

Sustainable Eco Friendly Trends In Processing And Application Of Animal Based Wastes: A Review On Natural Fibre Or Particle

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Abstract: In this modern era, more emphasis are on sustainable and environmental friendly materials. This demand has made the current advancement in the technological world to requires innovative and sustainable ways of materials production. The need to ensure a sustainable green future is currently the driving force for ensuring the complete replacement of non-biodegradable materials with biodegradable ones. Hence, available natural resources are now receiving more attention in environmental friendly processing methods. Thus, the use of wastes from animals in composite fabrication is one of the salient means of achieving this feat. Therefore, this review presents the potentials of various animal-based natural fibre which are not often discussed elaborately in many articles unlike plant-based natural fibre, though widely used. Hence, the review revealed that different animal fibers from wool and feather have their unique properties despite having basically keratin protein structure in animals and birds as well as fibroin structure in silk while animal-based particles from shells and bones possess essential structures in form of calcium carbonate and glucopyranose. These constituents and structures were observed to be responsible for improved performance in bio-composite development. Thus the review present sources, types and processing routes for several applications such as biomedical, transportation, electronics, building and construction, packaging and textiles.

Keywords: bio composite, eco-friendly material, natural fibre, fibroin, keratin, protein, silk.

I. INTRODUCTION

About a decade ago, the United Nations decided that the world countries need to satisfy current needs without putting the future of the world in jeopardy [1]. The movement gained the support of world leaders to create an inclusive, sustainable, and resilient future for the world. Environmental protection is the third of the three main goals; others are social inclusion and economic growth. Environmental protection involves promoting a combined and sustainable management of natural resources and ecosystems [2]. This drive toward ensuring a sustainable future has created a path for the mass utilization of natural fibers [3]. Natural fibers are becoming the choice material for most industrial applications, especially in the aerospace [4], automobile, [5], and marine industries. Natural fibers are also bio compatible, which makes them vital bio composites for medical applications [6]. The recent attention directed toward utilizing natural fibers in natural fiber-

reinforced composites (NFRC) applications is due to their low density, high specific strength, availability, stiffness, eco-friendly, and biodegradability[5,]. Natural fibers are divided into three broad categories, which are plant, animal, and mineral fibers [7].

There has been a proliferation of research into the development of natural fiber-reinforced polymeric composites with the aim of replacing the more expensive synthetic fibers with the readily available natural fibers which are hitherto wastes and contribute to environmental pollution due to problems with disposal. The use of these fibers as reinforcements in both thermoplastic and thermoset polymers gives the benefits of solving disposal problems and cost-effectiveness. Prominent among the natural fibers are animal fibers, specifically the hairs of mammals which contain structural proteins notably keratin that form an intricate network of intermediate filaments in the cytoplasm of epithelial cells, which fundamentally provides structural maintenance for cells and tissues. This gives them the ability to withstand various chemical and thermal treatments and an appreciable variety of physical and mechanical stresses without sustaining permanent damage [8].

Animal fibers are the fibers gotten from different parts of animals as wastes or by-products. The fibers can be obtained from cows, pigs, sheep, goats (cashmere and mohair), alpacas, Llamas, mohair, merino, silkworms (silk), camel, chicken, rabbits, musk oxen, bison, yak, vicuna, human hair, guanaco, muskox (qiviut) and many more [9]. They can either be wool (animals), silk (silkworms), or feathers (birds). The mechanical properties of the wool produced differ between animals while the properties of silk and feathers are also dependent on the specie used [10]. Prior research on animal fibers has been focused on their utilization in the textile industry [11], but now animal fibers are getting attention as composites in the engineering field [12]. The need for sustainability necessitates the utilization of natural fibers as replacements for conventional fiber reinforcement. There are lot of research and attention on plant fibers with promising results which necessitates consideration for animal fibers. Composite materials reinforced with natural fibers are called “Eco-composites” or “bio-composites”.

Natural fiber reinforced composites (NFRC) can be classified into three main categories based on the matrix of the composite, which are ceramic matrix, polymer matrix, and metal matrix composites. Metal matrix composites are utilized in combustion and heat exchange applications. Ceramic matrix composites are used in construction areas where toughness is a vital parameter. Polymer matrix composite is the most utilized form of fiber reinforcement because it does not require excessive temperature and pressure conditions for production and has excellent strength and low density, which makes them appreciable for structural applications [13].

In general, animal fibers are utilized to develop reinforced hybrid fibers for marine applications [12]. Also, in the aerospace industry, it is utilized because of its lightweight, which improves fuel efficiency. Although synthetic fibers have been utilized in the past for this purpose, the drive for a sustainable future makes natural fibers a better alternative. The advances in natural fibers are making the geometric control of shape and size comparable with that of synthetic fibers. When natural fibers are incorporated into composites to form natural fiber-reinforced composites (NFRC), their advantages over synthetic composites include low cost, renew-ability, biodegradability, and recycling. NFRC has been utilized for aircraft frames and engine construction in the aerospace industry where the advantages in composite development produce beneficial properties and performance [4, 15]. While many review papers are available for plant based fibers/particles, these review paper is on animal based fibers/particulate reinforced composites on availability of enormous wastes from animals. Hence, this review highlighted the sources and types of animal based fibers/particles, constituents or compositions of the materials, extraction techniques, and areas of applications for animal fiber/particulate reinforced composites.

II. SOURCES OF ANIMAL-BASED REINFORCEMENTS

The characteristic nature of animals is solely dependent on their origin. Currently, animal fiber is the second most important source of natural fibers and can be in the form of wool, silk, or feathers. There are many sources of animal fibers classified under the three main categories.

- i. Sources of wool include sheep, goats, horses, camels, rabbits, llamas, alpacas, horses, etc.
- ii. Sources of silk include silk moths, spiders, bombyx mori larvae, etc.
- iii. Sources of feathers are the avian species.

Sheep fibers are keratin fibers with a semi-crystallized polymer structure with amino acids linked through peptide bonds [16]. In alpacas, the diameter is larger and stronger ones gotten from wool. The alpaca fiber is finer, loner, softer, and more lustrous [17]. Camels have two kinds of fiber which are the outer protective coat, which is coarse, and the second is an

under layer for insulation, which is soft [18]. Like camels, llamas also have protective layers which predominantly coarsen the fleece, and the quality of the fiber can be greatly degraded with uncontrolled breeding and harsh climatic conditions [19]. The Angora rabbit fiber is flexible, lustrous, and very light [20]. Silkworm silk has excellent toughness, extensibility, and strength [21]. Bird feathers are also an important animal fiber that can be used as composite reinforcements. The feathers contain complex keratin structures, and like other keratin structure, it contains glycine, proline, cysteine, and serine [22].

Another important animal fiber that needs more research attention is human hair. Human hair has been proven to have excellent physical and mechanical properties. The viscoelastic characteristics of human hair describe the tensile, dynamic, and torsional behavior [23]. The biodegradability of human hair is also very low, and burning cause air pollution, making recycling essential for human hair [24]. Human hair contains keratin which determines the resulting mechanical property. Although human hair is being used extensively in the building and construction sectors in ceramic matrix composites, its use as reinforcement in polymers is gaining more attention [25]. The geometric shape of animal fibers is elliptical, meaning there are major and minor diameters in the fiber's cross-section [9].

The natural reinforcements gotten from animals can be divided into fibers or particles. While animal fibers are subdivided into wool, silk, and feathers, animal particles are divided into shell particles and bone (endoskeleton and exoskeleton) particles [23]. Compared to plant fibers, animal fibers are non-seasonal, with unlimited utilization throughout the year. Although during the harvesting seasons, plant fibers are in abundance compared to animal fibers. The cost incurred during the preparation of animal fibers prevents large-scale utilization [22]. The main advantage of animal fiber is the bio compatibility of the fibers for biomedical applications and the ability to be used for sophisticated applications [26]. Composites reinforced with animal products have found applications in the field of bioengineering, especially in the production of implants, sutures, and biosensors [22].

