Animal based bio-reinforcements for sustainable green composites advancement: a review on reinforcement classifications, processing and characterization of their bio-composites

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Abstract

Purpose – Wastes from plants and animals have a lot of potential and usefulness in technological development and most researchers have documented their findings on plant-based materials while animal-based materials have received less attention. Hence, this study aims to provide adequate information on existing animal-based bio-reinforcement classifications, their manufacturing and characterization processes, as well and their composites. This becomes necessary since a good understanding of these itemized areas of

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animal-based bio-reinforcements will advance the production and availability of animal waste materials thereby boosting the innovative creation of green materials from such wastes.

Design/methodology/approach – This study used a qualitative and quantitative methodical approach to find and analyze pertinent publications from databases including PubMed, Scopus, Web of Science and Google Scholar. The inclusion criteria of the study were specifically designed to consider studies that investigate the use of animal-based materials in the creation of environmentally friendly composites. The time frame for the articles included in the study ranged from 1990 to 2023. After a thorough evaluation of titles, abstracts and full-text papers, the authors collected relevant information on various types of animal-based bio-reinforcements, processes used for composite production, mechanical properties, environmental impact assessments and applications.

Findings – This review revealed the verse potentials and areas of applications for animal-based bio-reinforcement materials that are yet to be properly harnessed and the need for researchers to focus more on animal wastes. Animal wastes have been discovered to be a source of sustainable materials due to the increasing demand and production of animals for human consumption. Animal wastes are resources that cannot go into extinction due to the ease of animal production. Hence, these readily available and cheap resources are to be used to meet the growing human demands and as well as mitigate environmental problems associated with established synthetic materials. Another benefit of animal-based bio-reinforcement materials, as revealed in this review, is that they are biodegradable materials that will not pose any danger to the environment during and after use, which makes them the best materials for biomedical applications. Therefore, animal-based reinforcements can be recommended as the most suitable source of materials for human consumption due to their high similarity with human body constituents.

Research limitations/implications – The major limitation of this research was due to inadequate literature on its applications; hence, this review seeks to advance the potential and open a new vista for this application.

Originality/value – This manuscript, titled “Animal Based Bio-reinforcements for Sustainable Green Composites Advancement,” provides a unique synthesis and analysis of current research, investigating the use of animal-based bio-reinforcements in the creation of environmentally friendly composites. Through the critical analysis of existing data, and also provides a thorough and inclusive summary that emphasizes emerging patterns, identifies areas where information is lacking, and suggests prospective directions for further investigation and advancement in this rapidly developing area of study. This work not only gathers dispersed information but also provides new perspectives, therefore promoting comprehension and encouraging discussion in the field of sustainable materials science and engineering.

Keywords Bio-reinforcement, Animal waste, Green materials, Sustainability, Biocompatibility, Lightweight

Paper type Literature review

1. Introduction

The recent shift of attention toward using natural materials for the synthesis and fabrication of advanced materials has led to several areas of research and development where such materials are being used as matrix and reinforcements in composite development. As a result of the increasing demand for environmentally friendly materials and the desire to reduce the cost of artificial reinforcement materials, novel bio-derived reinforcement materials for the fabrication of composites are now being developed (Oladele *et al.*, 2020a, 2020b). Researchers have begun to focus attention on natural and bio-reinforced composites as bio-composites, which can be from either natural or synthetic resins that are reinforced with natural fibers/particles (Olajide *et al.*, 2019). Natural materials are broadly divided into three categories based on their sources, which are plant, mineral and animal (Khatib *et al.*, 2022; Amin *et al.*, 2022; Ramamoorthy *et al.*, 2015). Currently, all these natural resources are receiving more attention from researchers due to the need to protect the environment from various pollutions emanating from synthetic materials. While there are several reports on the use of plants as reinforcement/matrix materials for composites developments, there are limited reports on the use of animal wastes in these regard relatively. Therefore, there is a need to reveal the available promises of animal wastes for composites developments. The enormous potential in animal wastes as reinforcements in composite development is yet to be harnessed optimally, going by their availability and applications in recent times.

The population of all livestock, including poultry and the various bovine, caprine, ovine and swine species, is estimated to be 4.89 billion (Agbeboh *et al.*, 2019). Globally, there are a lot of livestock and poultry, which generate a lot of waste that ends up in the environment and amounts to a few million metric tons without any scientific intervention, causing socioeconomic and environmental problems (Agbeboh *et al.*, 2019). To effectively use these potential waste deposits, suitable waste management procedures are necessary, in which the conversion of these wastes to reinforcement materials is one of them (Mann *et al.*, 2023; Antor *et al.*, 2025). Animal-derived wastes comprise carcass waste/offals, hoofs, skin, tissues and body parts like feathers and hairs. With improvements in animal production techniques, it is now possible to recover these wastes, which will further significantly reduce pollution (Oladele *et al.*, 2018a, 2018b). However, the creation of composite materials reinforced with animal-based wastes may open the door to a more effective technique for handling waste originating from animals, leading to the development of cutting-edge biomedical, pharmaceutical, structural, manufacturing and nanotechnology applications (Oladele *et al.*, 2023). Composting, vermicomposting, the creation of biogas and the creation of value-added products are all conventional ways of waste management that have been thoroughly studied. However, these conventional methods are not yet effective for achieving a circular economy (Reshmy *et al.*, 2021; Sharma *et al.*, 2020). So far, healthful use of these animal wastes has, however, remained the subject of very few studies. Researchers from all over the world are in the quest for fresh, cutting-edge and environmentally responsible methods for the effective management of these animal wastes that will promote the circular economy as well as enhance technological development (Oladele *et al.*, 2022a; Oladele *et al.*, 2022b). Some of the most significant components made from animal-based wastes include hydroxyapatite, calcium phosphate, sponge, hyaluronic acid, keratin, spicules, chitosan and collagen (Zamri *et al.*, 2021; Li *et al.*, 2016; Agbabiaka *et al.*, 2020; Daramola *et al.*, 2021; Adeyanju *et al.*, 2017; Olajide *et al.*, 2017; Oladele and Adewole, 2015; Oladele *et al.*, 2023). Additionally, animal waste management techniques for bio-reinforcement development are more dependable because they recycle different animal waste components into useful end products while offering a sustainable and economical synthesis process (Tarafdar *et al.*, 2021). The creation of animal wastes is a continuous and increasing source of waste and environmental pollution due to the increasing demand for meat globally. Hopefully, this trend is expected to continue as long as human beings are living and feeding. Therefore, using animal wastes to create bio-reinforcement materials is a useful tactic that also contributes to lowering environmental pollution (Oladele *et al.*, 2025a, 2025b).

However, despite these promising availability and potential processing advances, significant research gaps remain. Existing literature has predominantly focused on plant-based natural fibers, with limited comprehensive reviews addressing animal-derived reinforcements. There is no unified classification framework that organizes animal-based reinforcement materials according to their sources, composition and functional performance. Furthermore, documented studies provide fragmented information on extraction and processing techniques, and there is an absence of systematic comparison of the mechanical, thermal and structural properties of composites reinforced with different animal-based materials. The lack of integrated knowledge linking source materials, processing routes, characterization outcomes and sustainability benefits has created a critical gap in understanding their full potential within a circular economy framework. These gaps necessitate a detailed, structured and holistic review of animal-based reinforcements and their derived composites. Hence, this review presents the classification, processing techniques and characterization of animal-based reinforcements and the ensuing composites to encourage further research in the use of animal wastes, which are more easily adaptable to human systems both internally and externally.

2. General classification of animal-based reinforcement

As shown in Figure 1, animal-based reinforcements are classified based on two major factors:

(1) based on their sources from the environment; and

(2) based on forms/shapes.

3. Classification of animal reinforcements based on their locations in the environment

Bio-reinforcements can be classified based on their sources from the environment. The classification of animal-based reinforcements based on their locations in the environments is broadly grouped into aquatic, aerial and terrestrial. Thus, the location and habitation of the animals within the universe can determine the type of animal and waste that can emanate

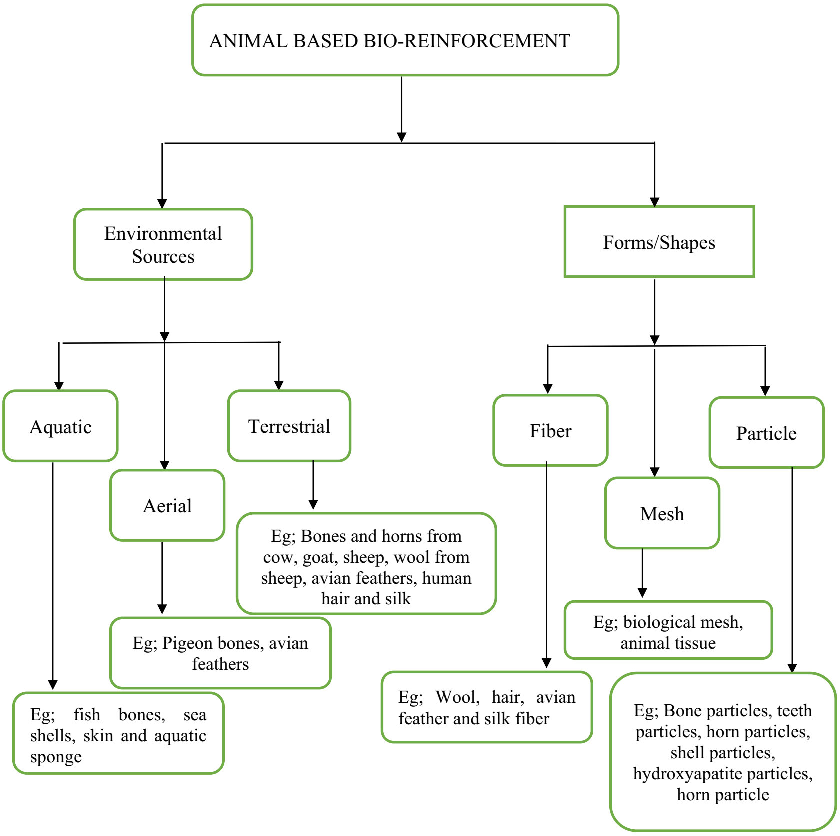

Figure 1. General classification of animal-based reinforcements

from them. From these three locations, animals within each of them have common unique features with unique reinforcement sources. Though some animals like chicken and silkworm do exhibit dual habitation potentials.

3.1 Aquatic animal-based reinforcements

Aquatic animal-based reinforcements are bio-reinforcement materials derived from animals, either vertebrate or invertebrates, which lives in water bodies (Oladele *et al.*, 2022a). These animals may breathe air or extract its oxygen from chemical elements dissolved in water through specialized organs or through their skin, making them rich in salts and other unique elements like protein, calcium and phosphorous (Adeyanju *et al.*, 2017). The reinforcement materials developed from aquatic sources are rich in protein and calcium, which make them suitable for biomedical applications. Examples are hydroxyapatite particles derived from fish bones and shells from sea animals like snails, fish skin used as a biomaterial for skin grafting and sea sponge spicules used as blueprints for bio-fabrication of biomaterial composites (Oladele *et al.*, 2023; Müller *et al.*, 2009; Oladele *et al.*, 2022a).

3.2 Aerial animal-based reinforcements

Aerial animal-based reinforcements are reinforcement materials derived from animals that live most of their lives or spend most of their time in air. They are also known as avian-based reinforcements (Oladele *et al.*, 2022b). This category consists of birds and other flying creatures. Their reinforcement materials are predominantly feathers, including those of pigeons and other birds (which includes chicken). Chicken is sometimes classified as an aerial-based animal because it can fly at times, but it is predominantly classified as a terrestrial-based animal because it spends most time on land (Agbabiaka *et al.*, 2020). The aerial-based animal reinforcements possess unique properties, which include good mechanical, chemical, thermal, lightweight and acoustic properties (Oladele *et al.*, 2022b; Agbabiaka *et al.*, 2020; Cheng and Ning, 2023). They are predominantly used for the fabrication of biomedical and structural bio-composites because of their biodegradability and unique physio-chemical properties (Oladele *et al.*, 2022b; Agbabiaka *et al.*, 2020; Cheng and Ning, 2023).

