the properties of the extracted keratin did not change as compared to that of the original feather. Further, they reported optimal extraction conditions to achieve 75.1% yield to be 60-min extraction time at 90°C, 10 wt.% Na_2SO_3, weight ratio of liquid/feather of 20 and 20 wt.% water in ionic liquid. Similarly, Wang et al. (2022) investigated keratin extraction from HH using ionic liquids and green solvents, reporting better solubilizing capacity after 9 h at 130°C, varying different parameters such as cations and anions, water content on IL and temperature.

Chilakamarry et al. (2021) reported that the extracted keratin using ionic liquids was largely composed of β-sheets rather than α-helix, which were disrupted during the extraction process. Moreover, Ji et al. (2014) reported that ionic liquids containing chloride were the most effective solvent for keratin dissolution, attributed to better nucleophilic action and higher concentrations of chloride ions breaking hydrogen bonds.

In contrast, Chilakamarry et al. (2021) reported that acid hydrolysis was efficient since fewer amino acids were destroyed compared to alkaline hydrolysis. For example, Bachir Ben Seghir et al. (2020) reported a 25% yield in alkaline hydrolysis using 2% NaOH and 80°C for 3 h. However, the heating process at such temperatures can be destructive to amino acids.

Another study by Bachir Ben Seghir et al. (2020) analyzed various methods of preparing keratins and keratin nanoparticles from wool, evaluating the physical and chemical properties of the derived keratin and extraction techniques as illustrated in Table 4.

Mousavi et al. (2018) described a simple process of producing keratin nanoparticles (KNP) from cleaned chicken feathers. They first extracted keratin from chicken feathers and then synthesized keratin nanoparticles from the keratin powder (EKP). The resultant KNP was characterized using a particle size analyzer, TEM, XRD, and FTIR spectroscopy. They reported a KNP size of 42 nm using

Table 4. Keratin extraction by different methods. Adapted from Seghir et al. (2020).

Method	Extraction solution	Operating conditions	Yield (%)
Reduction	Urea = 8 M; Thioglycolic acid = 0.2 M; pH = 11	Temperature (°C) = 50°C; Time (h) = 3 h	70
	Urea = 8 M; DTT = 0.2 M EDTA = 3 mM; 0.2 M Tris – HCl pH = 9	Temperature (°C) = 20°C; Time (h) = 16 h; Ratio (solid: liquid) (w/w) =////	60
	Urea = 8 M; DTT= 0.14 M; 0.05 M Tris – HCl pH = 8.6	Temperature (°C) = 25°C; Time (h) = 4 h; Ratio (solid: liquid) (w/w) = 1/50	50
	Urea = 8 M; L-cysteine = 0.165 M; NaOH up to pH = 10.5	Temperature (°C) = 75°C; Time (h) = 12 h; Ratio (solid: liquid) (w/w) = 1/10	72
	TCEP/$Na_2S_2O_5$	Temperature (°C) = 80°C; Time (h) = 5 h	80
Alkaline Hydrolysis	Wool (10 g) treated with 2 wt.% NaOH with HCl to pH = 7	Temperature (°C) = 80°C; Time (h) = 3 h	25
	0.5 N NaOH (pH 13.9) Wool	Temperature (°C) = 62–65°C; Time (h) = 3 h; Ratio (solid: liquid) (w/w) = 1/20	-
	Wool mixed with an alkali the solution of KOH: NaOH (14:1) at 0.5 to 3% (w/v)	ultrasonic irradiation for 30 min using a 20 kHz sonicator (40% amplitude of 750 W)	100
	NaOH solution (10 g/L)	Temperature (°C) = 120°C; Time (min) = 10 min; Ratio (solid: liquid) (w/w) = 1/10	53.5
Ionic Liquids (ILs)	[Bmim][Cl]	Temperature (°C) = 120°C; Time (h) = 0.5 h; Ratio (solid: liquid) (w/w) = 1/6	57
	[Bmim][Cl]	Temperature (°C) = 120°C; Time (h) = 0.5 h; Ratio (solid: liquid) (w/w) = 1/10	78.5
	[Bmim][OAc]	Temperature (°C) = 120°C; Time (h) = 0.5 h; Ratio (solid: liquid) (w/w) = 1/10	16.8
	[Emim][DEP]	Temperature (°C) = 120°C; Time(h) = 0.5 h; Ratio (solid: liquid) (w/w) = 1/10	70.2
Sulphitolysis	Urea = 8 M; Sodium metabisulphite = 0.5 M; NaOH up to pH = 6.5; SDS (g)/wool = 0.6	Temperature (°C) = 60°C; Time (h) = 5 h; Ratio (solid: liquid) (w/w) = 1/15	41
	Temperature (°C) = 60°C; Time(h) = 5 h; Ratio (solid:liquid) (w/w) = 1/15	Temperature (°C) = 100°C; Time (h) = 5 h; Ratio (solid: liquid) (w/w) = 1/30	22
	Urea = 8 M; LiBr = 0.1 M; SDS = 0.02; NaOH pH = 12	Temperature (°C) = 90°C; Time (h) = 4 h	50

TCEP – (tris(2-carboxyethyl) phosphine); SDS – Sodium dodecyl sulfate; DTT – Dithiothreitol.

Table 5. EKP and KNP extraction procedure from chicken feather. Adapted from Mousavi et al. (2018) and Nomura et al. (2007).

Extract	Extraction solution	Operating conditions & procedure
Extracted Keratin Powder (EKP)	Chicken Feather (10 g) hydrolyzed with 0.3 L of 0.3N NaOH solution	Resultant mixture blended = 25°C (48 h) → Centrifuged = 4000 rcf (15 Min) → Filtration = Undissolved matter → Filtrate precipitated with 1N HCl to pH = 4.2 → Centrifuged = 4000 rcf (20 Min) → Precipitated keratin (thoroughly washed) = Neutralize → EKP = Dried at −48°C (12 h)
Keratin nanoparticles (KNP)	EKP's solubility improved by Tris base (Creation of mild alkaline condition) = Ratio of Tris base to keratin weight is 0.09.	The resultant mixture stirred = 400rpm (25°C) for 16 h (for smaller particles)→ Sonicated = (300 W, 10 min) using probe ultrasonic device to reduce microparticles into nanoparticles → Generated KNPs =store under 4°C before use OR freeze dried at −48°C (6 h) if needed in solid form.

Table 6. EKP extraction procedure from Waste HH. Adapted from Unnikrishnan and Ramasamy (2020).