Many researchers have investigated the potential of animal fibers as reinforcement in bio-composites [27, 28]. Although animal fibers are mainly utilized in the textile industries, the recovered wool keratin can be utilized as reinforcement in bio-composites. Also, there is an increase in keratin material from the wool textile industry, slaughterhouses, poultry farming, and hair salons which was estimated to be around 40 million tons annually. Waste disposal techniques such as landfill and burning are unfavorable according to the United Nations standards for ensuring a sustainable future [29]. Therefore, research on the utilization of animal fiber as green reinforcements has not been completely explored compared to its counterpart-plant fiber [23]. Therefore, using waste natural fibers for engineering applications is essential for the future of mankind. There is a need to consider the futuristic input of using animal fibers in the novel bioengineering field that deals with developing nano fiber tissue-engineering scaffolds that can help millions of people with organ failure or tissue loss [30]. Presently, Australia is the highest producer of sheep wool while China is the highest producer of cashmere wool, camel hair, and angora wool. Likewise, South Africa is the highest producer of mohair wool while Peru is the highest producer of alpaca fiber [31]. Animal fibers have been extensively utilized for medical applications, bio diesel production, adhesive modification, and bio-composite reinforcement.

CHARACTERIZATION OF KERATIN AND FIBROIN

Keratin: Animal fibers mainly contain keratin ("Kera" means horn in Greek) fibers found in wool, horns, and hair while fibroin fibers are found in silk. Keratin is the most abundant structural protein in epithelial cells and collagen which is a vital animal bio polymer [32]. Keratin is a fibrous-rich cysteine protein found in the cytoskeleton and epidermal appendages such as hairs, feathers, wool, and nails [33]. The chemical component of keratin depicts the mechanical properties of the fiber; for example, hard keratin structures have higher sulfur content (more than 3 %) than soft keratin [34]. Keratins can be subdivided into alpha and beta keratin [35]. Alpha-keratin is mainly contained in wools, hairs, hooves, nails, horns, and stratum corneum, while beta-keratin is mainly contained in feathers, bird claws, and beaks, in reptile claws and scales. A combination of alpha- and beta-keratin is found in the reptilian epidermis and pangolin scales [36]. Table I and Fig. 1. showed the differences between the structures of α - and β -keratin. Fig. 2. showed the structures and comparison of alpha and beta keratin. In Fig. 2c, at the microscale, the structure of alpha and beta keratin converged into a microfibril keratinocyte cell with a pancake structure [44, 53].

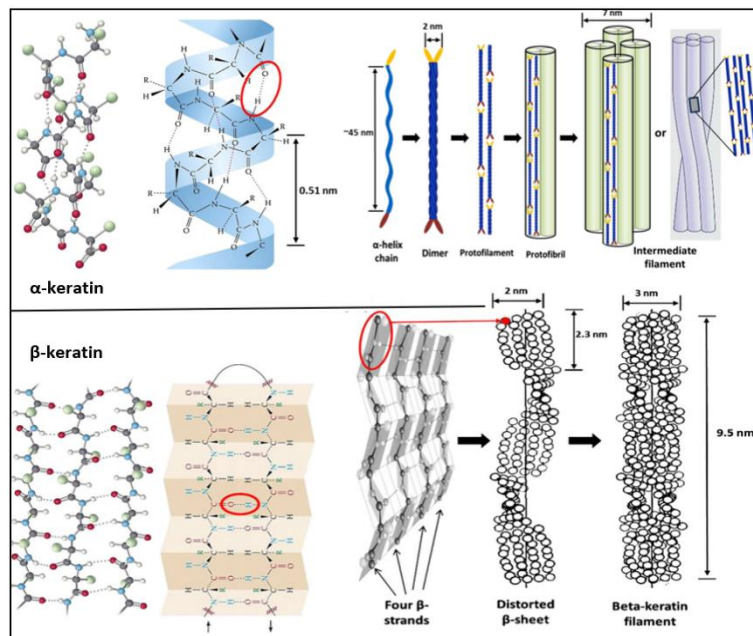


Fig. 1. The differences between the structures of α - and β -keratin [36].

Table I: The Differences Between α - And β -Keratin [36]

Criteria	α -Keratin	β -Keratin
Similarity: structural feature	Filament-matrix structure: IFs and beta-keratin filaments embedded in an amorphous matrix	IFs and beta-keratin filaments generate characteristic X-ray diffraction patterns
Diameters of the filaments (nm)	IFs: 7	Beta-keratin filaments: 3–4
X-ray diffraction patterns	Equatorial reflection with spacing 0.98 nm and a meridional reflection with spacing 0.515 nm	An axial repeat of 0.31 nm reflection and the equatorial reflection of 0.47 nm
Constituting proteins	The IFs consist of several kinds of low-sulfur proteins, while the matrix consists of high-sulfur and high-glycine-tyrosine proteins.	Do not have two different types of proteins; the filament and matrix are incorporated into one single protein.
Characteristic structure	Based on α -the helical structure	Based on β -pleated sheet structure
Molecular unit (MU)	Dimer	Distorted pleated sheet
Residue number of MU	Helical: 33–35; Non-helical: about 136	Pleated sheet forming: 34; Non-sheet forming: 59–168
Length of central MU	About 45 nm	2.3 nm
Diameter of MU	Around 2 nm	2 nm
Keratin assembly	Dimers organize into IFs; C-, N-terminal domains link with other molecules and matrix proteins, and these wind around IFs to form keratin	Pleated sheets arrange into IFs; C- and N-terminal domains compose the matrix, link with other molecules, and wind the central domain to form keratin
Solubility	Reduction: by potassium thioglycollate in urea to obtain 80–97% keratin from horn, hoof, and hair, and further by starch-gel electrophoresis into high-sulfur and low-sulfur fractions Oxidation: By treating wool with peracetic acid and dilute alkali Sulfitolysis: By sodium bisulfite with urea and an oxidizing agent	Alkaline thioglycollate: by sodium thioglycollate in the absence of oxygen at PH 11 to obtain 80–90% feather keratin. Combination of a disulfide bond-breaking reagent and a protein denaturant

Synthesis

At earlier stage, IFs (low-sulfur proteins) are synthesized; later as cells approach maturation, matrix proteins (high-sulfur content) are produced between the IFs and further synthesis takes place concurrently; finally, the proteins are insolubilized

There is no difference in the time course of synthesis of keratin proteins. The major keratins appear to increase in a coordinated fashion; the aggregation mechanism is poorly known

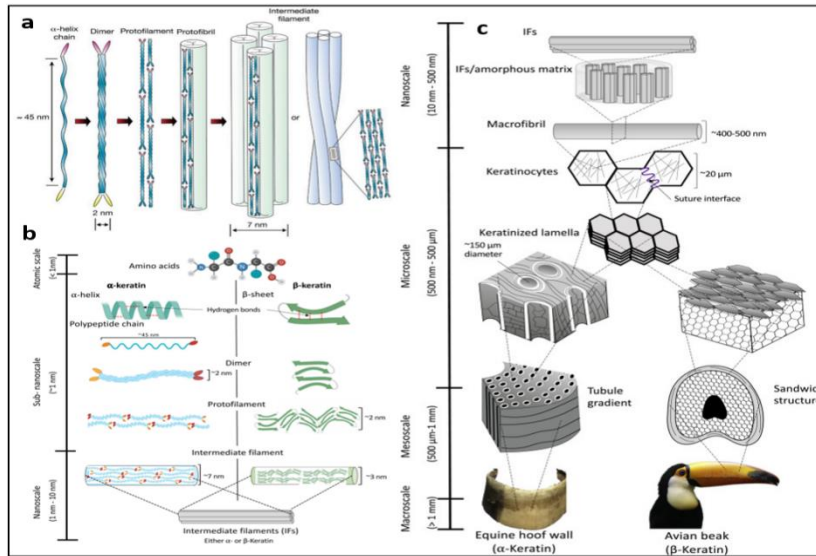


Fig. 2. The (a) structure of alpha-keratin, (b) comparison of the protein structures of alpha and beta keratin, and (c) comparison of the intermediate filament and convergence of alpha and beta keratin [33,37]

The chemical constituents, such as amino acid and sulfur content, structure, and hydration levels, influence the mechanical property of keratin. The amount of sulfur determines both the hardness and the amino acid determine the configuration of keratin, which can either be alpha, α -keratin, or β -keratin. Lazarus et al. [37] reviewed the investigation of keratins at different length scales and key mechanisms in operation at the corresponding scale. The result of their investigation is summarized in Table II. The type of bonds in keratin is described in Fig. 2c, while the stress-strain analysis of the mechanical behavior of keratin is shown in Fig. 3a, b, d, and e. Fig. 3a shows the idealized stress-strain curve for α -keratin showing the linear elastic, yield, and post-yield regions of the fibers, filaments, and matrix. The hydration-induced viscoelasticity for determining the properties of keratin was shown in Fig. 3b, while Fig. 3d and e represents the experimental stress-strain curves of avian feathers and claws and bio polymer strength, respectively. Table 4 represents the mechanical properties (young modulus and strength) of some keratinous systems.