3.3 Terrestrial animal-based reinforcements

Terrestrial animal-based reinforcements are reinforcement materials derived from animals that live predominantly or entirely on land (Tarafdar *et al.*, 2021; Oladele *et al.*, 2020b). This group may include animals that live both in water and on land (e.g. silkworm). Aside from chicken and silkworm, the majority of terrestrial animal-based reinforcements are majorly developed mammals which come in both fiber and particle forms (Oladele *et al.*, 2020a; Olajide *et al.*, 2019). The predominant animals used for developing these reinforcements are man, goat, sheep, cow, pig and chicken. The reinforcement materials gotten from this group are economical, easy to access and have better properties than the aquatic and aerial-based animal reinforcements (Oladele *et al.*, 2022a, 2022b; Zamri *et al.*, 2021; Li *et al.*, 2016). They are also predominantly used in the biomedical, structural and other manufacturing industries because of their excellent combination of physical and chemical properties (Oladele *et al.*, 2022a, 2022b; Zamri *et al.*, 2021; Li *et al.*, 2016). The fiber forms developed from terrestrial animal-based reinforcements have excellent biodegradability, good chemical reactivity, excellent bio-compatibility, light weight, excellent thermal conductivity, good thermal and fluid absorption and unique durability. Examples of these reinforcements are human hair, wool, silk fiber, hydroxyapatite particles and scaffolds (Khatib *et al.*, 2022; Amin *et al.*, 2022; Ramamoorthy *et al.*, 2015; Oladele *et al.*, 2017b; Oladele *et al.*, 2020b).

4. Classification of animal reinforcements based on forms/shapes

The frequently used classification of animal reinforcements is based on their forms/shapes. This classification consists of fibers, particles and meshes. These classifications are identified in this section.

4.1 Fibers

Animal-based reinforcements in the form of fibers are in strands with different thickness and length. The animal fiber reinforcements are predominantly used in the structural and manufacturing industries due to their elongation properties, thermal conductivity, good water and fluid absorbent and high tensile strength. This form of animal fibers is majorly sourced from aerial and terrestrial sources. They are found in their raw form in the form of wool, silk, hair and feathers, which are further processed to yield animal fibers (Khatib *et al.*, 2022; Amin *et al.*, 2022; Ramamoorthy *et al.*, 2015; Oladele *et al.*, 2017b; Oladele *et al.*, 2020b). Its application differs in terms of reinforcements and weight fractions, which impact their quality and effectiveness in composite fabrications for the structural and manufacturing industries.

The properties of selected animal fiber reinforcements are described below.

4.1.1 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 (Das and Natarajan, 2019). 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) (Kunz *et al.*, 2016), 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 has been found to be useful, especially for biomedical applications. The degumming process is done using boiling water (120°C for 105 min) because of the composition of their amino acids. Other standard techniques such as autoclaving, short alkaline (Na_2CO_3) boiling, long alkaline (Na_2CO_3) boiling and ultrasounds can also be used in degumming sericin from fibroin (Carissimi *et al.*, 2019; Wang and Zhang, 2015; Manesa *et al.*, 2022).

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 (Elzoghby *et al.*, 2015; Silva, 2017; Li *et al.*, 2022; Rakesh, 2019). Silk consists of 75% fibroin and 23% sericin; the remaining percentage is made of fat, wax and mineral salts (Rakesh, 2019; Song *et al.*, 2025). Fibroin fiber is the most widely utilized component of silk for commercial applications because of its strength and aesthetic properties. There are four main types of silk fibers, which are mulberry, tasar, muga and eri silk.

Mulberry silk is the most abundant silk fiber globally, with the most contributions from China, Japan and Korea (Saha *et al.*, 2024; Mansourieh *et al.*, 2024). The Mulberry silkworm, also known as Bombyx mori silkworm, produces soft and fine silk fibers with lustrous aesthetics (Yang and Fancey, 2025). Due to its composition and qualities, silk has exceptional potential. It has a variety of qualities, including high tensile strength, high elongation and chemical resistance and is made up of highly organized proteins (Das and Natarajan, 2019; Mussig, 2010).

Table 1 compares key properties of different silk fibers, including mulberry, tasar, eri and muga silk fibers, revealing distinct differences relevant to composite reinforcement. Mulberry shows low ash content, higher fatty matter and strong tenacity, making it the most uniform and widely preferred fiber. Tasar has higher ash content and lower strength, with a convoluted cross-section that affects bonding. Eri exhibits the highest moisture regain and elongation, offering good flexibility. Muga combines moderate ash content, golden coloration and strong triangular morphology that enhances mechanical interlocking. Overall, each silk type presents unique structural and mechanical characteristics suitable for tailored composite applications.

4.1.2 Wool fiber. Wool is an eco-friendly material (Russell, 2009). The structure and chemical makeup of wool fiber set it apart from other types of fiber; its enormous variety, heterogeneity of properties and benefits are unmatched by any other natural or synthetic fiber (Laitala *et al.*, 2018). Wool has been used in the production of clothing and textiles since antiquity. Wool has not, however, been used to its full capacity. The creation of new composite materials using natural fibers in place of synthetic fibers in technical applications is gaining popularity. Between 2000 and 2050, it is anticipated that the world's sheep population would grow from 1.7 billion to 2.7 billion (Thornton, 2010). Wool fiber layers are made up of two different types of cells: internal cortex cells and external cuticle cells, which create a sheath around the fiber. It stands out among textile fibers due to its cuticle cells (or scales), which cross over one another like roof tiles. Wool fibers are anchored in sheep skin by cuticle cells, which serve a vital purpose. Each cuticle cells exposed edge points from the fiber root to the tip (Rosegrant *et al.*, 2009). When a fiber is drawn against the scale as opposed to with the scale, this results in a higher surface frictional value. The frictional differential, which also causes wool to feel when stirred in water, aids in the removal of dirt and other impurities from the fleece (Allafi *et al.*, 2022; Pekhtasheva *et al.*, 2012; Huson, 2018). This unique property, which no other textile fiber possesses, makes it possible to create fabrics with extremely dense structures, such as blankets, felts and materials for overcoats. The natural softness of wool, which makes it one of the smoothest textile fibers, is also largely a result of the fiber surface. To optimize thermal processes, reduce the gap

Table 1. Properties of different silk fibers (Rakesh, 2019; Mussig, 2010)

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

between energy demand and supply, use waste heat that would otherwise be lost, implement peak load shifting strategies and improve the integration of renewable energies, thermal energy storage (TES) is crucial (Allafi *et al.*, 2022; Pekhtasheva *et al.*, 2012; Huson, 2018). However, one of the major downsides of the TES system is the expense of implementation; thus, because of its affordability and ease of deployment, wool is a more preferable upgrade to address this issue (Allafi *et al.*, 2022).

4.1.3 Hair fiber. Hair, a nondegradable matter, is creating an environmental problem, so its use as a fiber reinforcing material can minimize the problem, and it is available in abundance and also at a very low cost (Oladele *et al.*, 2018a; Oladele *et al.*, 2014). The hair fiber is made of mainly keratin protein with a primarily alpha-helix structure. About 91% of the hair is protein made up of a long chain of amino acids, which are long chains linked by peptide bonds. Human hair is the most abundant hair fiber and majorly used for composite reinforcements. The chemical structure of hair fibers is, like other natural animal fibers like wool, whose main composition is α-keratin (Cavallaro, 2020). The coiling of two α-keratin makes up the α-helix structure (Erik *et al.*, 2008). The constituents of keratin are amino acids such as cytosine, serine, glutamine, threonine, glycine, leucine, valine and arginine (Nanda and Satapathy, 2017). The shaft of hair fibers comprises the medulla, cortex and cuticle (Huang *et al.*, 2018; Chen *et al.*, 2013). The medulla is a noncrystalline 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 (Yang *et al.*, 2014). The average composition of hair fibers is composed of 45.68% carbon, 27.9% oxygen, 6.6% hydrogen, 15.72% nitrogen and 5.03% sulphur. Amino acid present in hair are containing cytosine, serine, glutamine, threonine, glycine, leucine, valine and arginine (Yang *et al.*, 2014). Hair fibers, as actual and potential reinforcement composites, offer many advantages: good strength properties, low cost, high toughness and biodegradability, however, in the case of cellulose fiber some disadvantages due to their intrinsic characteristic, incompatibility with hydrophobic polymer matrix, tendency to form aggregates during processing and poor resistance to moisture, finite length and large diameter, pose an important challenge to their use in advanced composite (Oladele *et al.*, 2018a; Oladele *et al.*, 2014; Cavallaro, 2020).

4.1.4 Feather fiber. Feathers are by-products of avian species, and the most abundant of these species is chicken.

In the USA alone, the chicken feather industry generates four billion pounds of trash each year (Kock, 2006). These feathers are either sold for a cheap price ($250/ton) as livestock feed or buried in landfills at a cost of $30/ton (Kock, 2006). Due to health concerns, the European Union has prohibited the use of poultry feathers as feed since 2001. Composite industries, which cannot be consumed by many other sectors, might use the large number of feathers. According to reports, chicken feathers have unusual qualities like low density and effective thermal and acoustic insulation (Oladele *et al.*, 2018b). Chicken feather fibers (CFFs) are made up of 88% water, 1% lipids and 91% protein (keratin) (Arunkumar *et al.*, 2013). Arunkumar *et al.* (2013) investigated the chemical makeup, elemental analysis, morphological structure, aspect ratio, apparent specific gravity, chemical durability and thermal insulation of these feathers. They reported that chicken feather fibers possess excellent physiochemical properties, which give them potential for composite reinforcements for structural and biomedical applications and replace synthetic fibers in composite production (Reddy and Yang, 2007; Kurien *et al.*, 2022a, 2022b). They are found to possess good mechanical, chemical, thermal and acoustic properties. The alignment of avian fibers in a biocomposite provides high stiffness and directional strength. They contain about 90% protein and β-keratin, with about one percent lipids and the rest is water. Its chemical constituents also include 16% serine, 12% proline, 11% glycine, 9% valine, 7% cysteine and numerous amino acids (Subramani *et al.*, 2014). As a biodegradable material, avian fibers possess strong covalent bonds resistant to forming three-dimensional protein structures, especially from the barbed valves (rachis and hollow shaft) (Oladele *et al.*, 2014). They have high thermal insulation properties, tensile strength and are lightweight, which makes them useful raw materials for biomedical industries (Tesfaye *et al.*, 2018). The uniqueness of this type of fiber is in its honeycomb structure, which possesses low density, high flexibility and spinnable length absent in other natural or man-made fibers (Tesfaye *et al.*, 2018). The mechanical properties of chicken feathers are described as having good impact strength, thermal stability and low energy dissipation but poor flexural and tensile strength due to the microvoids present within the biocomposite (Kumar *et al.*, 2021). The advantage of microvoids is their application in acoustic products. Also, chicken fibers are efficient corrosion-resistant agents on steel substrates for epoxy coating. They also absorb sound more effectively than composites made of plant fibers (Salazar and Rios, 2009; Reddy and Yang, 2010).

4.2 Particles

Animal reinforcements in the form of particles are micro- or nano-sized constituents developed from animal components (Oladele *et al.*, 2022a, 2022b; Agbabiaka *et al.*, 2020; Daramola *et al.*, 2021; Ariwoola *et al.*, 2021). These constituents are majorly developed from drying, crushing, grinding and synthesis of these animal components to yield micro or nano-sized constituents (Adeyanju *et al.*, 2017; Olajide *et al.*, 2017; Müller *et al.*, 2009; Cheng and Ning, 2023). Animal reinforcements in the form of particles have spectacular properties like excellent biodegradability and biodegradability, good thermal conductivity and fluid absorbent properties (Oladele *et al.*, 2022a, 2022b; Agbabiaka *et al.*, 2020; Daramola *et al.*, 2021; Ariwoola *et al.*, 2021). They are majorly used in the biomedical sector and find vast applications in almost all aspects of biomedicine because their chemical properties are similar with that of the human body (Oladele *et al.*, 2022a, 2022b; Agbabiaka *et al.*, 2020; Daramola *et al.*, 2021; Ariwoola *et al.*, 2021). They are mostly sourced from terrestrial sources and are synthesized from solid components.

The properties of selected animal particle reinforcements are described below.