Extract	Extraction solution	Operating conditions & procedure
Extracted Keratin Powder (EKP)	HHF (10 g) hydrolyzed with 7 M urea, 6 g SDS & 15 mL of 2-mercaptoethanol	HHF (10 g) was defatted for 2 days (Soxhlet's Apparatus)→ Refluxed with a mixture of Hexane & Dichloromethane (1:1 v/v)→Hydrolyzed with 7 M Urea, 6 g SDS & 15 mL of 2-mercaptoethanol at 60°C for 12 h under orbital shaker at a pH of 7→ The resultant solution is centrifuged at 6000 rpm for 15 min → Dialyzed against degassed water for 5–6 days→ kept in a deep freezer −80°C for liquid keratin or freeze-dried for powder keratin

particle size analyzer, with TEM confirming that the extracted KNP is spherical morphology. Moreover, they observed no change in their functional groups or structural alteration after synthesis. The extraction procedure of EKP and KNP is summarized in Table 5.

Similarly, Unnikrishnan and Ramasamy (2020) described a convenient procedure of extracting keratin from waste HH by alkali technique and analyzed the fertilizing efficiency of the wastewater generated from the extraction process, as shown in Table 6. They achieved this by pulverizing HH waste using 7 M urea, 6 g sodium dodecyl sulfate (SDS), and 15 mL of 2-mercaptoethanol at 60°C. Urea was used to break down non-covalent bonds, SDS disrupted intermolecular connections, while 2-mercaptoethanol splits the bonds of disulfide in keratin, thus improving its ability to dissolve. They reported a keratin extraction efficiency of 75.3%. The authors further investigated the morphology of HH before and after protein extraction by Field Emission Scanning Electron Microscope (FE-SEM), concluding that the SDS-Urea protein extraction method was more efficient.

In 2017, Shui-qing et al. (2017) successfully extracted keratin from HH using the alkali reduction method and analyzed the extracted keratin using SEM and FTIR. They reported an extraction efficiency of 75.3% and observed that keratin changed from α–helix to β–sheet during extraction. The extraction process is summarized in Table 7.

Natural fiber-reinforced composites

The use of natural fiber hybrid-reinforced polymer composites (FRC) has been on the rise in structural and non-structural applications due to their abundance and attractive properties, which address existing challenges of conventional materials (Atmakuri et al. 2020; Senthilkumar et al. 2018). Composites consist of a discontinuous material phase (reinforcing/filler) and a continuous material phase (matrix) separated by interphase. The performance of composite materials depends entirely on the composition of these phases. The fiber phase is the reinforcing phase of the composite, where its elements bear the load, while the matrix phase holds the fibers together, protects them from

Table 7. EKP extraction procedure from Waste HH. Adapted from Shui-Qing et al. (2017).

Extract	Extraction solution	Operating conditions & procedure
Extracted Keratin Powder (EKP)	HHF (1 g) was mixed with a 15 mL aqueous solution containing NaOH, Na_2SO_3 and sodium dodecyl sulfate (SDS, 15 g/L).	The mixture was stirred at 80°C→ After centrifugation, the filtrate was moved to a dialysis bag→ dialyzed against distilled water for 48 h → The resultant fluid was dried to obtain keratin powder.

environmental damage, and facilitates stress transfers (Bichang'a et al. 2022; Kamath, Sampathkumar, and Bennehalli 2017).

Reinforcements can be categorized as either synthetic (man-made) or natural (protein and cellulosic). These reinforcements can be further classified depending on their form: continuously aligned, discontinuous aligned, discontinuous random, particulate, or woven (Mostafa et al. 2016; Safri et al. 2018).

While synthetic fiber-reinforced composites exhibit better mechanical properties compared to natural fiber-reinforced composites, they face limitations such as non-degradability, high processing costs, and non-renewability. This has become a major concern, and therefore, minimal use of these composites is encouraged, especially where the strength of natural fiber-reinforced composites is sufficient (Bichang'a et al. 2022; Senthilkumar et al. 2018).

In contrast, natural fiber-reinforced polymer composites offer several benefits such as low cost, corrosion resistance, renewability, higher specific strength, non-toxicity, biodegradability, pollution-free processing, and light-weight properties (Sinha, Narang, and Bhattacharya 2020). These composites find numerous applications, especially in the automobile and housing industry such as in seat back, door panels, package trays, partitioning, and ceiling boards, among others (Mbeche, Wambua, and Githinji 2020; Safri et al. 2018). Natural fiber reinforcements and fillers range from human hair, wool, jute, sisal, banana, pineapple, flax, rice husk, and bamboo, to hemp, and are abundantly available in nature.

However, due to the relatively low mechanical properties, low thermal stability, and hydrophilic nature of most natural fibers, their use as reinforcements alone in polymer composites is not sufficient. The hydrophilic nature of these fibers results in poor fiber/matrix interfacial bonding, especially when they have absorbed water from the environment (Mbeche and Omara 2020; Pereira et al. 2020). Furthermore, natural fibers tend to aggregate during composite fabrication. These challenges have potentially decreased their use in polymer composites as reinforcements for non-structural and structural uses (Abd El-Baky et al. 2022). Most researchers have indicated that these limitations can be mitigated by hybridization, especially with synthetic/natural fibers, and by incorporating nanofillers (Hosseini 2017). According to a review conducted by Bichang'a et al. (2022) and Borba et al. (2014), the incorporation of small quantities of nanofillers has been known to improve the resultant composite's mechanical, thermal, and physical properties.

Human hair fiber reinforced composites

Human hair (HH) is a natural fiber usually considered of less value in most societies and therefore found in most dumping sites. The key building block of the HH is keratin protein, described as extremely strong, stable, and unsolvable in organic solvents and water. Due to these properties, it has been used as reinforcement in natural fiber-reinforced composites. Additionally, it has a low density and good mechanical properties (Fan et al. 2016; Nanda and Satapathy 2019; Srivastava, Kumar, and Sinha 2018).

Srivastava et al. (2018) explored the effect of treating HH with 0.25 and 0.5 M NaOH at room temperature for 1 h on the mechanical properties of HH-reinforced high-density polyethylene (HDPE) composites using hot compression molding. They reported that chemical or physical treatments on natural fibers result in the modification of their surfaces, creating additional reactive sites which facilitate better bonding. The surface of HH contains oil and wax, which, if not removed, can affect the fiber–matrix bonding of the resultant composite. Chemical treatment improved hair-matrix interfacial bonding and water absorption, as illustrated in Figure 8.

A similar study by Srivastava and Sinha (2018) investigated the effect of NaOH and acrylic acid treatment on HH used as reinforcement in HDPE composites. Composites with treated HH reported lower tensile strength of 15.64 MPa and 15.49 MPa, respectively. Additionally, as illustrated in Figure 9, the study reported a rise in water absorption as the fiber weight fraction increased from 5% −25% for untreated HF/HDPE composites. Further, there was an increase in water absorption after 0.25 N NaOH treatment probably because of the creation of roughness and pits on the surface of the fibers.