Table II: Structural And Mechanism Of Keratin At Different Length Scales [37]

Length scale	Hierarchical structure	Key mechanism
Atomic scale	Amino acid ordering and hydrogen bonding	Hydrogen bonding forms at moderate temperatures and prompts the formation of alpha-helices
Sub-nanoscale	Alpha-helix and Beta-sheet	Alpha-helical turns permit large tensile strains and extensibility due to uncoiling.
Sub-nanoscale	Dimer	Increased stability and resistance to mechanical deformation
Sub-nanoscale	Protofilament	Increased resistance to interfilamentous shear
Sub-nanoscale	Intermediate filament	Increased extensibility, stiffening, and superplastic properties
Nanoscale	IFs embedded in an amorphous matrix	IFs provide rigidity while the amorphous matrix distributes the applied load
Nanoscale	Macrofibril	Increased rigidity and extensibility
Sub-microscale	Keratinocytes	Organization of macrofibrils by cell boundaries
Sub-microscale	Suture interface	Provides an interlocking interface between neighboring cells, enhances flexibility, and tailored stiffness.

Microscale	Keratinized lamella	Layered structure makes up the relative thickness of the material and distributes stress across the material. Allows for local flexibility and increases extensibility due to the sliding of the lamella.
Mesoscale	Dependent on material but can include tubules, sandwich structures, etc.	Dependent on the structure. Tubules provide compressibility and crack deflection. Sandwich structures are lightweight yet stiff.

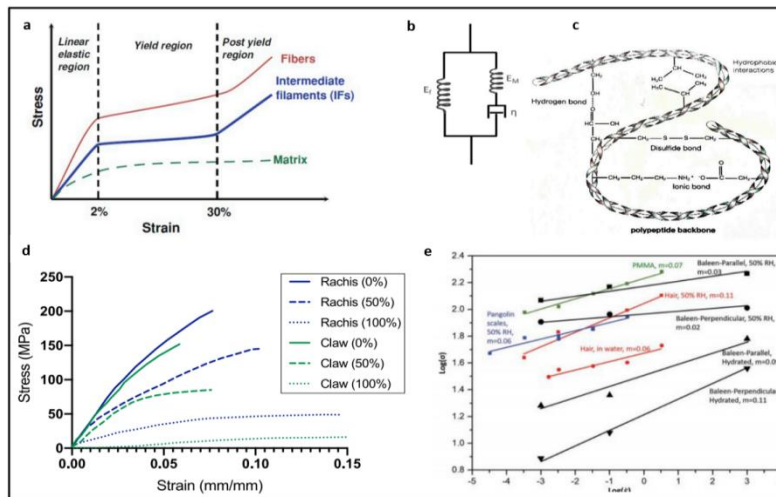


Fig. 3. The mechanical behavior of keratin and the structural bonds in keratin [37].

Table III: Mechanical Properties Of Some Keratinous Systems [6, 37].

Biological Material	Young Modulus (GPa)	Tensile Strength (MPa)
Wool	2.3 – 3.4	120 – 174
Camel hair	3.87	210 - 260
Catgut fiber	-	100
Quill	1.0 – 2.7	60 – 146
Horn	0.7 – 3.9	25 – 77
Hoof	0.4 – 14.6	9.18 – 38.9
Whale baleen	0.1 – 3.1	30.0 – 116
Hagfish slime threads	0.006	180
Feather	1.5 – 3.7	106.3 – 221.0
Beak	1.3	47.5
Claw	0.1 - 2.7	14.3 - 90.3
Pangolin scale	1.0	72.4
Fingernail	0.47 - 4.34	22.5 – 85.6
Hair	4.2	165-250
Gecko seta	2.1 - 3.7	237 - 262.5

Fibroin: Fibroin fiber is the main constituent of silk, whose main constituent is a natural polymeric protein. The macromolecular structure of silk is mostly found in the epithelial cells of silkworms [38]. The silk formation is from the secretion and spinning action of lepidopteran larvae such as moths and butterflies. The spinning action is from the salivary glands woven into protective tunnels, escape lines, and pupation cocoons containing elements such as cysteine and amino acids. Silk is termed a product of perfect evolution (over 250 million years) because of the ordered repetitive chains of silk proteins and highly conserved elements [39]. Another interesting silk is the trichopteran silk secreted by caddisfly, which is very similar to the Lepidoptera silk; the distinguishing feature is the presence of extra protein (P25 glycoprotein) and the slightly lower evolution period (150 million years). Both silks are naturally synthesized from pairs of labial glands and have two heavy fibroins and seven light fibroins [40].

Researchers have investigated the bio compatibility of silk fibers and discovered that fibroins devoid of their enclosure (serin) are bio compatible for both vivo and in-vitro biomedical applications [41]. Silk fibers are currently utilized in drug

delivery systems and tissue engineering. The increasing popularity of its utilization is because of easy processing, bio compatibility, regulated degradability, and versatility of application [42]. Fig. 4. shows the structural composition and mechanical properties of silk. The geometric diameter of silk is between 10 – 25 μm and is characterized by hydrophobic (forms the crystalline portion) and hydrophilic (non-crystalline portion) to form a semi-crystalline network with proportionate elasticity and toughness [38]. Generally, fibers can be made into reinforcements in the form of films, fibers, nets, meshes, membranes, yarns, sponges, hydrogels, and nanofibers, for making bio composites for tissue regeneration in bone, ligament, tendon, and cartilage replacement [43].

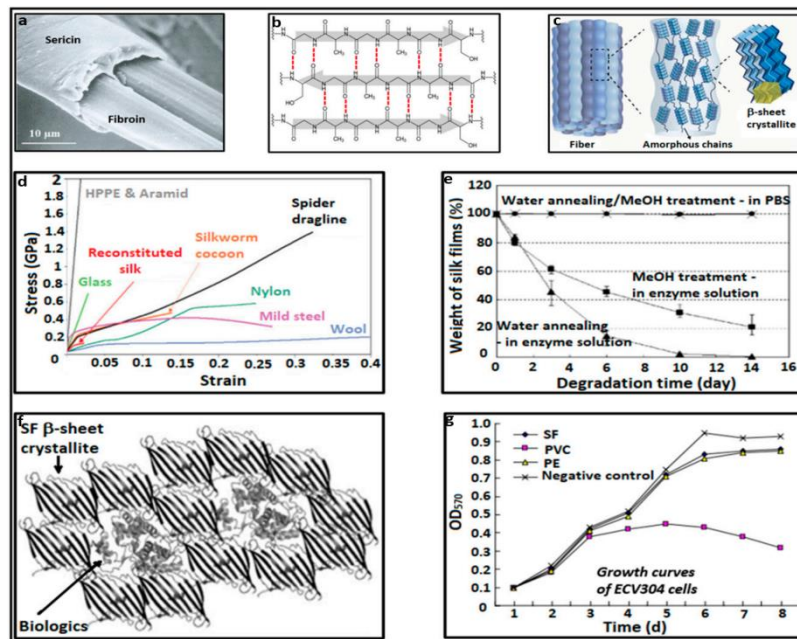


Fig. 4. The (a) protein structural composition, (b) amino acid sequence, (c) semi-crystalline network, (d) mechanical strength, (e) stabilization, and (f) bio compatibility of silk fibers [42].