4.2.1 Reinforcement particles from shells. Shell particles are animal products developed majorly from birds and sea animals (Oladele *et al.*, 2022a, 2022b; Agbabiaka *et al.*, 2020; Adeyanju *et al.*, 2017; Guo *et al.*, 2021). Shells provide the embryo with a protective layer against pathogens and give the embryo the necessary nutrients for development (Meng and Deng, 2017; Choi *et al.*, 2018; Ilyas *et al.*, 2022; Chatterjee *et al.*, 2022; Aranaz *et al.*, 2021; Taketa *et al.*, 2018; Piotrowska-Kirschling and Brzeska, 2020; Cheng and Ning, 2023). Shell particles are bio-ceramic material whose structure is columnar calcium carbonate ($CaCO_3$) and organic proteinaceous matrix (Guo *et al.*, 2021; Sun *et al.*, 2016; Li *et al.*, 2021). This structure protects the embryo from mechanical impact, regulates fluid exchange through the pores and prevents microbial invasion (Samuel *et al.*, 2021). The quality of shell particles can be determined by its breaking strength, deformation, uniformity in thickness and dynamic stiffness of the eggshell (Sun *et al.*, 2012). The calcium carbonate in shells is about 95% and about 3.5% protein organic matrix (Lin, 2004).

The advantage of shell particles over mineral calcium carbonate is due to the lower density and higher crystallinity. These advantages make shell particles an excellent reinforcement even for commercial biocomposite production (Ahmed *et al.*, 2021; Toro *et al.*, 2007). Shell particles can be converted into other commercial products, such as pure calcium carbonate, cosmetic and pharmaceutical products and water purifiers (Ahmed *et al.*, 2021). Shell particles have a cellulosic structure with their constituents as biosorbent amino acids. The chemical constituents of shell particles include CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, SO_3, K_2O and Na_2O. The physical properties of shell particles include about 1.2% water content, a density of about 0.9 g/cm^3 and a surface area of about 18.5 m^2/g (Alzerjawi *et al.*, 2018). It is important to note that the carbonization of the shell particles burns off all the impurities and provides better tribo-mechanical properties than uncarbonized shell particles (Zargar *et al.*, 2015; Bain, 2005; Sanni *et al.*, 2018; Guarnieri *et al.*, 2022; Kowshik *et al.*, 2023; Bose *et al.*, 2018).

4.2.2 Reinforcement particles from cattle. Bones are among the waste products produced by cattle that have received the greatest attention for their potential use in the creation of various materials with economic and social value (Miculescu *et al.*, 2018; Odusote *et al.*, 2019; Puri *et al.*, 2020). The biocompatible ceramic particles, hydroxyapatite particles, which are extracted from cow teeth and bones are a main and crucial reinforcement component, has found numerous biological applications (Khandan *et al.*, 2014; Nirmala *et al.*, 2011). According to a study by Fratzl (2006), de-fatting cow teeth and bones and then calcining them at 900°C is the best technique for hydroxyapatite production. Another study by Nirmala *et al.* (2011) used thermal decomposition and silver nitrate reduction with N, N-dimethylformamide to develop hydroxyapatite particles from bovine femur bone conjugated with silver nanoparticles. The synthesized hydroxyapatite-silver nanoparticle complex demonstrated good antibacterial ability and can be used in the biomedical industry for bioimplant fabrication (Nirmala *et al.*, 2011). In recent studies, researchers also developed an interest in developing bioceramic materials generated from fluorinated hydroxyapatite particles. This was motivated by the discovery that the presence of fluorine ions improved hydroxyapatite stability in biological systems and encouraged apatite production. Additionally, particle reinforcements from cow origin are used to develop osteoinductive and osteoconductive scaffolds for bone and tissue engineering (Puri *et al.*, 2020).

4.2.3 Reinforcement particles from pig. Biomaterials reinforcement particles made from pig origin have also been used in the biomedical sector in a number of ways. Bone quality, also known as bone performance, is influenced by the bone's architecture and material quality in addition to its shape and quantity (Fratzl, 206). Reinforcement particles from pig bones can be used as a biomedical material to replace a broken component. It has been proven by recent studies to be useful in allographing and xenografting (Ratner *et al.*, 2004). By weight, pig bone typically comprises of 60% mineral components, 25% water and 15% organic elements. With a little number of carbonates, magnesium, hydroxyl, fluoride, chloride and citrate ions, calcium and phosphate ions make up the majority of the mineral phase's ions (Hench and Best, 2004). The reinforcement particles from pig bone biomaterial interface have shown close relativity between the human bone, which exhibits mature bone features with more osteocytes, and porcine bone properties (Stefanini *et al.*, 2021; Orsini *et al.*, 2006).

4.2.4 Reinforcement particles from sheep/goat. The main application of the reinforcement particles from bone is the development of hydroxyapatite. Hydroxyapatite particles from sheep/goat sources, which have good biocompatibility, are majorly used for tissue engineering and bone replacement (Balázsi *et al.*, 2007). In comparison to synthetic hydroxyapatites, those generated from natural sources have been proven to be safer in terms of cross-reaction and other immunological reactions (Chattopadhyay *et al.*, 2007). Although hydroxyapatite particle synthesis from sheep/goat bones is frequently challenging and expensive. Cost-effective bioceramics are also manufactured using biological hydroxyapatites that are found in goat bones and teeth. In a study carried out by Akyurt *et al.* (2012), dentine hydroxyapatite particles from sheep teeth were used as a different source of bioactive biomaterial for grafting. They were extracted, cleaned and calcined in air at 850°C. It was discovered in their study that hydroxyapatite particles from sheep teeth possess exceptional biocompactibility properties. Various techniques, such as calcinations, chemical synthesis with hot-plating, ultrasonication or hydrothermal processes, are potential techniques that can be used to develop particle reinforcements from animal sources.

4.3 Mesh

Mesh is another form/shape of animal-based reinforcements that have not been exploited in the past, but have been gaining a lot of attraction by researchers and scientists in recent times. They are majorly found under the skin and on the tissues of animals, especially mammals. They have found vast application in tissue engineering for tissue and bone replacement. Its major application in tissue engineering is to slow adhesion development and a synthetic parietal side that promotes strong healing. It is also used in improving skin repair procedures. In a study carried out by Stefanini *et al.* (2021), vertical bone abnormalities were repaired using a modified connective tissue graft wall technique with an enamel matrix derivative. A coronally advanced flap was used, and an acellular dermal matrix made from pig tissue was put beneath it to mimic the buccal soft tissue wall of the bone defect. One year after the operation, coupled with radiographic bone defect fill, the interdental papilla's position and clinical attachment level gain both increased (Stefanini *et al.*, 2021). Thus, animal biomaterials in the form of mesh possess excellent biocompactibility and biodegradability properties.

Animal fiber/particle reinforcements are located in different and unique parts within the animal body, which shows natural diversity of bio-derived composite materials, as presented in Table 2. Avian species provide feather fibers, bone particles and shell-based particulates sourced primarily from the wings, legs and outer shells. Insects, including silkworms, beetles, honeybees and others, contribute silk fibers typically extracted from the head region, representing one of the most commercially valuable animal reinforcements. Humans provide hair fibers, also obtained from the head, which have been explored for low-cost composite applications. Mammalian livestock such as sheep, goats, pigs and cows supply a wide range of reinforcements, including wool fibers, hydroxyapatite particles, prosthetic mesh materials and hair fibers, obtained from external body parts, bones, teeth, tissues and tails. Fish serve as

Table 2. Location of animal fiber/particle reinforcement within the animal body

Animal	Reinforcement	Body location
Avian (birds)	Feather fibers, bone particles and shell particles	Wings, legs and shells
Insects (silkworm, beetles, raspy crickets, honeybee, weaver ants and lacewings)	Silk fiber	Head
Man	Hair fiber	Head
Sheep	Wool fiber and hydroxyapatite particles	External body parts, bone and teeth
Goat	Hydroxyapatite particles	Bone, teeth and nails
Pig	Hydroxyapatite particles and prosthetic mesh	Bone lamella, teeth and tissues
Cow	Hydroxyapatite particles, mesh reinforcements and hair fibers	Bone, teeth, tissue and tail
Fish	Hydroxyapatite particles and graft materials	Bones and scales

an additional source of hydroxyapatite particles and graft materials extracted from bones and scales. Collectively, these animals offer abundant and diverse reinforcement materials suitable for sustainable composite development.

5. Animal-based reinforced biocomposite manufacturing

There are different techniques for manufacturing polymer matrix bio-composites, which are pultrusion, hand lay-up, vacuum infusion, compression molding, vacuum infusion, resin transfer molding, vacuum bag molding process, spray-up, electrospinning and injection molding (Gómez-Suarez and Córdoba-Tuta, 2022; Rajak *et al.*, 2019). The quality of the final from any chosen technique is bound to be affected by moisture, type of fiber, fiber volume and length of biocomposite, chemical constituent, fiber modification and molding temperature (Gholampour and Ozbakkaloglu, 2020). The schematic representation of selected manufacturing techniques is shown in Figure 2. Each technique has its advantages and disadvantages, which are shown in Table 3.

5.1 The hand lay-up technique

The hand lay-up technique, also known as the wet lay-up method, is the oldest and one of the simplest fiber-reinforced composite production techniques. The fibers (woven, chopped, knitted or stitched) are placed into a mold and wetted with liquid resin using a hand roller to ensure interaction and adhesion between the fiber and the matrix. The first step is spraying with a mold release agent. Then a thin plastic sheet is placed at the top and bottom of the mold plate to ensure a good surface finish (Raji *et al.*, 2019). The fibers are then cut into required shapes and sizes and distributed uniformly together with the resin using a brush, and then rolled. More layers are created till the desired thickness is achieved and is left to dry at atmospheric conditions. A variation or improvement of this technique is the spray-up technique, where a single-sided tool under atmospheric conditions is used to spray resin and chopped fibers simultaneously (Jamir *et al.*, 2018; Leonelli and Romagnoli, 2015; Middleton, 2016).

5.2 Pultrusion

This is a process of filling the matrix (mostly thermoset) in a resin bath with continuous fibers. The fibers can be in the form of tape, woven material or mat, passed through a system that's heated, shaped and formed. The precision is achieved by making cuts of the required size (constant cross-sections with long lengths). Examples of biocomposite parts that can be produced with this include rods, ladder side rails, tool handles and electrical cable tray components. The parameters controlling the final products are the type and speed of fibers and matrix temperature (Joshi, 2012; Verma and Fortunati, 2019; Correia, 2023).