Nanda and Satapathy (2017) developed and studied the mechanical properties of short HH-reinforced epoxy composites by the hand lay-up method. They indicated that integrating short HH in the composite improves the mechanical properties of the resultant composite (Table 8). On the other hand, Salih (2019) developed a 10 wt.% HH-reinforced epoxy composite using a hand lay-up method. The researcher investigated its mechanical properties, including compressive strength, bending strength and impact strength, in comparison with unreinforced epoxy. The study results showed that the incorporation of HH reinforcement improved mechanical properties: Young's modulus increased by 13.52%, impact strength increased by 35%, and compressive strength increased by 36%. This is similar to what was reported by2017Nanda and Satapathy (2017). They further found that HH-reinforced composites absorb more water, and with the help of SEM, they noted that the interface between HH and the matrix was mostly attacked by water.

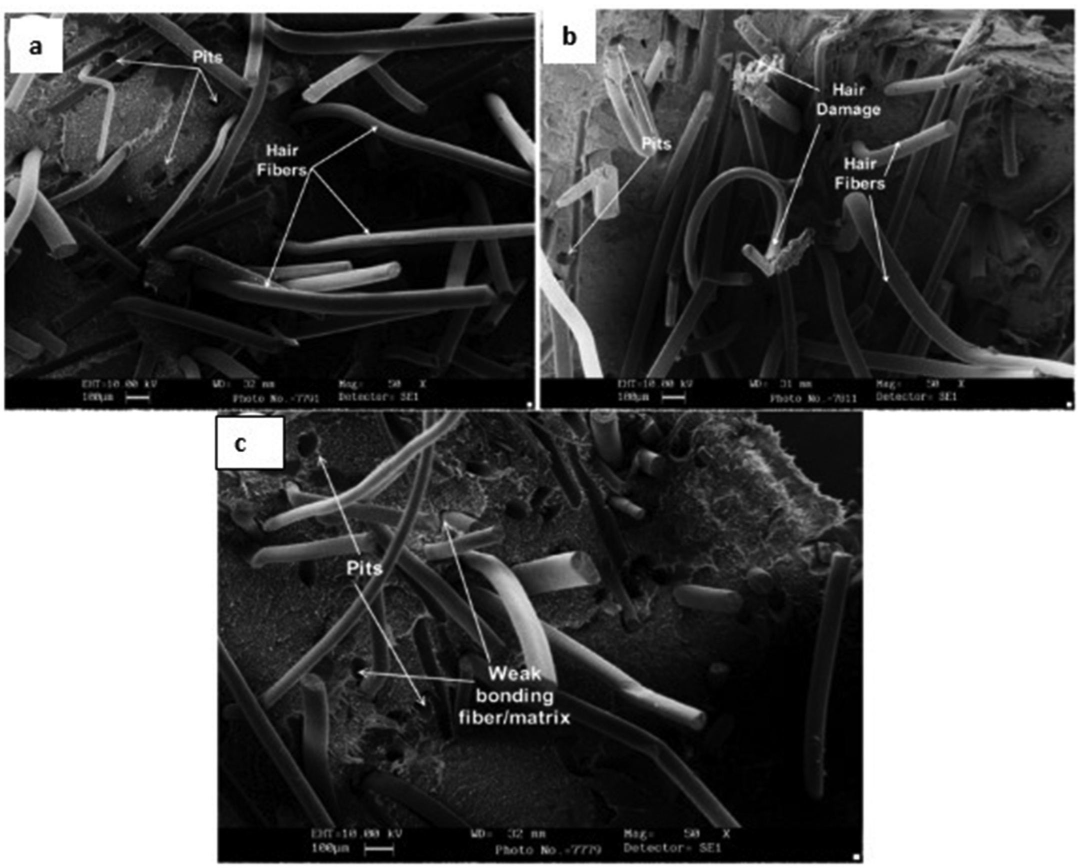

Figure 8. SEM micrographs. (a) Untreated hair fiber (15% composition) (b) 0.25 N NaOH treated hair fiber (15% composition) (c) 0.50 N NaOH. Source: Srivastava et al. (2018).

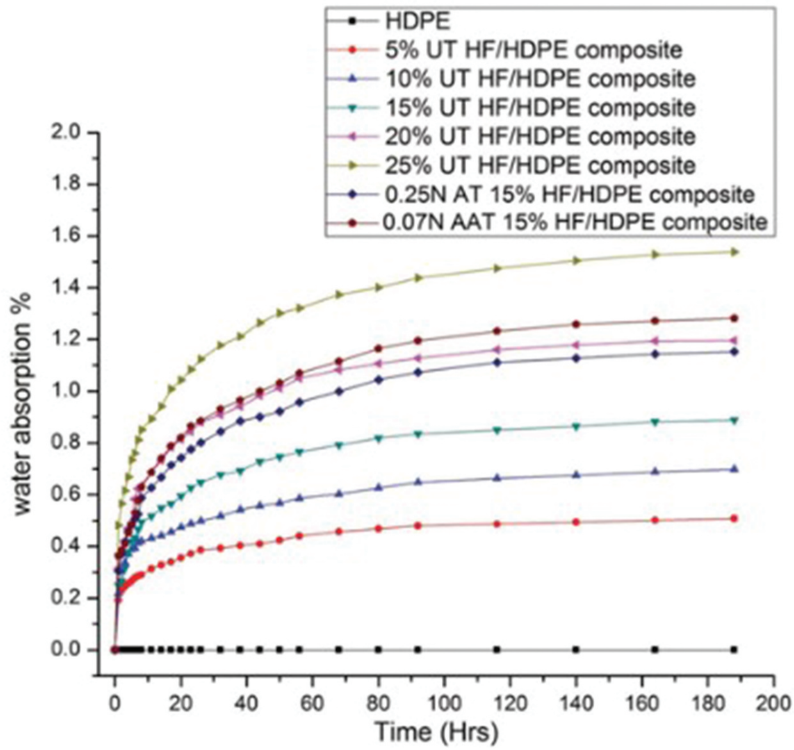

Figure 9. Water absorption behavior of HF/HDPE composites (UT: Untreated; AT: Alkali treated; AAT: Acrylic acid treated). Source: Srivastava and Sinha (2018).

Table 8. Mechanical properties of epoxy-SHF composites. Source: Nanda and Satapathy (2017).

SHF content (wt.%)	Tensile strength (MPa)	Flexural strength (MPa)	Compressive strength (MPa)
0	65	58	84
2	81	71	87
4	94	86	91
6	112	99	94
8	127	106	96

Nanda and Satapathy (2019) investigated the mechanical and thermal properties of HH-reinforced epoxy composites using the hand lay-up method. They observed that mechanical properties were improved by the mere incorporation of the HH fiber. Further, the addition of HH in the composite led to a considerable decrease in the actual thermal conductivity of epoxy composites and therefore improved their insulation properties. This was consistent with a study conducted by Wati and Dhanker (2017) where an improvement in mechanical properties was reported after incorporating HH fiber in epoxy resin.

Studies by Prakash et al. (2019) investigated the thermal properties of HH-reinforced composites. The samples were prepared using the hand lay-up method by varying HH loading of 5, 10, 15, 20, and 25 wt.%. The resultant samples were subjected to thermal measurements to determine their stability at elevated temperatures using thermogravimetric analysis (TGA) in a nitrogen atmosphere. A 14% weight loss was reported probably due to damage to the organic bonding between the epoxy resin and the fiber.