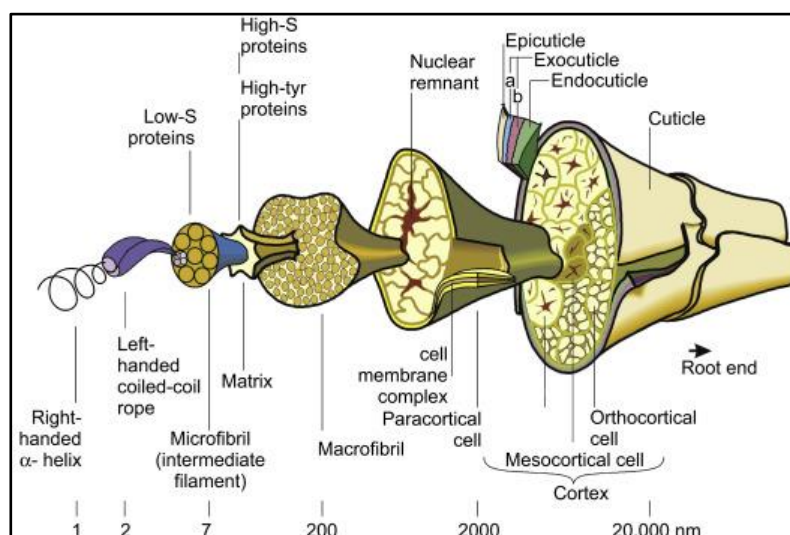


Fig. 5. The composition of wool fiber [45].

Human Hair Fiber: Another important natural animal fiber is human hair. The chemical structure of human hair is like other natural animal fibers whose main composition is α -keratin [46]. The coiling of two α -keratin makes an α -helix structure [47]. The constituents of keratin are amino acids such as cytosine, serine, glutamine, threonine, glycine, leucine, valine, and arginine [48]. The human hair shaft comprises the medulla, cortex, and cuticle [49]. The medulla is a non-crystalline region near the cortex center. The cortex contributes the highest mass of human hair and houses the keratin

proteins and structural lipids. The cuticle (dead cells) envelops and protects the cortex. The differences in hair structure are easily noticeable between genders and age gaps [50]. The genetic information present in human hair also has cultural significance with mechanical properties that offers protection.

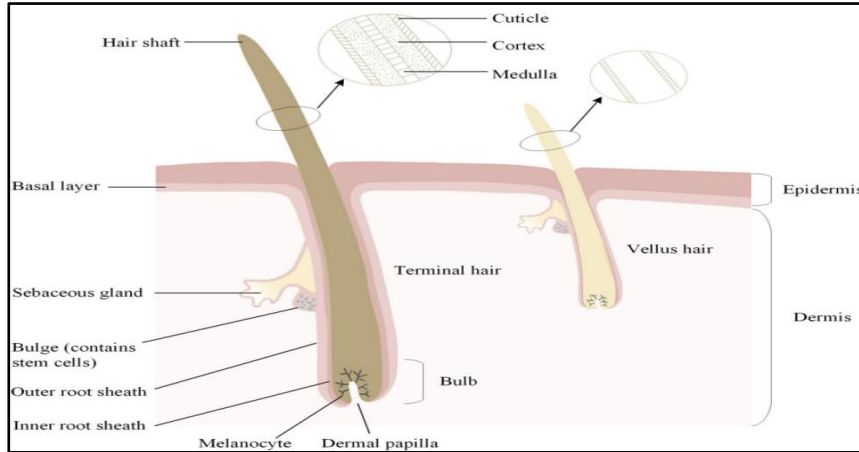


Fig. 6. The schematic of the human hair and skin [49].

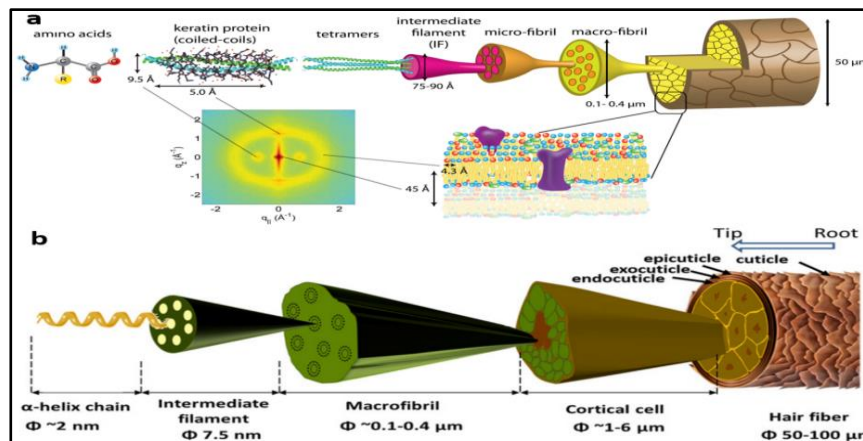


Fig. 7. The schematic representation of human hair [51].

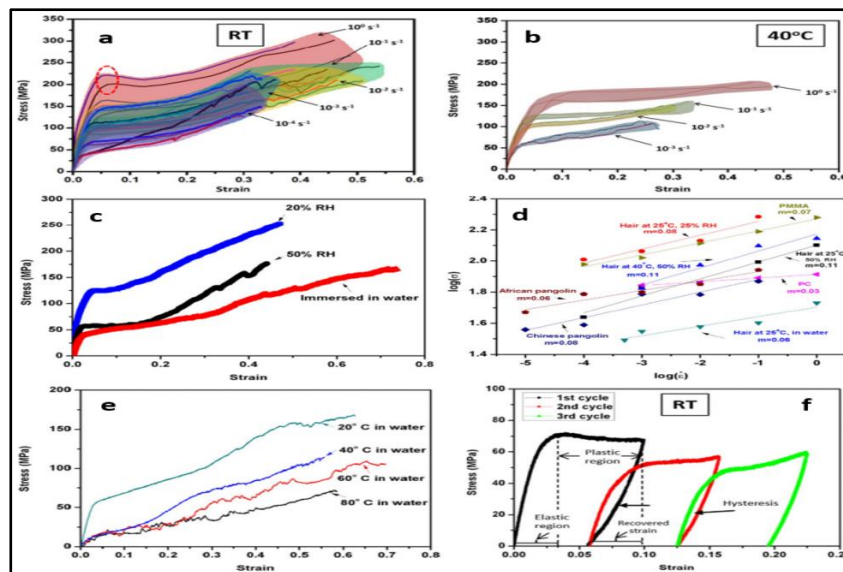


Fig. 8. The mechanical behavior of human hair at different temperatures, strain rates, and relative humidity [51]

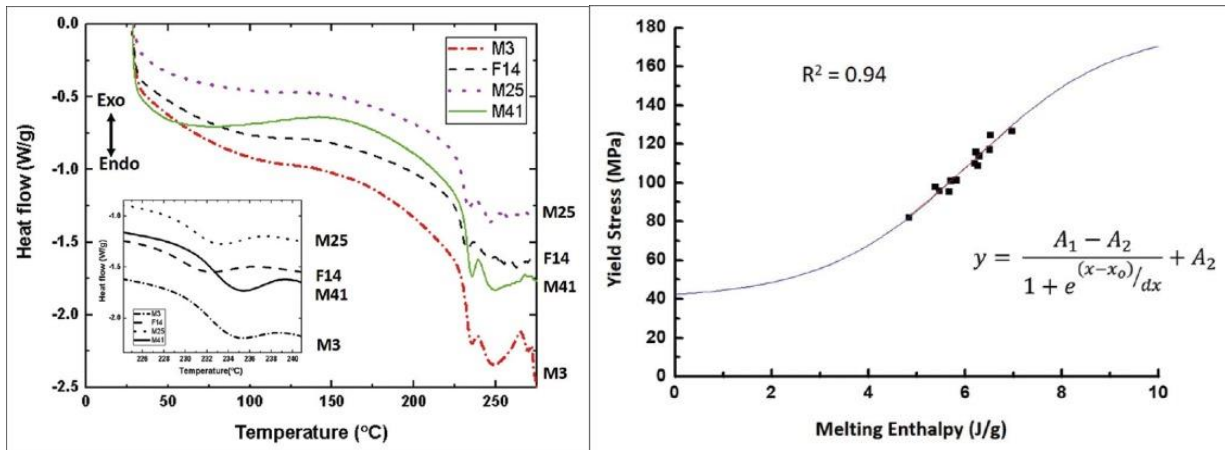


Fig. 9. The (a) thermal behavior and (b) correlation between the mechanical and thermal behavior of human hair [52]