5.3 Resin transfer molding

This is also known as liquid molding and is an intermediate molding technique that injects moderately pressurized resin (low-viscosity thermoset) into a closed mold cavity. This technique creates two surface finishes by filling the voids in the mold with resin and wetting all the surfaces of the reinforcing fiber. The animal fiber used in this technique can be in different forms, such as mats, fiber tows and woven structures. This technique is susceptible to microvoids and unwetted dry spots, which limits its utilization for critical applications, especially in the aerospace industry (Erden and Ho, 2017; Gupta *et al.*, 2022; Hamidi and Altan, 2018). The resin transfer molding has different variations based on the modifications

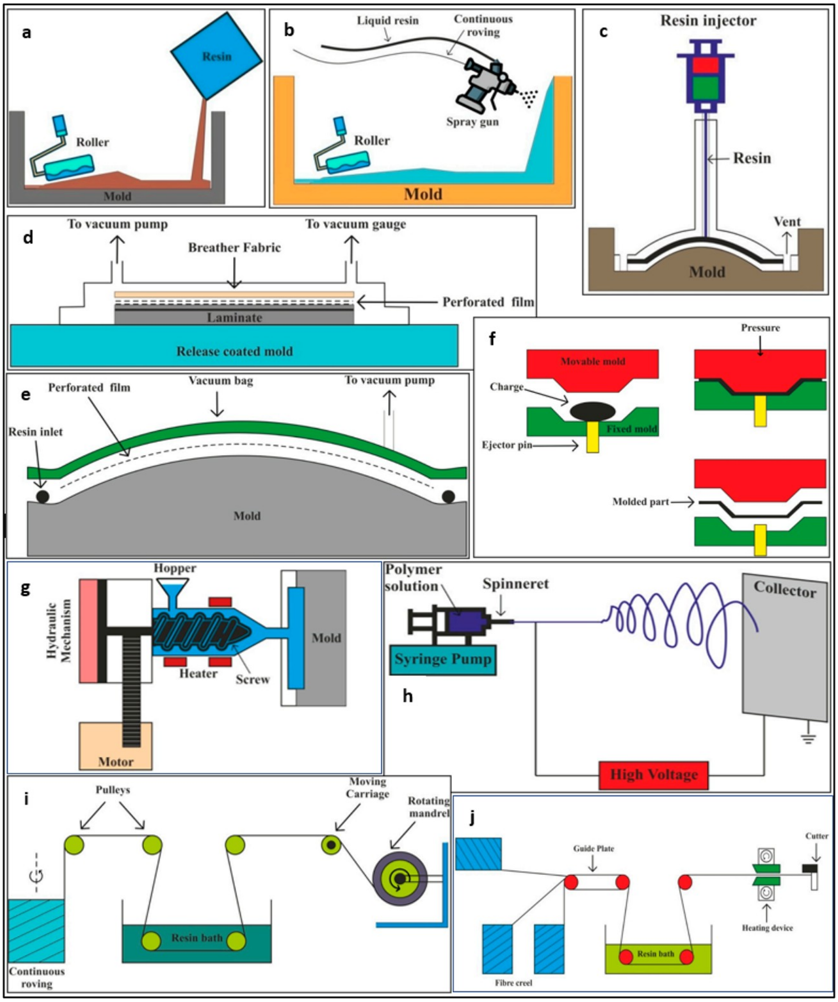

Figure 2. Manufacturing techniques: (a) hand layup, (b) spray-up, (c) resin transfer molding, (d) vacuum bag molding, (e) vacuum infusion, (f) compression molding, (g) injection molding, (h) electrospinning, (i) filament winding and (j) pultrusion process for manufacturing polymer matrix biocomposites (Rajak *et al.*, 2019)

in the technique of impregnating the fiber with resins. These modifications include autoclave, vacuum infusion and vacuum-assisted resin transfer attachments (Gupta *et al.*, 2022).

5.4 Vacuum bag molding

This is a common biocomposite molding technique in the aerospace industry for making prototypes. The main material for the initiation of the molding process is the prepreg, which means the resin (thermosetting polymer) has been preimpregnated with unidirectional or bidirectional continuous fibers and partly cured (120°C and 1 bar). The prepreg is then cut and

Table 3. Advantages and disadvantages of biocomposites manufacturing techniques (Gholampour and Ozbakkaloglu, 2020)

Technique	Advantage	Disadvantage
Compression molding	Fast setup time; low wasted material; low cost for large and complex composites; good surface finish; and even pressure distribution on the composites	Low production speed; suitable only for flat or moderately curved composite shapes
Sheet molding	Excellent part reproducibility; very high-volume production ability; and low labor requirements on a production level	Suitable only for the preparation of composites with a low fiber volume fraction
Extrusion molding	Fast setup time; low initial setup costs; and low production costs	Moderate production speed; suitable only for the preparation of composites with a uniform cross-section; and mediocre precision
Injection molding	Low operational cost; low cost in mass production; high throughput; flexibility to make parts with complex shapes; and high precision	High initial setup costs
Hand lay-up	Simple principles to teach; low tooling cost; wide choice of material types and suppliers; and flexibility in material design	Labor-intensive; styrene emission from unsaturated polyester and vinyl ester resins; dependency of the quality of the laminate on the skill of laminators; resins need to be low viscosity to be workable by hand
Resin transfer molding	Better product consistency than that of compression molding; tighter tolerance and more intricate parts than injection molding; and fast setup time, low setup costs and low maintenance costs	More material is wasted than with compression molding; and production speed is lower than that of injection molding
Resin infusion molding	Excellent surface quality on both sides; short process time; and highly even quality and material thickness	Slow cycle times and high consumable costs

arranged into the desired shape and size and then placed into a mold, which is the vacuum bag (air-removal), and then sealed. The temperature of the autoclave (180°C and 7–10 bars) is then raised until curing has been achieved. The result from this technique has fewer voids, even with thick laminate structures (Mallick, 2021; Schlimbach and Ogale, 2012).

5.5 Vacuum bag resin infusion

This uses an open mold rather than a closed mold. Although the tooling costs can be significantly less, the capital costs are high. The reinforcements are placed on the tool with the top layer as a resin distribution fabric. The stack is enclosed and sealed using a flexible plastic bag connected to a liquid resin and vacuum pump, such that upon squeezing through air-removal, the biocomposite takes the shape of the mold. This technique is used in manufacturing boat hulls and wind turbine blades for aerospace applications (Liu *et al.*, 2018; Spasojevic, 2019).

5.6 Compression molding

This is a simple technique for manufacturing polymer biocomposites using either thermosets or thermoplastics as a matrix from discontinuous animal fiber reinforcements.

The deformable material is placed between two heated halves, resulting in the formation of the intended part. This technique is easily automated to efficiently produce complex geometries with negligible waste (Park and Lee, 2012; Dumont *et al.*, 2023; Greene, 2021a, 2021b).

5.7 Injection molding technique

This is the choice technique for mass production with good surface finishes. The technique of operation is by heating the resin (thermoplastic) to obtain a viscous melt; then, the melt is pressurized through an orifice that has the intended shape of the parts to be produced. The produced parts are then cooled and extracted. The drawback of this technique is the inability to produce complicated shapes through the technique of heat transfer and pressure flow that are required by injection molding. This technique is not limited to polymer matrix composites because it can be used in producing modified ceramic suspensions. The final part produced will be a function of the type of material introduced, the pressure applied to the plunger, plunger speed, temperature of the heating cylinder and temperature of the mold (Ebnesajjad, 2015; Greene, 2021a, 2021b).

5.8 Electrospinning

This is an electrohydrodynamic technique that produces electrified liquid droplets to stretch and elongate fibers. The technique is simple, with components for a high-voltage power supply, syringe pump, hypodermic needle spinneret and conductive collector. The manufacturing process, upon electrification, is an electrostatic repulsion that deforms the liquid droplet into a straight line, which then turns into a Taylor cone as the projection continues (Xue *et al.*, 2019).

5.9 Filament winding technique

This is a manufacturing process that involves winding a fiber wetted by resin onto a rotating mandrel along a predetermined path. After the wounding process, the mandrel is removed by heating the resin. The process can be automated to produce axisymmetric and nonaxisymmetric biocomposite parts. Parts produced through this technique include pipe bends and aircraft fuselage (Rajak *et al.*, 2019).

6. Animal-based reinforced biocomposite manufacturing

Table 3 presents a detailed summary comparison of common biocomposite manufacturing techniques, outlining their respective advantages and limitations in terms of productivity, cost, material quality and process flexibility. Compression molding is highlighted for its fast setup time, low material waste and suitability for producing large, complex composite parts with good surface finish; however, it suffers from low production speed and is restricted to flat or moderately curved shapes. Sheet molding offers excellent reproducibility and high-volume production with minimal labor requirements, yet it is limited to composites with low fiber volume fractions. Extrusion molding is attractive for its low initial costs and continuous processing capability, but the technique is only suitable for uniform cross-sections and provides moderate precision. Injection molding excels in mass production through high throughput and the ability to form intricate geometries with great accuracy, though high initial setup costs remain a major drawback. Hand lay-up is valued for its simplicity, design flexibility and low tooling cost, while its disadvantages include labor intensiveness, dependency on operator skill and emissions from certain resin systems. Resin transfer molding improves product consistency, allows tighter tolerances and reduces maintenance costs, yet wastes more material than compression molding and has slower production speeds than injection molding. Finally, resin infusion molding produces excellent surface finish and uniform laminate quality, but it is characterized by slow cycle times and high consumable costs. Collectively, these techniques illustrate the trade-offs between cost, efficiency, precision and material performance in biocomposite manufacturing.

7. Animal-based reinforced biocomposite characterization

The morphological properties of animal fibers can be examined using tools like scanning electron microscope (SEM), but due to the nonconductive nature, ultra-high resolution

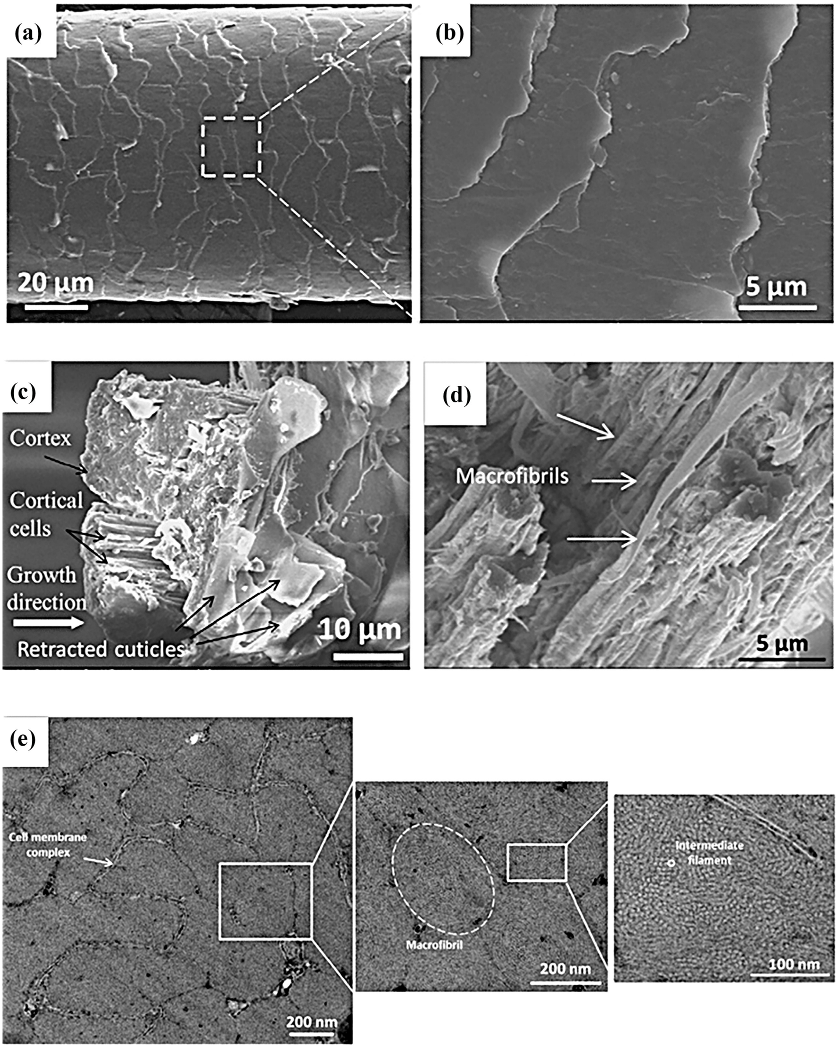

Figure 3. SEM images; (a–b) cuticles; (c) cross-section of cuticles; (d) macrofibrils; (d) SEM images of the human hair; and (e) TEM images of the human hair (Nanda and Satapathy, 2017; Yang *et al.*, 2014)

scanning electron microscopy is difficult. The specimens can be sputtered with iridium prior to observation. Transmission electron microscopy (TEM) can be used to study the hair by using osmium staining and lead poststaining (Yu *et al.*, 2017). The SEM and TEM image of human hair is shown in Figure 3.

Another characterization technique is X-ray diffraction analysis; the diffraction data can be obtained by using biological large angle diffraction experiment with 9 kW, i.e. accelerating voltage of 45 kV and current of 200 mA, and wavelength of 1.5418 Å while aligning the axis of the hair parallel to the beam for maximum illumination. The setup for the X-ray analysis is shown in Figure 4.