Rao et al. (2018) conducted a comparative study on the tensile properties of randomly oriented shampoo-treated HH-reinforced polyester (PE) composites. They prepared fibers by cutting them into various lengths of 50, 40, 30, 20, and 10 mm. The study reported an increase in modulus and tensile strength with an increase in fiber weight fraction, where an optimal value of 4.13 GPa and 31.45 MPa was reported at 20 wt.%, respectively. Additionally, better tensile properties were reported at a HH fiber length of 30 mm.

On the other hand, Deepmala et al. (2018) developed a mathematical model to optimize the tensile properties of the PE matrix reinforced with HH. In their study, they varied the fiber weight fraction from 5% to 25% in steps of 5 and fiber lengths (10 mm, 20 mm, 30 mm, 40 mm, 50 mm). The analysis of variance (ANOVA) result indicated that the fiber weight fraction influenced the tensile strength more than the length of the fiber. They reported maximum tensile properties of 29.3 MPa against an experimental value of 31.45 MPa at a fiber loading of 21.71% and a fiber length of 29.33 mm. The authors concluded that the value obtained by the response surface methodology (RSM) agreed with the experimental value.

In a separate investigation, Rao, Kiran, and Prasad (2019) employed a mathematical model to enhance the tensile properties of polyester composites reinforced with HH. The fabrication process involved creating samples using chopped HH, with volume fractions ranging from 5% to 25% by weight in steps of 5 and varying fiber lengths (10 mm, 20 mm, 30 mm, 40 mm, 50 mm) using the hand lay-up technique. The impact of fiber length and loading on the HH-reinforced composite was investigated using RSM. The analysis revealed that the highest tensile strength for the resultant composite was achieved at a fiber length of 29.33 mm and a fiber weight ratio of 21.71%. Furthermore, the recorded maximum tensile strength for the composite was 29.33 MPa, slightly deviating by 6.7% from the experimental stress value of 31.45 MPa. Notably, the optimum tensile strength predicted by the historical response surface methodology aligns well with the experimentally determined tensile strength.

Green composites were developed by reinforcing soy protein isolate (SPI) with 5% NaOH-treated HH using a compression molding technique. The SEM analysis indicated better interfacial bonding between the 2 wt.% treated HH and the SPI matrix, thus reporting optimum tensile properties of 17.23 MPa. Chitosan-coated green composites have also reported better properties (Deepmala et al. 2018).

A comparative study was conducted by Manik, Gajghat, and Joseph (2019) on the mechanical properties of jute, HH, and coconut coir-reinforced epoxy composites fabricated by hand lay-up technique. From their work, they rated the tensile properties of jute fiber-reinforced composites ahead (419 MPa), followed by HH (406 MPa) and lastly coir fiber-reinforced composites (129 MPa). The shear strength for HH and jute fiber-reinforced epoxy composites was noted to be very close, that is, 231 MPa and 219 MPa.

Choudhry and Pandey (2013) studied the effect of incorporating HH in polypropylene (PP) polymer at 3, 5, 10, and 15 wt.% on the mechanical properties of the resultant composite prepared through compression molding technique at a pressure of 60 MPa and varied temperatures and time of between 180°C–190°C and 0–10 min, respectively. From their experimental results, 5 wt.% HH fiber-reinforced PP composite exhibited better impact and flexural properties than pure PP. In contrast, experimental outcomes indicated that the tensile properties of PP were higher (40.41 MPa) than those of HH fiber-reinforced PP composites (9.7–24.87 MPa). The author attributed this poor performance of the HH-reinforced composite to improper distribution of HH within the PP matrix and poor fiber–matrix interface.

Poly(ethylene oxide) (PEO) reinforced with electrospun HH keratin composite nanofibers was developed by Liu et al. (2014) as a potential biomaterial. The authors prepared the samples by adding varying amounts of dissolved PEO to the extracted keratin solution extracted from HH by sulphitolysis procedure. Thereafter, they investigated the structure, morphology, and thermal properties of the resultant composite nanofiber prepared at different ratios of 30/70, 40/60, 50/50,60/40, 70/30, 80/20, 90/10 PEO/keratin with the help of SEM, FTIR, and Differential Scanning Calorimetry (DSC). From their studies, it was reported that 30/70 PEO/keratin reported bead-free composite nanofibers and better planned confirmation of keratin/PEO chains. Tables 9 and 10 summarize the most recent studies on HH fiber-reinforced polymer composites and their mechanical properties, respectively.

Human hair and natural fiber-reinforced composites

Human hair (HH) and natural fiber-reinforced composites refer to materials that incorporate HH or other natural fibers as reinforcements within a composite matrix. These composites leverage the inherent properties of natural fibers to enhance the mechanical, thermal, and sometimes environmental characteristics of the resulting material.

Selvan (2014) investigated the mechanical and machining properties of HH and jute fiber hybrid-reinforced epoxy composite developed using the hand lay-up method. The hybrid composites were fabricated with varying Jute/HH blend ratios of 100/0, 75/25, 50/50, 25/75, and 0/100. The researchers further investigated the effect of HH incorporation on the morphological structure of the resultant composite using a Scanning Electron Microscope (SEM). From the study, tensile, impact, and flexural properties were noted to increase as the HH fiber component was increased. It was also observed that 100% HH-reinforced epoxy composites had better mechanical properties than 100% jute-reinforced epoxy composites as illustrated in Table 11. An SEM investigation on tensile-tested specimens indicated good epoxy-jute bonding, while poor bonding was reported on the jute/HH (25/75) fiber-reinforced epoxy composites as shown in Figure 10.

Another study by Selvakumar and Meenakshisundaram (2019) analyzed the dynamic mechanical and mechanical properties of jute/HH epoxy-reinforced hybrid composites with varying jute/HH volume ratio of 25/0, 18.75/6.25, 12.5/12.5, 6.25/18.75, and 0/25 prepared by hand lay-up. Their study was in agreement with the previous study by Selvan (2014), which reported better mechanical properties for HH epoxy composites compared to jute epoxy-reinforced composites. Impact strength increased with the loading of HH with the maximum value of 4.25 J reported at 25% HH. Composites reinforced with 25% HH reported better tensile strength of 23.5 MPa as likened with 16 MPa for 25% jute fiber-reinforced composites. The authors attributed this to the hydrophobic nature of HH, which improves the interlocking between HH and epoxy. Further, they reported improved viscoelastic behavior and dynamic mechanical properties due to the better chemical interactions between jute and HH and the addition of jute and HH, respectively.