Silk Fiber: Silk fibers are a vital subdivision of animal fibers. The main component of silk is a natural protein (fibroin) that has excellent mechanical properties with excellent biocompatibility, biodegradability, and bioresorbability [54]. The component of silk is fibroin and sericin. Sericin is the protective protein glue adhered to the fibroin, although sericin is of great importance to the insect (*Bombyx mori*) producing it, i.e., it creates the perfect conditions for complete metamorphosis (adhesive for fibroins) [55] it has demerits unfavorable for commercial utilization. Therefore, sericin is removed from fibroin by a process called degumming. Sericin has been degummed and discarded in the past to improve the aesthetics, texture, and color of the resultant fibroin, but currently, due to its biocompatibility, it is useful, especially for biomedical applications. The degumming process is done using boiling water (120 °C for 105 minutes) because of the composition of their amino acids. The schematic representation of the composition of silk fiber and the degumming process is in Figure 10. Other standard techniques such as autoclaving, short alkaline (Na₂CO₃) boiling, long alkaline (Na₂CO₃) boiling, and ultrasounds can also be utilized in degumming sericin from fibroin [56].

Sericin is a hydrophilic polymer in the family of glycoproteins with about 18 amino acids (Aspartic acid, Serine, Glutamic acid, Glycine, Histidine, Arginine, Threonine, Alanine, Proline, Cysteine, Tyrosine, Valine, Methionine, Lysine, Isoleucine, Leucine, Phenylalanine, and Tryptophan) which are responsible for properties such as cross-linking and copolymerization, antioxidant, moisturizing, antibacterial, antimicrobial, antitumor, and radiation resistance [55]. Silk consists of 75 % fibroin and 23 % sericin; the left percentage is made of fat, wax, and mineral salt [57].

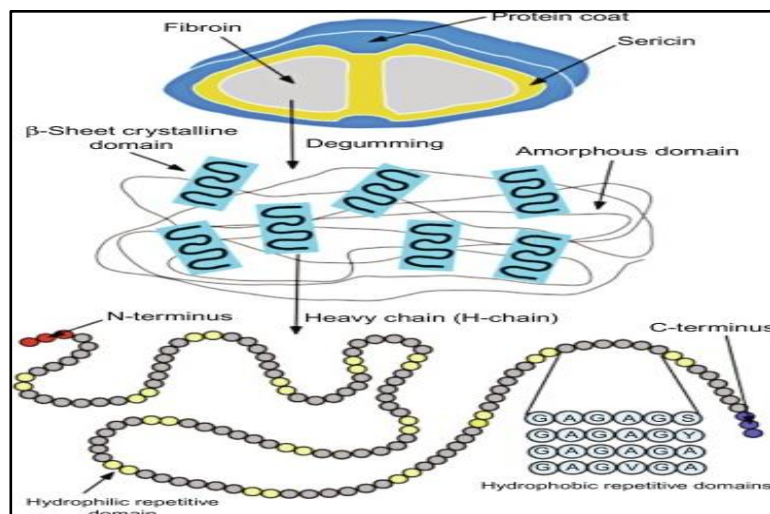


Fig. 10. The schematic representation of the composition of silk fiber and the degumming process [58]

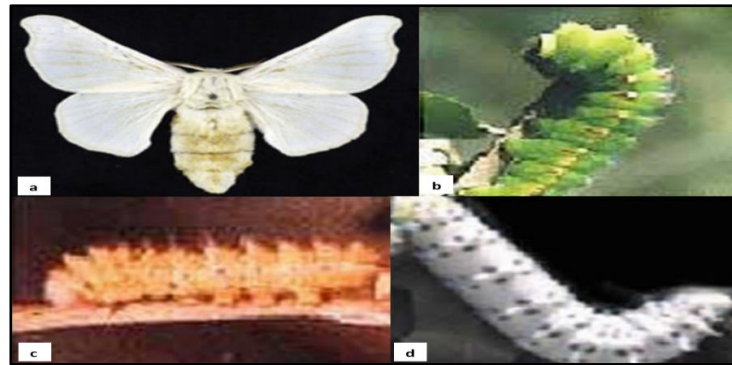


Fig. 11. (a) mulberry, (b) tasar, (c) muga, and (d) eri silk [57]

Table IV: The Properties Of Different Silk Fiber Types [57]

S/N	Properties	Mulberry	Tasar	Eri	Muga
1	Moisture regain % at standard atmosphere	11	8.44	11.18	10.9
2	Ash contents	0.5 – 0.9	2.75	1.62	2.06
3	Fatty matter %	2.3	1.8	-	0.08
4	Solvent	5% NaOH at the boil	12 N NaOH at the boil	12 N NaOH at the boil	12 N NaOH at the boil
5	Microscopical examination	Triangular cross-section with no well-defined striations	Wedge-shaped cross-section. Flat ribbon with convolutions	Flat rod-structured surface striations	Triangular cross-sectional surface striations
6	Natural color	White, yellow, or yellowish green	Brown	Brick red or creamy white	Light brown or golden
7	Tenacity (gm/Dn)	3.1 – 3.6	1.9	3.0	2.5 – 3.0
8	Elongation %	18	22 – 25	23 – 28	20 – 22

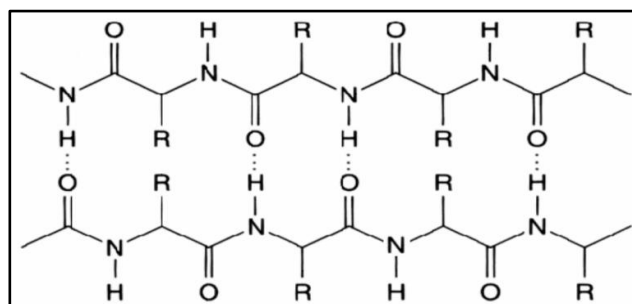


Fig. 12. The keratin structure of chicken fiber [59]

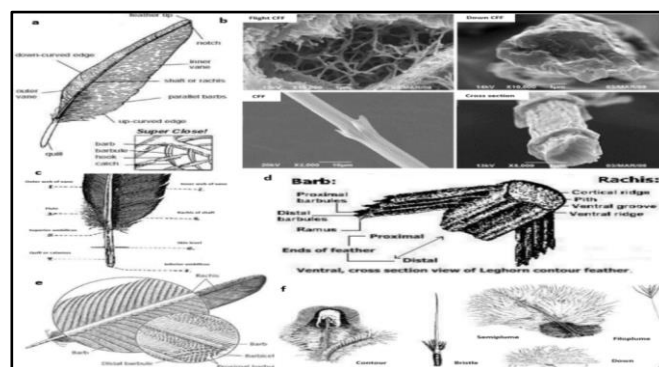


Fig. 13. The structure of a chicken feather [7]

TYPES OF ANIMAL BASED PARTICULATE FROM DIFFERENT SOURCES

Chitosan: Chitosan is derived from animals that possess exoskeletons, such as shrimps, crabs, and lobsters. Chitosan is a polysaccharide that can be utilized as a bio composite either as the matrix or the reinforcement [60]. It can be utilized as a graft material for biomedical applications owing to its strength, porosity, water retention, protein absorption capabilities, biodegradability, and bio mineral [61]. Other properties include anti-bacterial, cell adhesion, proliferation, and osteoblast differentiation [62]. Chitosan is a main constituent in the exoskeleton shell of crustaceans. Chitosan is a linear polysaccharide (sugar) that can serve as both reinforcement and as a matrix. Chitosan is the deacetylated derivative of chitin, containing differing amounts of N-acetyl-2 amino-2-deoxy-D-glucopyranose (glucosamine, GlcN – acetylated unit) and 2-amino-2-deoxy-D-glucopyranose (N-acetyl-glucosamine, GlcNAc - deacetylated unit) residues, with the repeating units linked by glycosidic bonds [64]. The sources of chitosan are sea animals, insects, and microorganisms [65]. The main chitosan producers are shown in Table V.