The functional groups present in biocomposites can be investigated using the fourier infrared technique or attenuated total reflection fourier transform infrared (Gea *et al.*, 2018). In a research carried out by Ali *et al.* (2021), the FTIR analysis for chicken feather fibers, cow hair fibers and leather fibers as reinforcements in unsaturated polyester resin matrix. The

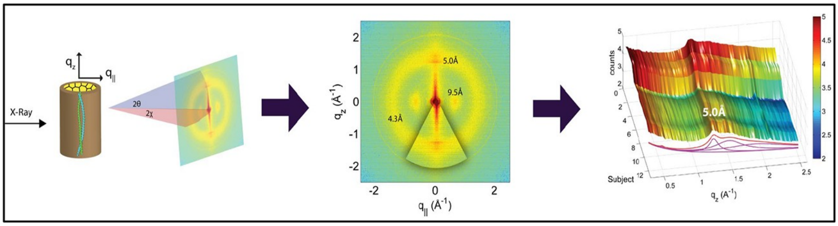

Figure 4. Schematic setup of X-ray diffraction experiment for human hair (Huang *et al.*, 2018)

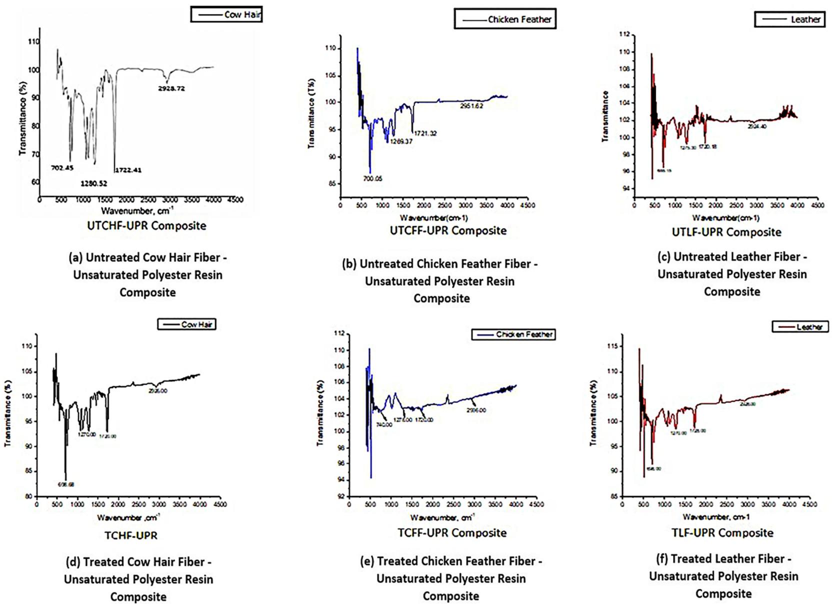

Figure 5. FTIR analysis of chicken feather fiber, cow fiber and leather fiber (Ali *et al.*, 2021)

results show peaks that represent the presence of carbonyl (C = O), =C–H, –OH, CH_3 and CH_2 groups as shown in Figure 5.

More importantly, it is noted that there is no chemical reaction between the matrix and the reinforcements. The thermal behavior of the chicken feather fibers, cow hair fibers and leather fibers biocomposite can be obtained using a thermogravimetric analyzer at a predetermined temperature and heating rate (Suarato *et al.*, 2020). The thermogravimetric analysis of chicken feathers, cow hair and leather fiber shows that 5% reinforcement displays good thermal resistance up to a temperature of 315°C, followed by a slow thermal degradation as the temperature increases until it reaches a critical temperature for rapid degradation (Ali *et al.*, 2021) as shown in Figure 6.

Oladele *et al.* (2018a, 2018b) performed elemental characterization on bird feathers; the result is shown in Table 4. Tesfaye *et al.* (2018) also made the proximate analysis and ultimate analyses of chicken feathers, and the results are shown in Table 5. XRD analysis and SEM analysis were performed by Awogbemi *et al.* (2020) on the eggshells, and the results are shown in Figure 7. The constituents of the eggshell, as characterized in XRD, are shown in Table 6. The textural properties of the eggshells are shown in Table 7.

Collectively, the results presented in Tables 4–7 demonstrate that chicken-derived wastes (feathers and eggshells) possess a rich and complementary chemical–mineralogical profile

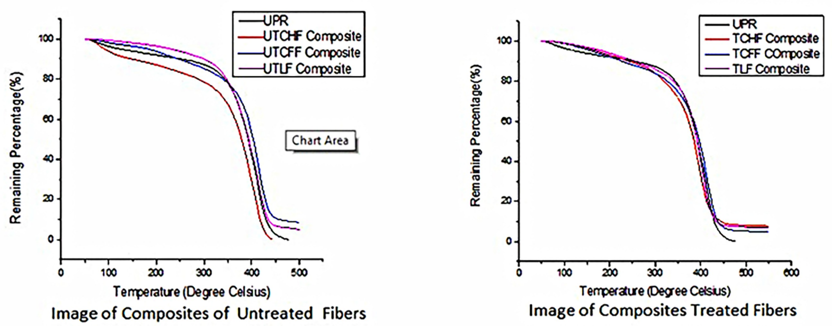

Figure 6. Thermogravimetric analysis for (a) untreated and (b) treated animal fibers (Ali *et al.*, 2021)

Table 4. Element analysis for chicken fiber (Oladele *et al.*, 2018a, 2018b)

Elemental composition	Mg	Zn	Fe	Cu	K	C
Amount (ppm)	3.65	2.90	1.54	0.08	201.50	99.86

Table 5. Proximate analysis and ultimate analysis of chicken fiber (Tesfaye *et al.*, 2018)

Composition	Crude lipid	Crude fiber	Crude protein	Ash	NFE	Moisture content
Percentage	0.83%	2.15%	82.36%	1.49%	1.02%	12.33%
Element	Carbon	Nitrogen	Oxygen	Sulfur		
Percentage	64.47%	10.41%	22.34%	2.64%		

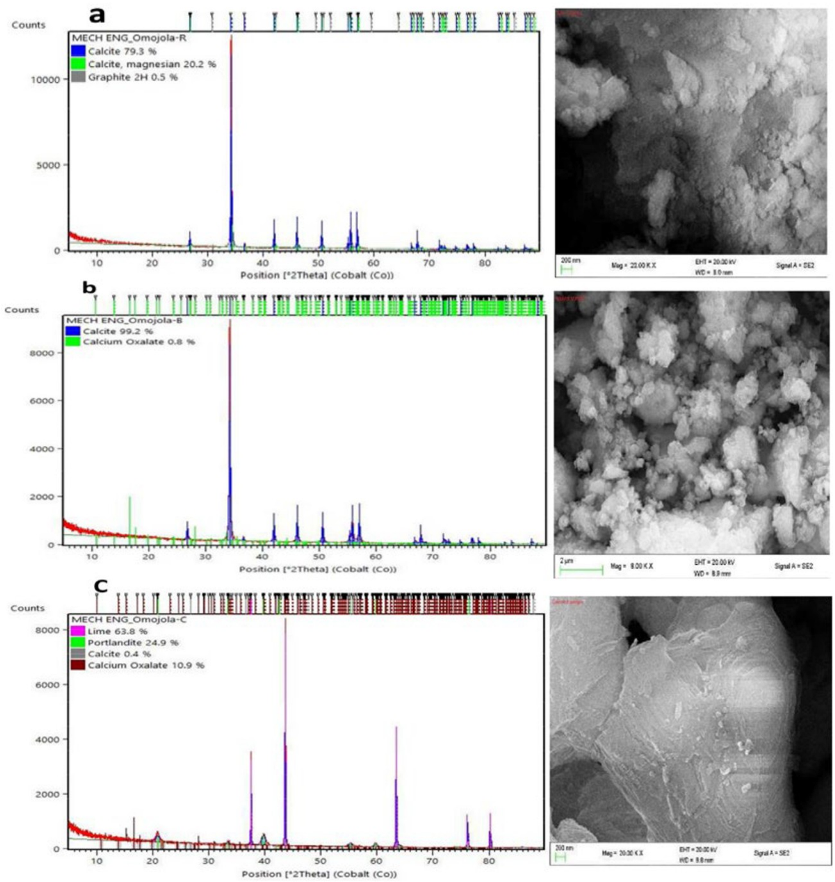

Figure 7. XRD analysis and SEM analysis for (a) raw, (b) boiled and (c) calcined eggshells (Awogbemi *et al.*, 2020)

Table 6. XRD composition of eggshell particles (Awogbemi *et al.*, 2020)

Compound	Chemical formula	Chicken eggshell samples concentration (%)		
		Raw	Boiled	Calcined
Line	CaO	–	–	63.8
Portlandite	$Ca(OH)_2$	–	–	24.9
Calcite	$CaCO_3$	79.3	99.2	0.4
Calcium oxalate	$C_2H_2CaO_5$	–	0.8	10.9
Calcite magnesium	$CaCO_3Mg$	20.2	–	–
Graphite	C	0.5	–	–

Table 7. Textural properties of eggshell particles (Awogbemi *et al.*, 2020)

Properties	Raw	Chicken eggshell samples Boiled	Calcined
BET surface area (m^2/g)	2.33	3.26	4.6
External surface area (m^2/g)	2.49	3.49	4.57
Average pore radius (Å)	115.67	138.28	116.06
Pore volume (cm^3/g)	0.013473	0.029482	0.026708
Micropore volume (cm^3/g)	−0.000105	−0.000204	−0.000004

that makes them attractive as bio-reinforcement resources. Elemental analysis of chicken feathers (Table 4) shows the presence of nutritionally and functionally important trace elements such as Mg, Zn, Fe, Cu and K, together with a very high carbon content, reflecting the organic, keratinous nature of the fiber. The proximate and ultimate analyses in Table 5 confirm that chicken feathers are strongly proteinaceous, with crude protein exceeding 80%, low lipid content, modest ash and moisture levels and a dominant elemental composition of C, N, O and S. The relatively high nitrogen and sulfur contents are characteristic of keratin and indicate a high density of peptide and disulfide bonds, which are beneficial for thermal stability, char formation and potential interfacial interactions when used as reinforcement in polymer matrices.

In contrast, eggshells represent an inorganic, calcium-rich by-product. XRD data in Table 6 reveal that raw and boiled shells are dominated by calcite ($CaCO_3$), with small amounts of magnesium-bearing calcite, graphite and calcium oxalate, whereas calcination transforms the material into more reactive phases such as lime (CaO) and portlandite [$Ca(OH)_2$]. This phase evolution with processing temperature implies that heat-treated eggshells can act not only as stiff, low-cost fillers but also as chemically active reinforcements capable of contributing to alkalinity, bioactivity or interfacial bonding in cementitious and polymeric composites. The textural properties in Table 7 further show that boiling and calcination progressively increase BET and external surface areas, pore volume and, to some extent, pore radius, indicating the development of a more open and accessible pore structure. Such increases in surface area and porosity generally enhance mechanical interlocking, resin wetting and potential adsorption or catalytic behavior.

Taken together, the organic, nitrogen–sulfur-rich chicken feathers and the inorganic, calcium-dominated eggshells provide a synergistic combination for green composite design: lightweight, protein-based fibers can improve toughness and impact resistance, while mineral-rich eggshell particles contribute stiffness, dimensional stability and possible functional properties (e.g. bioactivity, fire resistance or barrier behavior). The microstructural changes reported by Awogbemi *et al.* (2020) through XRD and SEM, along with the BET data, also indicate that simple processing steps such as boiling or calcination can be used to tune phase composition and surface characteristics, allowing the tailoring of interfacial bonding and overall performance of poultry-waste-derived biocomposites within a circular-economy framework.