Ansari, Dhakad, and Agarwal (2020) developed a hybrid epoxy composite reinforced with HH and NaOH-treated sisal fiber fabricated using a hand lay-up technique. Fiber weight fraction varied from 5%, 10%, and 15%. In their work, they reported that the hybridization of natural fibers in polymer composites leads to improved mechanical properties. Tensile and impact strength were noted to increase with fiber weight fraction with an optimum value of 27.7 MPa and 46.18 J/m reported at 15 wt.%. On the other hand, better hardness properties were also reported at a fiber weight fraction of 5 wt.%.

A hybrid epoxy composite was developed by Teja and Reddy (2017) from a 30 mm alkali treated HH and coconut coir fiber by hand lay-up method, and its mechanical properties were investigated. A fiber weight fraction of 40% reported a higher impact strength (77.8J/m), while a 20% fiber weight fraction reported maximum flexural strength.

Michael, Harish, Bensely, and Lal (2010) investigated the electrical insulation properties of sisal/HH/coir/banana fiber hybrid epoxy composites at freezing temperatures using the hand lay-up method. The authors' interest was to develop a practical method of diagnosing electrical insulation degradation status for the resultant composite material. They achieved this by examining the breakdown voltages, at room temperature of 26.85°C and liquid nitrogen of −203.15°C of both natural fiber-reinforced epoxy composite laminates (HH, coir, banana, and sisal) and glass fiber-reinforced polymer epoxy composite laminates. Their results indicated that at room temperature, a breakdown voltage of 52.92 kV/cm, 134.5 kV/cm, 22.93 kV/cm, 18.16 kV/cm, and 20.31 kV/cm was recorded for coir, human hair, banana, and sisal-reinforced composite laminates, respectively. However, at cryogenic temperature, a breakdown voltage of 118.99 kV/cm, 177.86 kV/cm, 127.67 kV/cm, 120.84 kV/cm, and

Table 9. Recent studies on HH-reinforced polymer composites.

Matrix	Reinforcement	Fabrication method	Properties observed	Effect of the reinforcement	Ref
Epoxy	Human Hair (0–8 wt.%)	Hand lay-up	Tensile strength, Flexural strength, and compressive strength	Incorporation of short human hair in the epoxy matrix improved the mechanical properties of the resultant composite	(Nanda and Satapathy 2017)
Epoxy	Human Hair (10 wt.%)	Hand lay-up	Compressive strength, bending strength, impact strength and water absorption	Improved mechanical properties i.e., young's modulus improved from 1083.75MPa to 1230.32MPa, impact strength increased by 35% and compressive strength increased by 36%. Water absorption was increased with the incorporation of human hair fiber.	(Salih 2019)
Epoxy	Human Hair	Hand lay-up	Mechanical and thermal properties	Improved mechanical properties and substantial reduction of effective thermal conductivity	(Nanda and Satapathy 2019)
Epoxy	Human Hair	Hand lay-up	Mechanical properties	Reported improved mechanical properties with the incorporation of human hair fiber	(Wati and Dhanker 2017)
Epoxy	Human Hair (5, 10, 15, 20 and 25 wt.%)	Hand lay-up	Thermal analysis	14% weight loss was reported (Due damage of the organic bonding)	(Prakash, R, and Paul 2019)
Polyester	Human Hair (cut into 10, 20, 30, 40 and 50 mm)	Hand lay-up	Tensile properties	Tensile strength increased to 31.45MPa and modulus of 4.13 GPa at 20 wt.%	(Rao, Kiran, and Prasad 2018)
Polyester	Human Hair	Hot compression molding	Optimization of tensile properties based on fiber loading (5, 10, 15, 20, 25 wt.%) and fiber length (10, 20, 30, 40, 50 mm)	Fiber weight fraction influenced tensile strength than fiber length	(Deepmala et al. 2018)
Concrete	Human Hair	Hand lay-up	Optimization of compressive strength by varying fiber weight fraction and fiber length	Incorporation of human hair improved the compressive properties. An optimum value of 38.15 MPa was reported at a 3.2 wt.% and 0.752-inch fiber length	(Santos et al. 2020)
Concrete	Human Hair (0,1,2,3 & 4 wt.%)	Hand lay-up	Compressive, Flexural and Tensile strength	Improved compressive strength by 8.15% after 28 days and at 1 wt.% HHF. Flexural and Tensile strengths increased by 12.71% and 21.83% after 28 days and at 2 wt.% HHF	(Bheel et al. 2020).
Clay soil	Human hair (0,0.5,1,1.5,2 & 2.5 wt.%)	Hand lay-up	Influence of Human hair in clay soil	Better mechanical properties and minimum cracks propagation were reported	(Butt, Mir, and Jha 2016)
Epoxy	Human hair, Jute & coconut coir	Hand lay-up	Comparative study on the mechanical properties i.e., Tensile strength and shear strength for the 3 composites	It was noted that Jute epoxy reported a higher tensile strength of 419MPa followed by human hair epoxy (406MPa) and coir epoxy (129MPa). Shear strength of human hair and jute epoxy was noted to be very close i.e., 231MPa and 219MPa respectively	(Manik, Gajghat, and Joseph 2019)

(*Continued*)

Table 9. (Continued).

Matrix	Reinforcement	Fabrication method	Properties observed	Effect of the reinforcement	Ref
Polypropylene (PP)	Human Hair (0,3,5,10 & 15 wt%)	Hot compression molding	Tensile strength, Flexural strength, Elongation at break, Flexural modulus & Izod Impact strength	Better flexural (38.89MPa) & Impact (12.55MPa) strengths were reported at a HHF of 5 wt %. In contrast, pure PP reported a better Tensile of 40.41MPa as compared to HHF/PP composite	(Choudhry and Pandey 2013)
Poly (ethylene oxide) (PEO)	Human Hair Ratio: 30/70, 40/60, 50/50,60/40, 70/30, 80/20, 90/10 PEO/Keratin	Hand lay-up	Structure, morphology, and thermal properties	30/70 PEO/keratin reported bead-free composite nanofiber; Keratin was extracted using sulphitolysis technique	(Liu et al. 2014)

102.29 kV/cm was recorded for human hair, glass fiber-reinforced plastic, coir, sisal, coir, and banana, respectively, as shown in Table 12. From their work, they concluded that natural fiber dielectrics can be used as an insulation material for cryogenic uses.

Most recently, Ali et al. (2023) fabricated a PE reinforced with HH and natural fillers such as marble dust, fly ash, and rice husk. The reinforcements (HH) were thoroughly washed, dried under the sun, cut into smaller pieces, and then sieved with a sieve size of 4.0 mm. They indicated an improvement in tensile and flexural properties by incorporating HH in rice husk/fly ash/marble dust PE reinforced composite. Further, rice husk/HH/PE reported better tensile, impact, and flexural properties of 22 MPa, 60 Jm^{-1}, and 30 MPa, respectively, while fly ash/HH/PE and marble dust/HH/PE reported better flexural modulus and hardness of 4.5 MPa and 120.00 HV, respectively. Water absorption was high for the fly ash/HH/PE composite as compared with the other composite combinations. The authors concluded that the incorporation of HH in the composite improves the mechanical properties of the resultant composite.