Table V: The Main Chitosan Producers [66]

Sea animals	Insects	Microorganisms
Crustaceans	Scorpions	Green algae
Coelenterata	Brachiopods	Yeast (β -Type)
Annelida	Cockroaches	Fungi (cell walls)
Mollusca	Spiders	Mycelia penicillium
Lobster	Beetles	Brown algae
Shrimp	Ants	Chytridiaceae
Prawn		Ascomydes
Krill		Blastocladiaceae
Crab		Spores

Eggshells: Eggshells are animal products that birds, reptiles, and fishes produce (oviparous animals) [67]. The oviparous animals consist of animals such as chickens, ducks, geese, turkeys, peacocks, flamingos, ostriches, alligators, snakes, swans, echidnae, etc. [68]. Eggshells provide the embryo with a protective layer against pathogens and give the embryo the necessary nutrient for development [99]. The eggshell is a bio-ceramic material whose structure is columnar calcium carbonate ($CaCO_3$) and organic proteinaceous matrix [67]. This structure protects the embryo from mechanical impact, regulates fluid exchange through the pores, and prevents microbial invasion [69]. The quality of an eggshell can be determined by its breaking strength, deformation, uniformity in thickness, and dynamic stiffness of the eggshell [70]. Elevated temperature conditions have adverse effects on the properties of eggshells [71]. The calcium carbonate in eggshells is about 95 % and about 3.5 % protein organic matrix. The component of the eggshell is a multi laminate resilient structure of membranes, mammillary cone layer, palisade, and cuticle [72].

Eggshells have a cellulosic structure with their constituents as bio sorbent amino acids. The chemical constituents of eggshells include CaO , SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , SO_3 , K_2O , and Na_2O . The physical properties of eggshells include about 1.2 % water content, a density of about 0.9 g/cm^3 , and a surface area of about $18.5\text{ m}^2/\text{g}$ [73].

The composition of the eggshell powder is shown in Table VI. Other sources of particulate animal reinforcements are snail shells, goat bone, cow bone, and other mammals that are readily available [74].

Table VI: The Composition Of Eggshell Powder [76].

	White eggshell powder	Brown eggshell powder
Moisture (%)	0.46	0.20
Protein (%)	3.92	5.04
Ash (%)	94.61	94.28
Fat (%)	0.35	0.08
Calcium (%)	34.12	33.13
Magnesium (%)	0.29	0.36
Phosphorous (%)	0.04	0.07
Potassium (%)	0.03	0.04
Sodium (%)	0.05	0.04
Copper (ppm)	<1ppm	<1ppm
Iron (ppm)	22ppm	<1ppm
Manganese (ppm)	<1ppm	<1ppm
Zinc (ppm)	<1 ppm	<1ppm

PREPARATION OF ANIMAL FIBERS/PARTICLES

Fiber Preparation: Carbon fibers can be produced from animal fiber by carbonization at elevated temperatures for silk fibers since they contain β -keratin. The structure of β -keratin can change at elevated temperatures (1000°C) into a heat-resistant multi-hexagonal structure [93]. Carbon fibers produced through this technique are found to be electro-conductive with excellent mechanical properties. Another technique to produce carbon fiber by Li et al [78] is through pyrolysis of chicken feathers by sterilizing the chicken feathers, followed by pyrolysis, and milling. Carbon fiber can also be gotten from chicken collagen by wet-spinning of collagen materials to form a triple α -helix structure, followed by carbonization to produce carbon fibers [79]. The tensile and yield properties of derived carbon fibers from animal extracts can be improved by improving the cross-linking properties of the fiber at elevated temperatures (800°C) under a nitrogen atmosphere. Cross-linking agents can be used to alter the type of bonds desired in the carbon fiber; the agents include succinic acid, sebacic acid, disulfonic acid, dialdehyde, and dianhydrides [80].

The chicken feathers can be prepared by pyrolysis under a nitrogen atmosphere at elevated temperatures of about 215 °C for up to ten hours, although holding time highly depends on how fiber retainage is required. The SEM images of untreated and treated chicken fibers are shown in Figure 14.

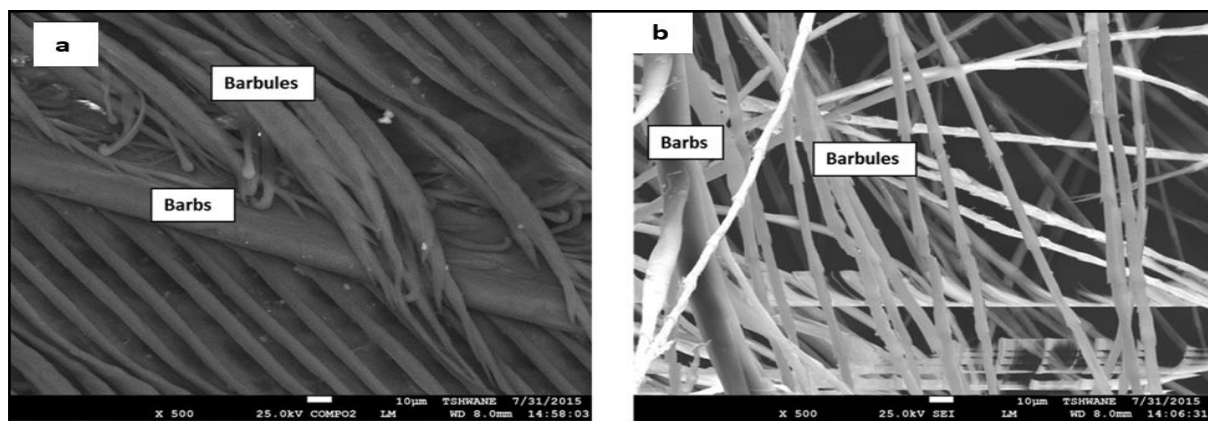


Fig. 14. The SEM shows the difference between the (a) untreated and (b) treated chicken fibers [81]

Other techniques for the preparation and modification of animal fibers before incorporating them into polymer, metal, or ceramic matrix are either physical modification or chemical modification. The physical modification includes using techniques such as corona, plasma, ultraviolet, fiber beating, and heat treatment to change and improve the surface morphology of the fiber. This enhances the wettability, compatibility, and mechanical interlocking strength of the fiber to the matrix [82].

Chemical modification on fibers reduces the low level of adhesion between the fiber and the matrix caused by the inherent hydrophobicity of both materials. Chemical modification techniques include treating the fibers with different classes of chemicals, such as alkaline, silane, sodium chlorite. The alkaline treatment means washing the fibers in alkaline solutions such as sodium hydroxide (NaOH) [83, 84].

Particulate Preparation: Eggshells particles are prepared by drying the shells and grinding them into powder in a milling machine at about 250 rpm and sieved to get the appropriate size, mostly about 40 - 100 μ m, after which the powder is treated with sodium hypo chloride (NaOCl) for deproteinization, which is visible and easily detected by physical observation. Thereafter the removed layer will be decanted out, and the remnant will be washed in a mixture of ethanol and isophthalic acid for one hour. The precipitate is then oven-dried, which forms the animal particle that can be utilized as reinforcements for bio composites [86]. Also, eggshells can be processed to obtain carbonized eggshell particles. This can be done by chipping the shells and filling them into a graphite crucible and heated to a temperature of about 900 °C. After this, the carbonized eggshells are ground and sieved to obtain the needed reinforcement. Carbonization of the eggshells burns off all the impurities [87] and provides better tribo-mechanical properties than uncarbonized eggshells [88]. The preparation route for eggshells and chitosan particles are shown in Figure 15 and Figure 16, respectively.