For the FTIR analysis on eggshell particles, the results show $CO^{2-}{}_3$, OH^{-1} and OAH functional groups in all the eggshells. The thermogravimetric analysis showed that due to the decomposition of calcium carbonate in the calcined eggshells, the decomposition temperature was lower than in the boiled and raw eggshells, as shown in Figure 8. In chitosan, the FTIR analysis showed the characteristic peaks of Amide I and Amide II, while thermogravimetric analysis showed a gradual wavey degradation curve starting at a

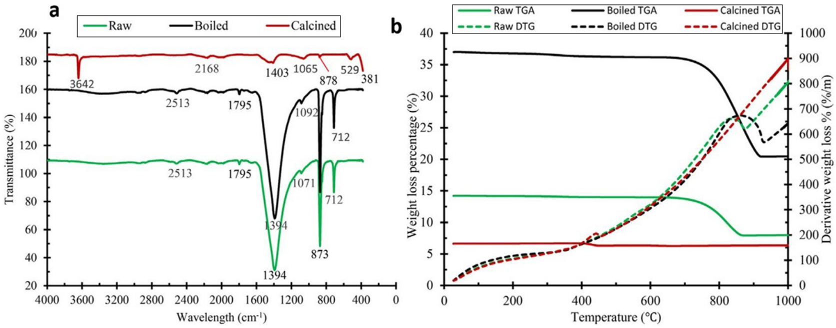

Figure 8. (a) FTIR and (b) thermogravimetric analysis of eggshells (Awogbemi *et al.*, 2020)

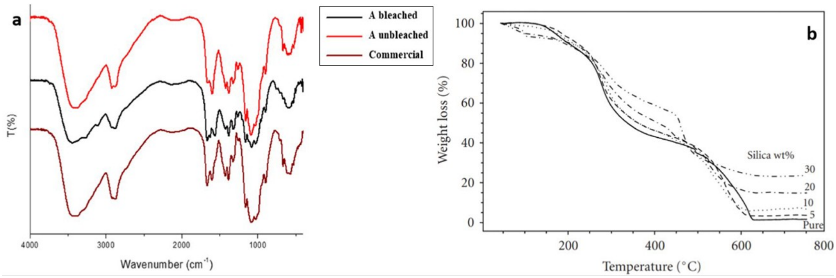

Figure 9. (a) FTIR and (b) thermogravimetric analysis of chitosan (Zhu *et al.*, 2019)

temperature of 200°C (Guarnieri *et al.*, 2022; Zhu *et al.*, 2019). The FTIR and thermogravimetric plots of Chitosan are shown in Figure 9.

8. Mechanical behavior of biocomposites

The mechanical behavior of biocomposites is strongly governed by the intrinsic properties of the reinforcement, the matrix and, crucially, the quality of the fiber–matrix interface (Akinwekomi *et al.*, 2024). Natural reinforcements, including animal-derived fibers such as silk, feather, wool, keratin and mineral phases from eggshell or bone, generally exhibit high specific strength and stiffness but also significant variability in diameter, surface chemistry and defect content (Rodopoulos and Karathanasopoulos, 2025; Shelly *et al.*, 2025). When these fibers are combined with thermoplastic or thermoset matrices (e.g. polypropylene, PLA, polyester and epoxy), the resulting mechanical response typically reflects a balance between the load-bearing capacity of the fiber and the deformability of the matrix (Islam *et al.*, 2025; Li and Roh, 2025). Studies on natural-fiber-reinforced polymers consistently report improvements in tensile and flexural properties at low-to-moderate fiber loadings, provided that good interfacial bonding is achieved through appropriate surface treatments or compatibilizers (Ermeydan, 2024; Mylsamy *et al.*, 2024).

Comparative literature on animal fibers shows that silk-reinforced composites often display superior tensile strength and modulus relative to many plant-fiber systems, owing to silk's highly ordered β-sheet crystalline domains and excellent extensibility (Yang *et al.*, 2025). When embedded in epoxy or polyester matrices, silk fibers can impart high tensile strength and fracture toughness, making such biocomposites suitable for structural or biomedical components (Anulaya and Kandasubramanian, 2025; Faheed, 2024). In contrast, chicken feather and wool fibers, which contain micro- and macro-voids in their medulla and a scaly surface morphology, tend to yield composites with lower stiffness but enhanced impact resistance and energy absorption (Gorur Avsaroglu, 2025; Thenmozhi and Thilagavathi, 2024). Several authors have reported that feather-reinforced thermoplastics exhibit reduced density and improved damping behavior, making them attractive for lightweight panels and acoustic insulation, even when tensile properties remain below those of glass-fiber composites (Santhosh *et al.*, 2024). Where keratin fibers are well dispersed and chemically bonded (e.g. via coupling agents or alkaline/oxidative pretreatments), notable gains in tensile strength and flexural modulus relative to neat matrices have been observed; however, poor treatment or high moisture content can promote fiber pull-out and interfacial debonding, leading to premature failure (Raydan, 2024).

Mechanical behavior is also highly sensitive to fiber volume fraction, orientation and aspect ratio (Gonabadi *et al.*, 2025). Many studies report an optimum reinforcement content beyond which tensile and flexural strengths begin to decline because of fiber agglomeration, voids and stress concentrations. For instance, increasing animal-fiber content generally enhances stiffness and strength up to a critical loading, but at higher contents the matrix becomes insufficient to wet and encapsulate each fiber, resulting in brittle behavior and decreased elongation at break. Unidirectionally aligned or woven animal fibers (e.g. silk fabrics) typically deliver higher tensile strength and modulus along the alignment direction compared with randomly oriented short fibers, which provide more isotropic but lower overall properties (Patti and Acierno, 2023; Wang *et al.*, 2025). Similarly, finer fibers with higher aspect ratios improve stress transfer efficiency and crack bridging, while coarser fibers or particles primarily act as fillers that may increase stiffness but offer limited strength enhancement (Arunprasand and Nallasamy, 2025).

The choice of matrix profoundly affects the overall mechanical response. Thermoset matrices such as epoxy and vinylester, with inherently higher stiffness and better wetting characteristics, often produce animal-fiber biocomposites with superior tensile and flexural performance and improved dimensional stability compared with those based on commodity thermoplastics (Thapliyal *et al.*, 2023). Epoxy–silk or epoxy–wool systems, for example, typically exhibit higher tensile strength and flexural modulus than comparable polypropylene-based systems at equivalent fiber loadings, due to stronger interfacial adhesion and lower residual stresses after curing (B H *et al.*, 2024; Onwubu *et al.*, 2025). On the other hand, thermoplastic matrices (e.g. polypropylene, polyethylene, PLA and PHA) offer beneficial ductility and recyclability; feather- or wool-reinforced thermoplastics can show significant improvements in impact strength and toughness even when stiffness increases only modestly (Devarshi, 2023; Tao *et al.*, 2023). Biodegradable matrices such as PLA and PHA, when reinforced with animal fibers, have been reported to display an attractive balance between stiffness, strength and environmental performance, though their brittle nature often requires careful optimization of fiber content and plasticization to avoid catastrophic failure (Radhakrishnan *et al.*, 2024).

Another key finding across the literature is the role of chemical composition and hierarchical structure of animal-derived reinforcements in damage mechanisms. Keratin-rich fibers (feathers, wool and human hair) contain disulfide bonds and heterogeneous microstructures that favor fiber pull-out, fibrillation and microcracking under load, leading to increased toughness and energy absorption (Mishra *et al.*, 2024). This behavior is distinct from more brittle mineral fillers such as eggshell or bone-derived hydroxyapatite, which mainly enhance stiffness and hardness but may induce stress concentrations and microcracks if not finely dispersed (Oladele *et al.*, 2022a, 2022b). Hybrid biocomposites that combine organic animal fibers with mineral phases (e.g. silk or feather plus eggshell particles) have been shown to exhibit synergistic effects: the fibers bridge cracks and provide toughness, while the mineral particles increase rigidity, wear resistance or compressive strength (Oladele *et al.*, 2025a, 2025b). Such hybrids can therefore be tailored to meet specific mechanical performance targets for structural, biomedical or packaging applications.

Fatigue, impact and fracture behavior of animal-fiber biocomposites have also received attention. Under cyclic loading, good adhesion and flexible matrix systems help to delay crack initiation and slow crack growth, resulting in improved fatigue life compared with neat polymers (Malekinejad *et al.*, 2023). Silk-based composites, for instance, often maintain a stable stiffness over repeated loading cycles due to the reversible stretching of the protein chains, whereas feather-reinforced systems may show gradual stiffness reduction but superior damping and vibration attenuation (Lyu *et al.*, 2022). Impact studies generally reveal that the inclusion of ductile animal fibers increases impact strength and reduces notch sensitivity, as fibers can undergo pull-out and plastic deformation, dissipating energy (Oladele *et al.*, 2022a; 2022b; 2025a; 2025b). Conversely, composites filled predominantly with stiff mineral particles from eggshell or bone show higher hardness and compressive

Table 8. ASTM standard for measuring the properties of concrete biocomposites (Akbar *et al.*, 2022)

S/N	Properties	Standard
1	Soundness of cement	ASTM C187-16
2	Setting time of cement	ASTM C403
3	Fineness modulus of sand	ASTM C136
4	Abrasion value of coarse aggregates	ASTM C 535
5	Crushing strength and impact value of coarse aggregates	ASTM D5821
6	Flakiness, elongation and angularity no. of course aggregates	ASTM D 4791
7	Specific gravity and water absorption of coarse aggregates	ASTM D7172-14
8	Slump	ASTM C143
9	Compression	ASTM C39
10	Flexural	ASTM C1161-18
11	Split tensile	ASTM C496
12	Scanning electron microscopy (SEM)	ASTM C1723-16
13	RSM	Design expert

Table 9. ASTM standard for measuring the properties of polymer biocomposites (Rahman *et al.*, 2023; Ashter, 2014; Lucon and Santoyo, 2017; Hamidi *et al.*, 2018; Aranberri *et al.*, 2017)

S/N	Properties	Standard
1	Tensile strength	ASTM D638-14
2	Flexural strength	ASTM-D790-00
3	Impact strength	ASTM D4812
4	Hardness	ASTM D2240
5	Shear	ASTM D2344
6	Izod impact	ASTM D256
7	Charpy impact	ASTM E23
8	Density measurement and volume fraction determinations	ASTM D792
9	Void percentage	ASTM D22734-94
10	Water absorption	ASTM D570-98

strength but lower impact resistance, underscoring the need to balance fiber and particle contents depending on the load case (Oladele *et al.*, 2022a; 2022b; 2025a; 2025b).

To test the mechanical behavior of ceramic matrix biocomposites, Akbar *et al.* (2022) highlighted the ASTM standards for checking the mechanical properties of human hair fiber concrete. Table 8 shows the technique for measuring the mechanical properties.

There are ASTM standards for determining the mechanical properties of human hair-reinforced polymer biocomposites, described by Rahman *et al.* (2023a, 2023b), shown in Table 9.

Performing tensile test analysis requires making tensile sample specimens as described by the ASTM standards. The mechanical tests are performed using a universal testing machine. Tensile samples are dog-bone-shaped specimens and are stressed at a predetermined strain rate until failure (Rahman *et al.*, 2023a, 2023b). The flexural strength of the biocomposites can be determined by a three-point bending test or a four-point bending test at a predetermined strain rate until failure. The formula for determining flexural strength and modulus for biocomposites is shown in equations (1) and (2) (Nanda and Satapathy, 2017; Rahman *et al.*, 2023a, 2023b). Compression tests are also important mechanical behavior testing criteria performed on a universal testing machine. To perform the test, there is a need to ensure the stability of the testing conditions to avoid wobbling and misalignments until a strain of 0.5 is achieved (Jerabek *et al.*, 2010). In the shear test, the two edges of the specimen are compressed while examining the force. The relative displacement between the two fixtures (strain gauge elements) placed at the center of the specimen and at 45° to the loading axis gives the estimation of the shear response of the biocomposite.

It is also essential to estimate the voids entrapped in the biocomposite, as it can contribute to lower adhesion between the fibers and matrix. There are different techniques for estimating the voids present in the specimen. These include density measurement, ultrasound testing, X-ray tomography, radiology and other microscopy techniques. Equations (3) and (4) are used in estimating the voids in biocomposites.