Rahman et al. (2023) fabricated two hybrid polyester composites from Jute and betel nut husk (BNH), as well as HH, jute, and BNH. These composites were fabricated through the hand lay-up method, with 20% volume fraction and equal fiber ratio by weight for each type of fiber used. The fibers (HH, BNH, and Jute) were first prepared by cutting them to a 3–4 mm and treated with 10% NaOH for 2 h, 5% NaOH for 4 h and 2% NaOH for 4 h, respectively. The authors investigated the impact of HH on the mechanical properties, including flexural, tensile, hardness, and impact strength of the resulting composite. Their findings indicated a substantial increase in strength for composites embedded with HH compared to those without embedding. Specifically, tensile, flexural, and impact strengths showed a 75% improvement, and hardness demonstrated a 19% increase in HH-embedded composites. Further, they investigated the fiber–matrix bonding using an SEM. The results revealed that HH-embedded composites exhibited enhanced bonding, fewer voids, and micro-cracks, along with outstanding energy absorption strength, capacity, and hardness.

Espín-Lagos et al. (2022) examined the mechanical characteristics of polyester composites reinforced with long and short HHs. To achieve this, they created composite samples with diverse fiber sizes, orientations, and volume fractions. Among the specimens, the first group, consisting of 70% matrix and 30% reinforcement with a longitudinal fiber orientation at 0°, stood out, exhibiting maximum tensile strength, flexural strength, and impact energy of 28.47 MPa, 66.24 MPa, and 1.37 J, respectively. In conclusion, when compared to other composite materials, the composite material based on HH demonstrated remarkable potential as an environmentally friendly solution for applications in the furniture and automotive industry, thanks to its high flexural strength. Table 13 summarizes the mechanical properties of HH/natural fiber-reinforced polymer composites.

Table 10. Mechanical properties of HH hair-reinforced polymer composites.

Reinforcements	Matrix	Fiber loading (wt. %)	Treatments	Fabrication method	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength	Compressive strength (MPa)	Hardness (Rockwell Hardness No.)	Ref.
HH	HDPE	15	0.25 and 0.5 N NaOH at room Temp.,1 H	Hot Compression	-	24.00	-	-	-	Srivastava et al. (2018)
HH	HDPE	15	0.25 and 0.5 N NaOH at room Temp., 1 H	Hot Compression	15.64	-	-	-	-	Srivastava and Sinha (2018)
HH	HDPE	15	Acrylic acid 0.07N, 0.14N and 0.21N for 1 hr at room temp.		15.49	-	-	-	-	Srivastava and Sinha (2018)
HH	Epoxy	8	-	Hand-lay-up	127.00	106		96.00	-	Nanda and Satapathy (2017)
HH (10–30 mm)	Epoxy	10	-	Hand-lay-up	-	-	3.8 KJ/ mm^2	73.73	-	Salih (2019)
HH (30 mm)	Polyester	20	shampoo-treated	Hand-lay-up	31.45	-	-	-	-	Rao et al., (2018)
HH (29 mm)	Polyester	21	-	Hand-lay-up	29.30	-	-	-	-	Deepmala, Jain, Singh, and Chauhan (2018)
HH (29.33 mm)	Polyester	21.71	-	Hand-lay-up	29.33	-	-	-	-	Rao et al. (2019)
HH	soy protein isolate (SPI)	-	5% NaOH treated	compression molding	17.23	-	-	-	-	Deepmala et al. (2018)
HH	Epoxy	50	-	Hand-lay-up	406.00	-	-	-	42.00	Manik, Gajghat, and Joseph (2019)
HH	polypropylene	5	-	compression molding	24.87	38.89	12.55 J/ m	-	-	Choudhry and Pandey (2013)

Table 11. Average values of mechanical properties for each composite. Source: Selvan (2014).

	Fiber composition in the blend (jute/HHF)				
Composite	100/0	75/25	50/50	25/75	0/100
Tensile Strength (MPa)	16	18.5	20	18	23.5
Tensile Modulus (MPa)	393. 95	477.05	492.06	343.27	351.12
Flexural Strength (MPa)	66.6	61.63	81.49	75.35	80.83
Flexural Modulus (MPa)	10.3	27.39	19.52	23.05	27.65
Impact Strength (MPa)	0.3	0.55	0.6	2.4	4.25

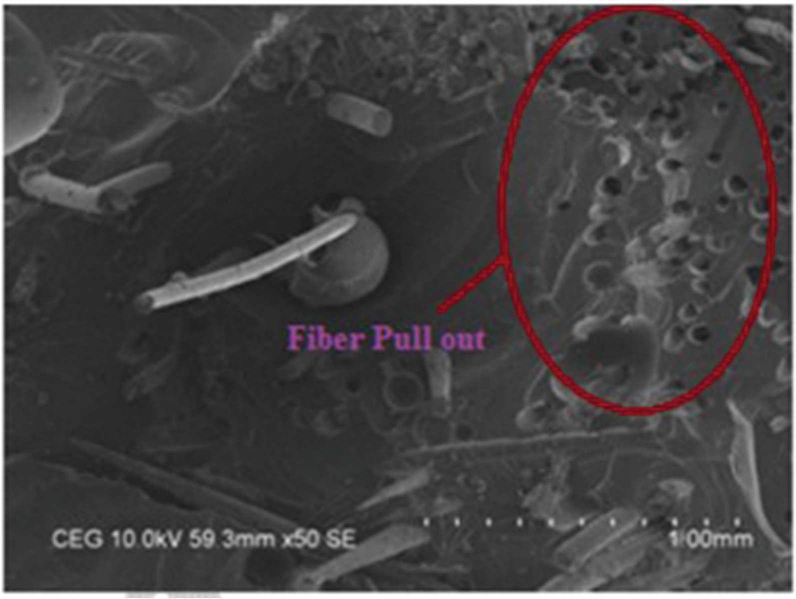

Figure 10. SEM images. (a) 25% jute and 75% HHF-reinforced composite after tensile test (b) 100% jute fiber-reinforced composite. Source: Selvan (2014).

Table 12. Comparison between room and cryogenic temperatures. Source: Michael et al. (2010).

		Room temperature		Cryogenic temperature (77K)	
S. No.	Type of sample	Breakdown voltage (kV)	Breakdown strength (kV/cm)	Breakdown voltage (kV)	Breakdown strength (kV/cm)
1	Sisal	8.29	20.31	41.48	127.67
2	Human Hair	21.91	52.92	46.36	118.99
3	Banana	7.13	18.16	44.73	102.26
4	Coir	7.61	22.93	39.45	120.84
5	GFRP	41.58	134.5	55.67	177.86

Human hair and synthetic fiber-reinforced hybrid composites

These hybrid composites are prepared by combining HH with synthetic fiber to create materials with enhanced mechanical, thermal, or other specific characteristics. Prasad and Satapathy (2018) developed and investigated the wear characteristics of short HH fiber-reinforced glass microsphere-filled epoxy composites with a fiber loading of between 2 and 6 wt.% using the hand-lay-up technique. From their study, it was reported that the incorporation of short hair fiber (SHF) in the composite improved the mechanical properties of the composite to 112 MPa, 99 MPa, and 94 MPa for tensile, flexural, and compressive strengths, respectively. Additionally, wear resistance performance improved with the addition of solid glass microspheres.