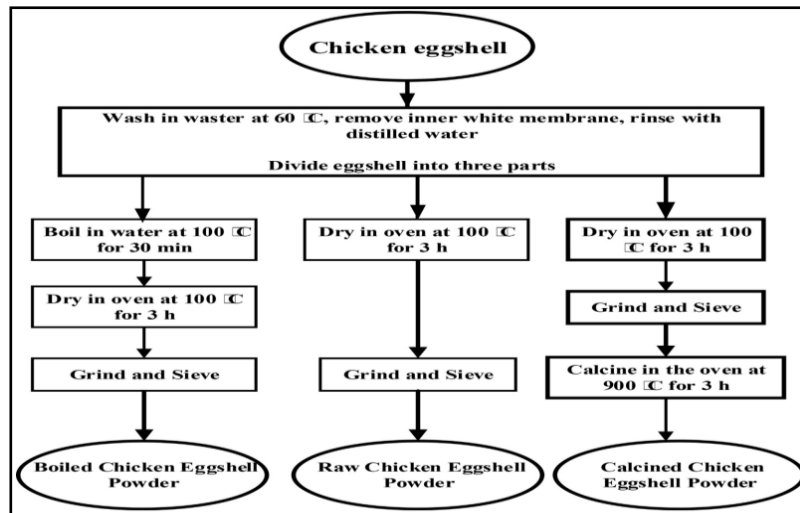


Fig. 15. The processing routes for eggshell particles [89].

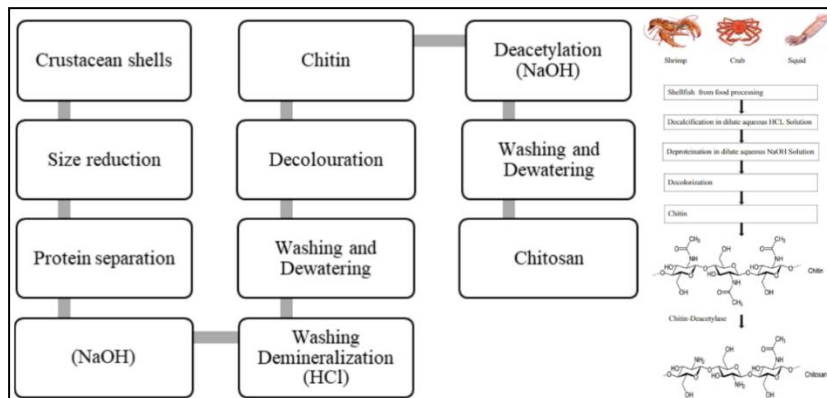


Fig. 16. The processing routes for chitosan [73, 90].

DEVELOPMENT OF ANIMAL REINFORCED BIO-COMPOSITES

There are different techniques for preparing bio-composites. The preparation technique depends on the matrix, which can be a metal, a polymer, or a ceramic. The matrix phase is the environment that holds the reinforcing materials together. The properties of the matrix include environmental tolerance, surface appearance, stability, resilience, and durability [31]. The matrix must also be capable of transferring tensile forces from the surface uniformly to the reinforcing phase to develop resistance toward crack nucleation and propagation within the bio composites. Utilizing animal fibers can be tricky in producing metal matrix composites, which is due to the elevated temperatures of molten metals. This might result in the degradation of the fiber.

Metal Matrix Bio-composites: Researchers like Bedmar et al. [91] have utilized carbon fiber in Aluminum Matrix Composites under high-pressure Die Casting without any form of degradation in the carbon fiber, but grain refinement was noticed in areas surrounding the carbon fiber. Similarly, Shirvanimoghaddam et al. [92] review the utilization of carbon fibers in aluminum, titanium, magnesium, copper, bronze, nickel, tin-lead, and zinc matrix composites. Carbon fibers can be produced from animal fibers, but due to the difficulty in making carbon fibers on a large scale from animal fibers, there is only a few literature that have considered making animal-based carbon fiber. Also, Chaithanyasi and Umasankar [93] used eggshell particles as reinforcement in an Aluminum matrix using the powder metallurgy technique, with a good distribution of the particles within the matrix. The results showed that the hardness of the bio composite increased. Bose et al. [94] similarly proved that eggshell-reinforced aluminum matrix bio composite produced by stir cast has improved mechanical properties such as tensile strength, hardness, and fatigue strength but decreased corrosion rate, fracture toughness, and ductility. Post-casting heat treatment will induce appreciable corrosion resistance in the metal matrix bio composites.

Ceramics Matrix Bio-composites: Using animal fiber in ceramics is not novel; horsehair has been utilized since the early 20th century to produce mud bricks. The presence of animal fibers greatly improves the mechanical behavior of concretes depending on the percentage and level of adhesion. The reasons behind using animal fibers in concrete are to reduce the plastic and drying shrinkage, improve permeability, and improve shatter resistance, impact, and abrasion strength. Human hair was utilized as reinforcement for ceramic bio-composite by Kumar et al. [95] and Verma and Singh [96]. According to them, the presence of fiber reinforcement in the concrete improves the structural integrity of the concrete. The α -keratin structure in human hair gives flexibility, resistance to stretching, elasticity, hydrophilicity, and mechanical resistance. The properties of the hair utilized in the experiment are 100 to 120 μ m diameter, 60 mm hair length, 500 to 600 aspect ratio, a tensile strength of 380 MPa, and an ultimate tensile strain of 0.5. The addition of human hair increased the flexural, compressive, and tensile strength of the concrete. Similarly, Akbar et al [97] studied the effect of human hair fibers on concrete; the hair improves the ductility of the concrete by reducing the macro-cracks and improving the flexural, compression, and split tensile strengths.

Polymer Matrix Bio-composites: Polymer matrix bio composites are more researched than ceramic and metallic matrix bio composites. The matrix, commonly called resins, are petrochemical based, which are sourced mainly from petroleum. The resins can be classified into two groups. One, fully degradable and partly degradable, and two, thermoplastics and thermosets [31]. The subdivisions of the first classification are shown in Fig. 17, Table VII, shows the advantages and disadvantages of thermoset, thermoplastic, and bio-based resins. Rahman et al. [98] prepared the human hair to be utilized in polymer matrix bio composite by hand stretching and soaking in NaOH for two hours, washed, and dried. The human hair was determined to be greasy compared to other animal fibers, which was attributed to the hair care lubricants used by many people. Similarly, Oladele and Agbeboh [99] used the same technique in treating cow hair to develop a mathematical model for polymer bio composite. The result from the studies shows that the untreated fiber-reinforced composites have better mechanical properties compared to the treated fibers. Nanda and Satapathy [48] also collected human hair and washed it using detergent, cut it into pieces of about 4 mm long, and dried it in sunlight before using it as reinforcement for polymer bio composites by hand lay-up technique.

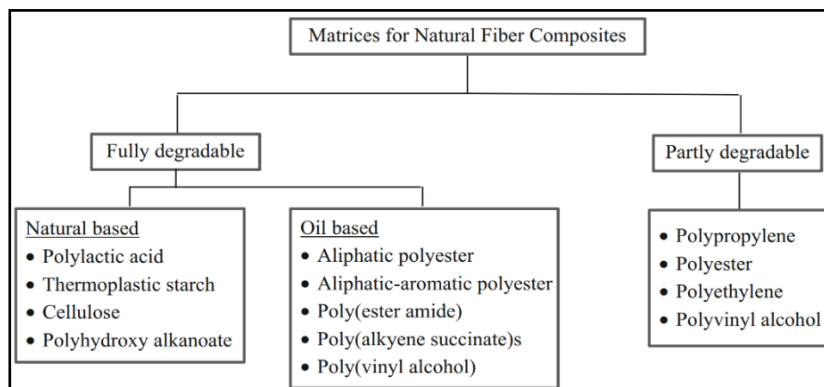


Fig. 17. The subdivisions of polymer matrix for bio-composites [31].