Gholampour and Ozbakkaloglu (2020) reviewed the mechanical properties of animal fibers and their composite; the result is shown in Table 10. Animal fibers such as silk, feather and wool generally exhibit high tensile strength relative to their low densities, making them attractive lightweight reinforcement materials. Silk stands out for its exceptional strength and elasticity, while feathers and wool offer moderate stiffness with varying elongation capacities, allowing them to enhance toughness and energy absorption in composites. In contrast, thermoplastic resins such as polypropylene, polyethylene and polystyrene typically possess lower strength and stiffness but offer excellent ductility, processability and cost-effectiveness. Engineering thermoplastics like nylon and biopolymers such as PLA and PHA show improved mechanical performance, making them suitable matrices for structural biocomposites. Thermoset resins, including polyester, vinylester, epoxy and phenolic systems, generally exhibit superior strength, stiffness and thermal stability compared to thermoplastics, making them ideal for high-performance applications. Lightweight animal fibers with durable polymer matrices enable the development of biocomposites with tailored mechanical behavior suitable for diverse engineering applications. In general, the mechanical behavior of biocomposites reinforced with animal-derived materials is characterized by a complex interplay between reinforcement morphology, chemical composition, matrix type and processing conditions. Literature consistently indicates that when fiber–matrix compatibility is optimized – through surface treatment, coupling agents or appropriate processing parameters – animal-fiber biocomposites can achieve tensile and flexural properties competitive with, or complementary to, many plant-fiber systems, while offering unique advantages such as low density, enhanced toughness, acoustic damping and the valorization of waste streams. These findings highlight the technical

Table 10. Mechanical properties of animal fibers and resins (Gholampour and Ozbakkaloglu, 2020)

Fiber/resin	Density (kg/m^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Flexural strength (MPa)	Flexural modulus (GPa)
Fiber						
Silk	1,300	100–1,500	5–25	15–60	–	–
Feather	900	100–203	3–10	6.9	–	–
Wool	1,300	50–315	2.3–5	13.2–35	–	–
Thermoplastics						
Polypropylene	890–910	26–41.4	0.95–1.77	15–700	40	1.5
Low-density polyethylene	910–925	40–78	0.055–0.38	90–800	9	0.2
High-density polyethylene	940–960	14.5–38	0.4–1.5	2–130	32	1.2
Polystyrene	960–1,040	25–69	4–5	1–2.5	70	2.5
Nylon 6	1,120–1,140	43–79	2.9	20–150	85	2.3
Nylon 6,6	1,130–1,150	12.4–94	2.5–3.9	35–300	103	3.1
Starch	1,000–1,390	5–6	0.125–0.85	31–44	52	2.4
PLA	1,210–1,250	21–60	0.35–3.5	2.5–6	51–70	4.2
PHA	1,180–1,260	18–24	0.7–1.8	3–25	94	2.7
Thermoset resin						
Polyester	1,040–1,400	41.4–89.6	2–2.6	2–2.6	70–110	2–4
Vinylester	1,200–1,400	69–83	3.1–3.8	4–7	130–140	3
Epoxy	1,110–1,400	55–130	3–6	2–10	110–150	3–4
Phenolic	1,160–1,210	50–60	4–7	1	80–135	2–4

feasibility and sustainability potential of animal-based biocomposites and motivate further research into microstructural tailoring, hybridization with mineral phases and long-term durability under realistic service conditions:

$$E = \frac{L^3}{48I}\left(\frac{P}{\delta}\right) \tag{1}$$

$$\sigma = \frac{3}{2}\left(\frac{\mathrm{P}L}{wt^2}\right) \tag{2}$$

$$\rho_c = 1/\left(\frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}\right) \tag{3}$$

$$V_v = \left(\frac{\rho_a - \rho_c}{\rho_a}\right) \tag{4}$$

where E represents the flexural modulus, σ represents the flexural strength, L represents the distance between support spans, w represents the width of the beam specimen, t represents the beam thickness, I represents the beam moment of inertia, δ represents the mid-span deflection and P represents the applied force. (P/δ) represents the slope of the force vs deflection plot. σ for the biocomposites is estimated using the peak value of "P" of the respective plot. In equations (3) and (4), $\mathrm{W_f}$ and Wm represent the weight fractions of the fibers and matrix. ρ_f, ρ_m and ρ_c represent the density of the fibers, matrix and composites, respectively. ρ_a and V_v represent the actual density and volume fraction of voids in composites. The actual density, ρ_a, is estimated using the volume and weights of fibers and the matrix used to fabricate the composites (Nanda and Satapathy, 2017). The schematic and equipment setup for testing the mechanical behavior of biocomposites are shown in Figures 10 and 11, respectively.

To perform volume fraction measurement of biocomposites, the density of each of the constituents must be estimated, and volume fraction is calculated using equations (5)–(7):

$$V_f = \frac{\rho_{Laminate} - M_{Silk}}{\rho_{Silk} M_{Laminate}} \tag{5}$$

$$V_r = \frac{\rho_{Laminate}}{\rho_{Epoxy}} \times \frac{M_{Laminate} - M_{Silk}}{M_{Laminate}} \tag{6}$$

$$V_v = 1 - (V_f + V_r) \tag{7}$$

ρ_{Epoxy} represents the density of epoxy, ρ_{Silk} represents the density of silk fiber, $\rho_{Laminate}$ represents the density of laminate, V_f represents the volume fraction of fiber, V_r represents the volume fraction of resin, $M_{Laminate}$ represents the measured mass of the laminate, M_{Silk} represents the measured mass of the silk fibers and V_v represents the void volume fraction (Hamidi *et al.*, 2018). The percentage of water absorption can be calculated using equation (8). To calculate the thermal stability, thermogravimetric analysis is used. The experiment is performed at temperatures

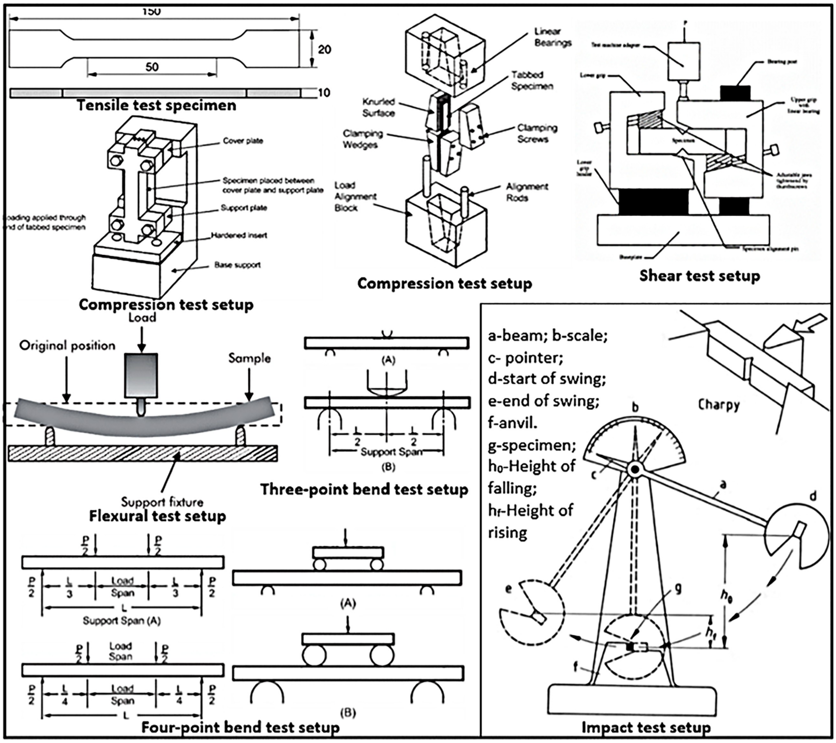

Figure 10. Schematic setup for testing the mechanical behavior of biocomposites (Zhao and Guo, 2014)

between 25°C and 600°C (heating rate −10°C/min) with nitrogen to prevent oxidation. The temperature at predetermined weight loss is then estimated. Equation (9) is used to obtain the degree of crystallinity of the biocomposite. Where ΔH_m and ΔH_{cc} represent the enthalpy of fusion and cold crystallization at melting and crystallization temperatures, respectively, w represents the weight fraction of neat polymer in the sample, and ΔH^0_m represents the melting enthalpy of the 100% crystalline polymer (Aranberri *et al.*, 2017; Jerabek *et al.*, 2010).

$$WA\ (\%) = \frac{wet\ weight - conditioned\ weight}{conditioned\ weight} \times 100 \quad (8)$$

$$X_c(\%) = \frac{100}{w} \times \frac{|\Delta H_m - \Delta H_{cc}|}{\Delta H^o_m} \quad (9)$$

9. Challenges of design, processing, manufacturing and characterization of animal-based reinforced bio-composites

The design, processing, manufacturing and characterization of animal-based reinforced biocomposites are accompanied by a set of challenges that are often more complex than

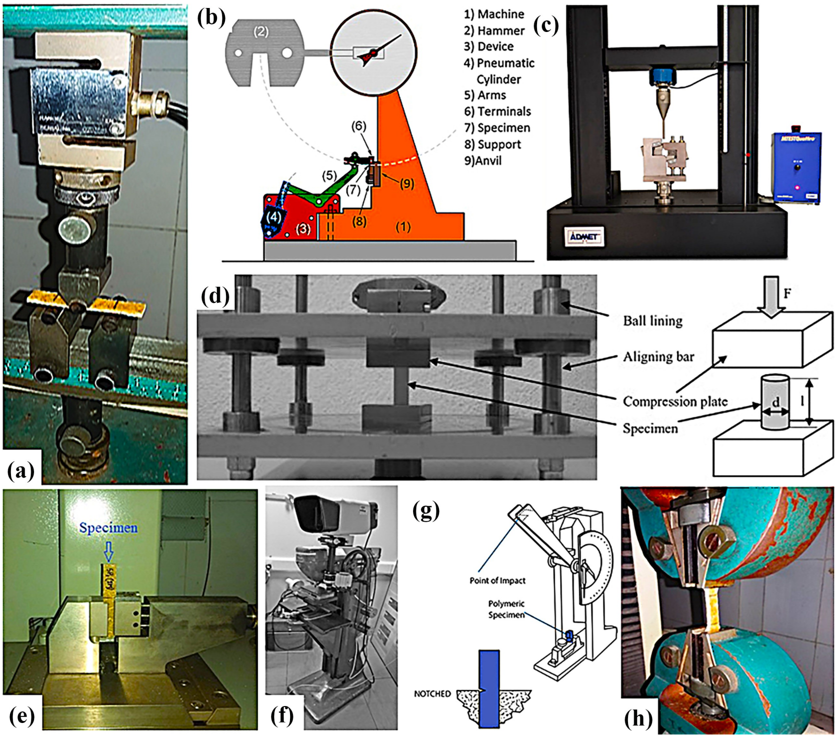

Figure 11. Equipment setup for (a) flexural test, (b) Charpy impact test, (c) shear test, (d) compression test, (e) hardness test, (f) hardness test, (g) Izod impact test and (h) tensile test (Ferreirós *et al.*, 2018; Moore and Booth, 2015)

those encountered with conventional synthetic or even plant-based systems. At the design stage, one of the most fundamental issues is the inherent variability of animal-derived reinforcements such as feathers, wool, silk, hair, eggshell and bone-derived particles (Roy *et al.*, 2025). Their dimensions, microstructure and chemical composition can vary with species, age, diet and even body location (Oladele *et al.*, 2023). As a result, several studies report large scatter in mechanical properties and difficulties in generating reliable design allowables (Al-Shalawi *et al.*, 2023). Where glass or carbon fibers are sold with tight specifications, keratin fibers or eggshell powders often lack standardized grades, making it challenging to predict stiffness, strength and long-term behavior using conventional micromechanical models. This variability also complicates numerical simulation; models that work reasonably well for plant fibers frequently require re-parameterization or additional assumptions when applied to hollow feather fibers or highly crystalline silk (Kurien *et al.*, 2022a, 2022b).

Processing presents another major bottleneck. Most animal fibers are rich in proteins (keratin, collagen and fibroin) and are thermally less stable than typical polymer matrices (Banasaz and Ferraro, 2024; Timorshina *et al.*, 2022). Many thermoplastics are processed above 170°C–200°C, a regime where feathers, wool or hair begin to degrade, discolor or emit volatiles (Röhl and Müssig, 2022). Several experimental studies on feather- and wool-reinforced polypropylene or PLA highlight a trade-off between achieving good melt flow and avoiding thermal damage to the reinforcement; excessive residence time or shear leads to embrittlement and loss of tensile strength and moisture sensitivity further complicates processing (Kukcu and Dasdemir, 2024). Keratin fibers are hygroscopic and can carry significant bound water; if not carefully dried, this moisture can generate voids, porosity and hydrolytic degradation during extrusion or injection molding (Ramesh *et al.*, 2022). By contrast, mineral reinforcements such as eggshell or bone-derived hydroxyapatite are less moisture-sensitive but can agglomerate easily, requiring high shear to disperse, again at the risk of degrading the organic matrix or fibers in hybrid systems (Oladele *et al.*, 2022a, 2022b).