Another study by Nanda and Satapathy (2020) improvised an epoxy hybrid composite by solution casting method from short HH fiber and solid glass microspheres (SGM) revealed a 27% decrease in thermal conductivity of epoxy by the incorporation of 10 wt.% of SGM and 20 wt.% of SHF.

A comparative study on the mechanical properties of HH/glass/coconut coir fiber-reinforced hybrid epoxy composite for automobile and other areas of applications such as building was done by Senthilnathan et al. (2014). Mechanical tests were conducted on the six fabricated laminates that are coconut coir-reinforced polymer (CCRP), Glass fiber-reinforced polymer, HH-reinforced polymer, Coconut coir/glass/HH/coconut coir hybrid composite (CGHCRP), Glass/Coconut coir/HH/Glass hybrid composite, and HH-coconut coir-glass-HH hybrid composite (HCGHRP). From their findings, CCRP reported optimum tensile strength, HCGHRP reported comparable impact strength and CGHCRP reported a higher hardness value.

Another approach was presented later by Senthil Nathan et al. (2016) who reinforced epoxy with coconut fiber, glass fiber, and HH fiber with fiber loading of 30, 40, and 50 wt.%, respectively, using the hand lay-up method. The authors investigated the machinability and mechanical properties of the resultant composite, where better tensile, flexural, and compressive properties of 40 MPa, 60 MPa, and 32 MPa, respectively, were reported at a fiber loading of 40 wt.%. Further, a fiber loading of 30 wt.% reported a better impact strength of 1.5J.

Jayaprakash et al. (2016) developed a HH fiber reinforcement polymethyl methacrylate (PMMA) composite hybridized with copper fiber. They analyzed impact strength, transverse strength, and thermal conductivity properties. From this analysis, PMMA reinforced with HH reported better impact strength than when reinforced with copper fibers. The incorporation of copper fibers in the PMMA matrix increased the thermal conductivity of the resultant composites, probably because of the good thermal conductivity properties of copper. Table 14 summarizes the mechanical properties of HH/synthetic fiber-reinforced polymer composites.

Keratin-reinforced composites

Due to the nature of keratin, the fiber–matrix bond is poor, and based on this, a few authors have incorporated coupling agents when preparing keratin/polypropylene (PP) composites from feathers with (β) keratin as the main component. The study by Donato and Mija (2020) reported better properties after the incorporation of coupling agents which improves the keratin/PP bond.

Shavandi and Ali (2019) published a literature review summarizing the properties, processing conditions, and surface modifications of feather/wool keratin blends with polypropylene (PP) and polyethylene (PE) polymer matrices. From their work, they concluded that surface treatment of keratin fibers boosted the fiber–matrix bond.

A study by Bertini, Canetti, Patrucco, and Zoccola (2013) evaluated the properties and thermal degradation of wool. They prepared keratin hydrolyzates from wool fibers by green hydrolysis to be used as reinforcements in polypropylene (PP) matrix composites with maleic anhydride grafted polypropylene as the compatibilizer. They investigated the mechanical, morphological, and thermal properties by varying the percentages of compatibilizer and keratin. They reported improved polypropylene/keratin bonds with the incorporation of the compatibilizer due to the effective stress transfer between the bio-filler and the matrix. Further, there was an enhanced thermal degradation resistance reported in compatibilized composites and the presence of keratin improved the mechanical and elastic modulus properties of the resultant composite. However, this was not the case with low keratin loading, where elongation and strength were comparable with those of unadulterated polypropylene.

Another study by Fan et al. (2016) investigated various techniques for improving the mechanical properties of HH keratin/polyethylene oxide (PEO) and its electrospinning properties by material cross-linking. The keratin was extracted by sulfitolysis method as earlier reported by Yang, Peng, Wang, and Liu (2010) and prepared 90% keratin/10% PEO nano-fiber mat by cross-linking it with the help of ethylene glycol diglycidyl ether (EGDE). This resulted in an improved

Table 13. Mechanical properties of HH/natural fiber-reinforced polymer composites.

Reinforcements	Matrix	Matrix fiber loading (wt. %)	Treatments	Fabrication technique	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength	Compressive strength (MPa)	Thermal properties	Hardness	Ref.
Jute/HH	Epoxy	(100/0, 75/25, 50/50, 25/75 & 0/100)	-	Hand-lay-up	20 (50/50)	81.49 (50/50)	12.4 J (25/75)	-	-	-	Selvan (2014)
Jute/HH	Epoxy	25/0, 18.75/6.25, 12.5/12.5, 6.25/18.75 & 0/25	-	Hand-lay-up	23.5 (0/25)	-	4.25 J (0/25)	-	-	-	Selvakumar and Meenakshisundaram (2019)
HH/Sisal	Epoxy	15 (50/50)	NaOH (Sisal) 48 H	Hand-lay-up	27.7	38.16	46.18 J/m	-	-	78 HRB	Ansari, Dhakad, and Agarwal (2020)
HH/Coconut	Epoxy	(20/20, 20/40, 40/20, 40/40)	-	Hand-lay-up	13.87 (20/20)	22.28 (40/40)	72.1 J/m	-	-	76.4 HRB	Teja and Reddy (2017)
HH/Natural Fillers (marble dust, fly ash and rice husk)	Polyester	40/20/40 (matrix, filler, & fiber)	-	Hand-lay-up	22	30	60 Jm-1	-	-	120HV	Ali et al. (2023)
Jute and betel nut husk (BNH) and HH, Jute and BNH (3–4 mm)	Polyester	1:1 and 1:1:1 respectively (Jute & BNH fiber)	HH (10% NaOH for 2 H); -BNH (5% NaOH for 4 H) and Jute (2% NaOH for 4 H)	Hand-lay-up	9.68	31.82	0.0086 J/mm	-	-	58.3 D	Rahman et al. (2023)
		1:1 and 1:1:1 respectively (Jute, BNH fiber & HH)			22.05	58.99	0.0187 J/mm	-	-	69.39 D	
HH (short & Long)	Polyester	7:3 fiber ratio (0° fiber orientation)	-	Hand-lay-up	28.472	66.24	1.371 J	-	-	-	Espín-Lagos et al. (2022)

Table 14. Mechanical properties of HH/synthetic fiber-reinforced polymer composites.