Table VII: The Types, Advantages, And Disadvantages Of Resins [31].

Resin	Advantage	Disadvantage
Thermoplastic resins		
Polyethylene	High ductility and impact strength; Good fatigue resistance; Lightweight; Low moisture absorption; Low cost	Poor weathering resistance; Flammable; High thermal expansion
Polypropylene	High-temperature resistance; High dielectric resistance; Excellent chemical resistance; Good fatigue resistance	Difficult to process; Comparatively expensive; Limited availability
Polystyrene	Good chemical resistance; Resistance to stress cracking; Very low moisture absorption; Weather resistance	Flammable; Low impact resistance; Brittle

Polyvinyl chloride	High impact resistance; Versatility; Good chemical resistance; Flame retardant; Low cost; Good dimensional stability.	Poor resistance to UV; Poor resistance at low and high temperatures
Thermoset resins		
Epoxy	High thermal and mechanical properties; High water resistance; Low curing shrinkage; Long working times ability	More expensive than vinyl ester; Corrosive amine hardener; Difficult to process
Polyester	Easy to use; Lowest cost	High curing shrinkage; Limited range of working times; Moderate mechanical properties; High styrene emissions in open molds
Vinyl ester	Very high chemical and environmental resistance; Higher mechanical properties than polyester	High curing shrinkage; More expensive than polyester; High styrene content; Requires post-curing for good properties
Phenolic	High fire resistance	Difficult to process
Bio-based resins		
Starch	Fully biodegradable; Low cost	Brittle; Difficult to process; Water-sensitive
Polylactic Acid (PLA)	High modulus and strength; Nontoxic; Relatively low cost	Brittle; Relatively poor impact strength; Low thermal degradation temperature
Polyhydroxyalkanoates (PHA)	High molecular weight; Fully biodegradable	Low stability; Brittle; Low deformability; More expensive than other bio-based polymers
Cellulose	Abundant; Relative low cost; Ease to modify; Moderate impact resistance; Moderate heat resistance	High moisture absorbance; Relatively low decomposition temperature

Suaranto et al. [29] washed raw wool fibers with equimolar solutions of acetone and methanol for six hours, then transferred them into the water for cleansing before drying at room temperature. Then keratin was extracted from the wool by immersing the wool into reagents such as reduction agents β -mercaptoethanol, dithiothreitol, thioglycolic acid, sodium metabisulfite, and Tris(2-carboxyethyl) phosphine at 60 °C for four hours. This is then filtered, and the extracted keratin is dialyzed using distilled water for two days before centrifuging at 9000 rpm for 20 minutes at 4 °C. The bio composite was prepared by adding PVC powder to the extracted keratin in a ratio of 3:1 using an electrospinning technique. Rakesh [57] complied with a silk fiber-reinforced polymer composite shown in Table VIII. Similarly, Asha and Chandra [86] showed that the addition of eggshell particles into polyamide/nylon black matrix significantly improves the mechanical properties such as the flexural, tensile, and impact strengths of the composites. The composite made from nylon black showed better mechanical behavior compared to the one from polyamide.

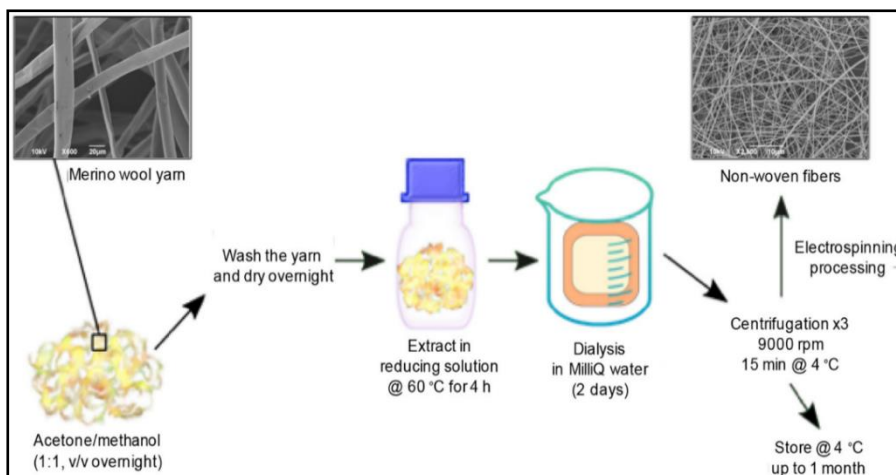


Fig. 18. The extraction and bio composite production process [37].

Table VIII: Silk Fiber-Reinforced Polymer Composite With Varying Percentage [57].

Composites	Tensile Modulus (GPa)	Tensile Strength (MPa)	Flexural Modulus (GPa)	Flexural Strength (MPa)	Remarks
Silk/PLA	2.54 - 4.08	62.08 - 70.6	4.6	97.41	5 wt%, long fiber
Silk/gelatin	0.65	44.5	3.7	63	20 wt%, long fiber
Silk/PP	1.8262	54.7	3.5707	58.3	20 wt%, long fiber
Silk/HDPE	0.4184	31.1	-	-	6 wt%, chopped fiber
Silk/PBS	1.6 - 2.3	42 - 50	3.9 - 6.5	119 - 155	30 - 50 wt%, chopped fiber
Silk/PCR	-	11.45	-	-	20 wt%, chopped fiber
Silk/PP	0.4546	38.9	-	-	6 wt%, chopped fiber
Silk/PC	0.6968 - 2.3	36.7 - 50	5.1 - 6.5	150 - 155	3 - 50 wt%, chopped fiber
Silk/epoxy	0.844 - 6.5	58.35 - 111	1.503 - 6.4	60.81 - 250	25 wt%, fabric to 45.2 vol%, plain woven fabric
Silk/epoxy	1.478 - 1.949	31.49 - 48.74	1.98 - 1.119	43.66 - 188.07	5 - 20 wt%, short fiber
Silk/epoxy	-	41.1	-	53	10 wt%, long fiber
Silk/EPCNSL	1.067	69.98	1.92	71.21	25 wt%, fabric
Silk/PBS	0.72 - 1.03	40.6 - 82.6	0.59 - 0.87	33.09 - 65.19	30 - 75 wt%, fabric
Silk/wheat protein	1.089 - 1.605	18.8 - 28.4	-	-	1.5 - 5 wt%, short fiber

III. CONCLUSION

This review presented the relevance of animal based fibers and particles in the modern days demand for sustainable and green materials for several applications. Due to the high demand for green materials in numerous areas of human needs, animal based materials have been highly utilized. The materials were discovered to be readily available from different sources due to their non-seasonality unlike plant. It was learned from the review that, there has been less consumption of wastes from animal resources compared to plant based materials, hence, the need for more research in this regards. The need to clean our environments, and made them void of environmental pollution has contributed immensely to the necessity to look for alternative means of handling most commonly generated wastes in our environments, hence, further research should be done on bioengineering composites, like the natural fiber reinforced composites (NFRC), classified to categories based on ceramic matrix (utilized in construction areas for toughness and vital parameter), polymer matrix (utilized in fiber reinforcement because it does not require much temperature and pressure for production, having good strength and reduced density in its application), and the metal matrix composites (utilized in combustion and heat exchange applications). Also, Hybrid composite materials can be developed by incorporating various reinforcement of fiber, whether they are Natural or synthetic. The natural fibers bonded together with synthetic material, exhibit increased mechanical properties which are environment friendly and of low cost. Therefore, application of natural fibers as a substitute for chemical fibers draws great interest due to its less weight, lower raw material price, and ecological benefits of using green resources which are biodegradable and renewable. Though, most of these animal waste resources need to be treated either by physical or chemical techniques to improve their quality and adhesion to matrix, which are still cost effective and environmental friendly. Based on high biological potentials, they are mostly used for biomedical applications because animal wastes from meat sources are richer in protein which is human friendly. It is expected that in the future, more of animal based resources that are yet to be discovered will be applicable in most advanced materials applications such as in bioengineering and technology.

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