Reinforcements	Matrix	Matrix Fiber loading (wt. %)	Treatments	Fabrication technique	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength	Compressive strength (MPa)	Thermal properties	Ref.
HH/glass microsphere	Epoxy	2–6	-	Hand-lay-up	112	99	-	94	-	Prasad and Satapathy (2018)
HH/glass microspheres	Epoxy	20/10	-	Solution casting	-	-	-	-	Resulted to 27% decrease in thermal conductivity	Nanda and Satapathy (2020)
Coconut/glass/HH	Epoxy	30	-	Hand-lay-up	40	60	1.5 J	32	-	Senthil Nathan et al. (2016)
HH/Copper fibers	PMMA	2:1	-	Compression molding	-	87.14	0.635 J	-	Incorporation of copper fibers in the PMMA matrix increased thermal conductivity	Jayaprakash et al. (2016)

Table 15. Effect of hybridizing human hair fiber on the physical and mechanical properties of the resultant composite.

Hybrid composite	Matrix	Fabrication method	Properties observed	Effect of hybridization	Ref.
Human hair/Jute	Epoxy	Hand lay-up	Mechanical & Machining properties. SEM-morphological structure study	Tensile, impact and flexural properties as the HHF component increased in the blend. 100% HHF epoxy composite reported better mechanical properties than 100% Jute.	(Selvan 2014)
Sisal/Human hair (5 wt.%, 10 wt.% and 15 wt.%)	Epoxy	Hand lay-up	Tensile and Impact strength	Hybridization led to improved mechanical properties with an optimal value reported at 15%. Better hardness properties were reported at 5 wt.%	Ansari, Dhakad, and Agarwal (2020)
Human hair/ coconut coir	Epoxy	Hand lay-up	Impact and flexural strength	Hybridization improved the resultant composite's mechanical properties, with maximum properties reported at 40 wt.%	(Teja and Reddy (2017)
Human hair/glass microsphere	Epoxy	Hand lay-up	Investigation of mechanical and wear characteristics of the resultant hybrid composite	Mechanical properties increased with HHF loading with the maximum fiber loading of 6 wt.% reporting a tensile strength of 112MPa, Flexural strength of 99MPa and compressive strength of 94MPa.	(Prasad and Satapathy 2018)
Human hair/solid glass microspheres	Epoxy	Solution casting method	Thermal conductivity	Reported a decrease of 27% in thermal conductivity of epoxy by the incorporation of 10 wt.% of SGM and 20 wt.% of SHF	(Nanda and Satapathy 2020)
Glass/coconut coir/ human hair	Epoxy	Hand lay-up	Mechanical properties (Impact strength and tensile strength)	CCRP reported optimum tensile strength; HCGHRP reported comparable impact strength and CGHCRP reported a higher hardness value.	(Senthilnathan et al. 2014)
Human hair/copper	PMMA		Impact strength, Transverse strength and thermal conductivity properties	The incorporation of copper fiber increased the thermal conductivity properties. PMMA reinforced with HHF reported better impact strength than reinforced with copper fibers	(Jayaprakash et al. 2016)
Human hair/fly ash/ rice husk/marble dust (40/20/40-PE, Fillers & HHF)	Polyester (PE)	Hand lay-up	Mechanical Properties (Impact, Tensile, Flexural, strengths & Hardness)	The incorporation of HHF in PE reinforced with fly ash/rice husk/ marble dust fillers improved its mechanical properties. Fly ash/ HHF/PE composite reported high water absorption.	(Ali, Rohit, and Dixit 2023)

electrospinning process of the blend, thermal stability, and crystallinity, which the authors attributed to an increased molecular weight of the keratin fiber bio-composite. The resultant bio-composite was recommended for biomedical applications. The effect of hybridizing HH with natural fibers and synthetic fibers on the physical and mechanical properties of the resultant composites is summarized in Table 15.

Further, the effect of HH chemical treatment on the physical and mechanical properties of the resultant composite is summarized in Table 16.

Conclusions and future work

This review aims to summarize recent developments in utilizing waste HH as a reinforcement in polymer composites and the possibility of obtaining keratin nanohhparticles from HH and using it as a nano-filler in natural fiber-reinforced polymer composites. The review highlights

Table 16. Effect of chemical treatment on human hair fiber on the physical and mechanical properties of the resultant composite.

Composite	Fabrication method	Chemical treatment	Fibres	Effect of fiber treatment	Ref.
Human hair fiber-reinforced soy protein isolate composite	Compression molding	5% Alkaline treatment & Chitosan coating	Human Hair	SEM analysis indicated improved interfacial bond: Optimum tensile properties of 17.23 MPa. Chitosan-coated composite also reported better properties.	(Deepmala et al. 2018)
HHF-reinforced HDPE composite	Hot compression	alkali and acrylic acid treatment	Human Hair	Alkali-treated HHF reported a tensile strength of 15.638MPa while those treated with acrylic acid reported a tensile strength of 15.487MPa. There was an increase in water absorption after 0.25 NaOH treatment.	(Srivastava and Sinha 2018)
HHF-reinforced HDPE composites		Alkali treatment	Human Hair	Chemical treatment modified the HHF surface and therefore improved the hair-matrix interfacial bonding.	(Srivastava, Kumar, and Sinha 2018)
-	-	5% NaOH treatment	Human hair, *Caryota obtusa*, *Delonix regia*, *Sterculia foetida*	Untreated HHF reported high tensile strength (155–200 MPa) compared to the other fibers treated for 1 h reporting the highest strength of 214.9 MPa.	(Kathiresan and Meenakshisundaram 2022)

HH's mechanical strength and distinctive surface characteristics, making it a significant reinforcing phase in composite materials. Various composite systems, including HH/natural fiber composites, HH/synthetic fiber composites, and keratin-reinforced composites, have been investigated. These innovative materials demonstrate enhanced energy absorption capacity, mechanical, hardness, and thermal properties, making them promising choices for engineering applications. Efforts to improve the interfacial adhesion between HH and the matrix material through surface modification approaches have been successful. Additionally, methods for isolating and purifying keratin from HH have been developed, enabling its use as a reinforcement in composites.

In the future, incorporation of HH and keratin nanoparticles (KNP) into polymer composite materials holds promise for sustainable and cost-effective material development in the long run. It is worth saying that future research should focus on utilizing extracted KNP as a natural alternative to petroleum-based inorganic nanofillers in polymer composites to enhance their properties. Further, optimization of fabrication parameters is also crucial for tailoring HH/natural and HH/synthetic fiber hybrid composites for specific applications. Overall, the potential of HH and keratin nanoparticles in polymer composites presents exciting opportunities for advancing sustainable and high-performance materials.

Highlights

- Hybridization and chemical treatments of human hair and other natural fibers have been highlighted as possible ways of improving the physical and chemical properties of resultant composites.
- Incorporation of small quantities of nanofillers in composites is another critical way of enhancing the physical and mechanical properties.
- Keratin nanoparticles have been highlighted as potential nanofiller materials to be used in enhancing the properties of resultant natural fiber-reinforced composites.

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Authors' contributions

SMM performed the literature search and wrote the first draft of the manuscript. All authors revised and approved the final manuscript.

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