Interfacial adhesion and surface treatment are recurring themes across the literature (Kabir *et al.*, 2012; Maiti *et al.*, 2022). The outer surfaces of feathers and wool are coated with lipids and possess scale-like or smooth morphologies that do not bond strongly to nonpolar matrices (Ghosh *et al.*, 2015). Many authors therefore use alkaline treatment, oxidation or coupling agents to improve wetting and create chemical bridges (Kabir *et al.*, 2012; Khalid *et al.*, 2021; Mohammadi *et al.*, 2024). While such treatments can significantly improve tensile and flexural properties (Feng *et al.*, 2020; Khan *et al.*, 2018), they introduce new challenges: process complexity, chemical waste, possible fiber damage and difficulties in scaling from laboratory to industrial quantities (Mundhe *et al.*, 2024; Ghosh *et al.*, 2025). Excessively aggressive treatments can erode the cuticle layers of keratin fibers (Onyuka, 2010; Duit, 2016) or partially demineralize or over-react eggshell-based fillers, altering phase composition and degrading mechanical performance (Owuamanam *et al.*, 2021; Sunardi *et al.*, 2023). For mineral fillers, high loadings often increase stiffness but simultaneously reduce impact strength due to brittle behavior and poor stress transfer (Altay *et al.*, 2021), and induce microcracking driven by thermal expansion mismatch between filler and matrix (Awaja *et al.*, 2016). Balancing fiber or particle content, surface modification and processing constraints is therefore nontrivial, as emphasized in filler and natural-fiber composite reviews (Shubhra *et al.*, 2013; Ahmed *et al.*, 2025).

On the manufacturing side, the choice of technique (compression molding, extrusion, injection molding, resin transfer molding and hand lay-up) introduces additional constraints for animal-based biocomposites (Masri and Sam, 2021; Imon, 2024). Injection molding and extrusion are attractive for high-volume production, yet the high shear stresses and repeated passes through the screw tend to shorten fragile fibers such as feathers and hair, reducing aspect ratio and reinforcing efficiency (Rabbi *et al.*, 2021; Elfaleh *et al.*, 2023). Compression molding of preforms or mats can better preserve fiber length but is less suitable for intricate geometries and can suffer from nonuniform fiber distribution (Billah *et al.*, 2021). Hand lay-up and vacuum infusion allow gentle processing of continuous silk or wool fabrics, but they are labor-intensive, sensitive to operator skill and prone to void formation (Imon, 2024). Several studies report that achieving homogeneous dispersion of lightweight hollow fibers (e.g. barbed feathers) is particularly difficult because they float in liquid resins or melt, segregating to the surface; this leads to local stress concentrations and unpredictable mechanical behavior (Murillo *et al.*, 2024). Industrial up-scaling must therefore address not only throughput and cost but also robust handling, dosing and mixing of low-density, irregular reinforcements (Murillo *et al.*, 2024; Olanrewaju *et al.*, 2025).

Characterization of animal-based biocomposites introduces its own set of methodological challenges. Standard test methods for tensile, flexural and impact properties were originally developed for isotropic plastics or synthetic fiber composites, and may not fully capture the anisotropy and heterogeneity of biocomposites (Bharath and others, 2016). Determining the exact fiber volume fraction is nontrivial when dealing with hollow feathers or porous mineral particles; density-based back-calculations can be inaccurate and chemical digestion methods risk altering the microstructure (Patrucco *et al.*, 2024). In mechanical testing, natural scatter arising from biological variability often produces high standard deviations, demanding larger sample sizes and more rigorous statistical treatment (Patrucco *et al.*, 2024). At the microstructural level, distinguishing fiber and matrix contributions in techniques such as DMA, DSC or TGA can be difficult because thermal transitions and degradation peaks overlap (Chang *et al.*, 2020). XRD characterization of keratin and collagen is complicated by their partially crystalline, partially amorphous nature, while SEM sample preparation must avoid artifacts such as charging, shrinkage or pull-out that can misrepresent true interfacial adhesion (Patrucco *et al.*, 2024).

A further challenge emphasized in several works is long-term durability and environmental ageing. Animal-based reinforcements are prone to moisture uptake, microbial attack and UV-induced degradation (Chang *et al.*, 2020). Studies on outdoor exposure of feather- and wool-reinforced composites show gradual reductions in tensile strength and increased brittleness, often attributed to interface degradation, swelling–shrinkage cycles and photo-oxidation of both matrix and fibers (Chang *et al.*, 2020; Patrucco *et al.*, 2024). When biodegradable matrices such as PLA or PHA are used, disentangling the degradation mechanisms of matrix vs reinforcement becomes even more complex (Chang *et al.*, 2020). Accelerated ageing protocols and life-cycle assessments (LCA) are still relatively scarce, and few long-term data sets exist compared with those for glass or carbon fiber composites (Chang *et al.*, 2020).

Finally, there are nontechnical but closely related challenges: sourcing, hygiene and public perception. Animal wastes such as feathers and eggshells are abundant, yet they must be collected, cleaned and sanitized to remove blood, pathogens, fats and odors before use (Murillo *et al.*, 2024). Several studies note that inadequate cleaning can lead to unpleasant smell during processing, corrosion of equipment or even bio-safety issues (Murillo *et al.*, 2024). Standardization of supply chains – from poultry farms or slaughterhouses to compounding facilities – remains underdeveloped in many regions, leading to batch inconsistency and logistic barriers (Olanrewaju *et al.*, 2025). At the same time, regulatory frameworks for using animal by-products in consumer products or biomedical devices can be stringent, requiring traceability and compliance with health regulations (Murillo *et al.*, 2024).

In summary, the literature shows that animal-based reinforced biocomposites hold considerable promise in terms of lightweighting, toughness and waste valorization, but their realization is hindered by multi-scale challenges in design, processing, manufacturing and characterization (Olanrewaju *et al.*, 2025; Chang *et al.*, 2020). Key findings consistently point to the need for better control of raw-material variability, gentler yet efficient processing routes, optimized surface treatments and more sophisticated characterization protocols that capture both the biological complexity and engineering performance of these materials (Masri and Sam, 2021; Patrucco *et al.*, 2024). Addressing these challenges will be essential for transitioning animal-derived reinforcements from niche applications to reliable, industrially adopted components within a circular, bio-based economy.

10. Applications of animal-based reinforced bio-composites

The applications of animal-based reinforced bio-composites span structural, functional and biomedical domains, reflecting both the versatility of animal-derived materials and the drive toward circular-economy solutions, as presented in Table 11 (Dutta *et al.*, 2024; Donato and Mija, 2019; Khan *et al.*, 2022). Keratinous fibers (feather, wool, human hair and silk) and mineralized wastes (eggshell, bone and fish scales) are increasingly exploited as low-cost reinforcements or functional fillers in polymer matrices (Ali *et al.*, 2024; Rahman *et al.*, 2023a, 2023b; Thimmegowda *et al.*, 2025). Their relatively high specific strength and

Table 11. Applications of biocomposites

Animal source/waste	Reinforcement type and form	Typical matrix/system	Processing/product form	Target/demonstrated properties	Application areas	Key advantages	Key challenges
Chicken feathers	Keratin fibers, chopped fibers and mats	PP, PE, PLA, PU and thermoset	Extrusion, injection molding, compression molding and mat infusion	Low density, energy absorption, insulation and flame retardancy	Automotive panels, helmets, packaging, insulation and filtration	Abundant waste, lightweight and good damping	Moisture, odor and dispersion issues
Wool	Staple fibers and woven/nonwoven mats	Epoxy, polyester and PU foams	Lay-up, infusion, molding and foaming	Toughness, damping and acoustic/thermal insulation	Building insulation, textiles and interior panels	Renewable and good fire resistance	Moisture sensitivity and moth attack
Silk	Continuous fibers and fabrics	Epoxy, polyester, PCL and PLA	Lay-up, RTM, film stacking and printing	High strength, modulus and biocompatibility	Biomedical scaffolds, dental composites and sports parts	Superior mechanical performance	Cost, humidity and sensitivity
Human hair/keratin	Short fibers and chopped strands	Polyester, epoxy and concrete	Compression molding, extrusion and concrete mixing	Toughness, crack-bridging and reduced density	Construction boards and low-cost panels	Abundant, low-cost and sustainable	Variable quality and odor
Collagen/keratin proteins	Films, hydrogels and nanofibers	PEO, PVA, PLA and chitosan blends	Electrospinning, freeze-drying and casting	Cell adhesion, elasticity and bioactivity	Wound dressings, drug delivery and scaffolds	Biocompatible and tunable degradation	Low strength and sterilization issues
Eggshells	$CaCO_3$, CaO and hydroxyapatite particles	Polyester, epoxy, PP, PLA and PMMA	Melt compounding, casting and cement mixing	Increased stiffness, hardness, barrier properties and UV-blocking	Toys, machine parts, dental PMMA and packaging films	Low-cost filler and improves stability	Agglomeration and brittleness at high loads
Bone, fish scales	Hydroxyapatite and collagen-HA hybrids	PLA, PCL and cements	Powder blending, 3D printing and injection molding	Bioactivity and osteoconductivity	Bone grafts, dental fillings and orthopedic cements	Chemical similarity to bone	Controlling brittleness/resorption
Chitosan + animal fillers	Chitosan films, hydrogels + $CaCO_3$	Chitosan composites	Casting, cross-linking	Mechanical strength, antimicrobial and UV-blocking	Non-food packaging and mulch films	Biodegradable and strong synergy	Durability and not for food contact

(continued)

Table 11. Continued

Animal source/ waste	Reinforcement type and form	Typical matrix/ system	Processing/product form	Target/demonstrated properties	Application areas	Key advantages	Key challenges
Collagen–keratin blends	Pellicle films, coatings	Protein blends	Casting, spraying	Controlled nutrient release and tailored surfaces	Agricultural seed coatings, cosmetics	Value-added use of waste	Formulation complexity
Feather/silk/ keratin textiles	Nonwovens, yarns and coated fibers	Standalone or blended textiles	Spinning, needling and coating	Breathability, insulation and antibacterial effects	Medical textiles and eco-fabrics	Lower environmental footprint	Durability and washing resistance

stiffness, intrinsic porosity and rich surface chemistry allow them to deliver combinations of lightweighting, toughness, flame retardancy or bioactivity that are difficult to obtain with purely synthetic fillers (Kurien *et al.*, 2022a, 2022b; Khan *et al.*, 2022; Mosnáčková *et al.*, 2021). However, as highlighted in many studies, converting heterogeneous animal wastes into reliable, application-grade reinforcements still requires careful control of processing, interfacial chemistry and long-term stability (Dutta *et al.*, 2024; Donato and Mija, 2019; Kaufmann *et al.*, 2025).

10.1 Structural/automotive applications

In structural and automotive applications, animal-based biocomposites are primarily used where weight reduction, impact absorption and cost savings are critical (Thimmegowda *et al.*, 2025; Kaufmann *et al.*, 2025). CFF–reinforced polymers have been proposed for interior panels, impact-absorbing elements, helmets and car fenders because of their low density, good energy absorption and intrinsic thermal and electrical insulation (Kurien *et al.*, 2022a, 2022b; Khan *et al.*, 2022; Dutta *et al.*, 2024). Kurien *et al.* (2022a, 2022b) report that CFF composites exhibit favorable impact and energy-absorbing behavior, suggesting their use in protective gear and lightweight automotive parts, while Khan *et al.* (2022) emphasize their flame-retardant tendencies, making them interesting for fire-safe housings and electronic casings. Waste eggshell particles, rich in $CaCO_3$, have been used as fillers in polyester, PA12, PMMA and PLA matrices to produce low-cost, stiff, wear-resistant components for machine parts, toys, electrical housings and even aerospace and automotive components (Homavand and Yari, 2024; Mustapha *et al.*, 2020; Alkaron and Alsaadi, 2023; Carranza *et al.*, 2025). These systems typically show improved hardness, stiffness and dimensional stability at relatively low filler contents, although toughness may decrease and careful dispersion is required to avoid embrittlement (Mustapha *et al.*, 2020; Alkaron and Alsaadi, 2023). A key challenge across this literature is optimizing filler loading and surface treatment to exploit stiffness gains without sacrificing impact resistance or processability – particularly important in dynamic, vibration-rich environments like vehicles (Dutta *et al.*, 2024; Mosnáčková *et al.*, 2021; Thimmegowda *et al.*, 2025).

10.2 Packaging and insulation

In packaging and insulation, the combination of low density, biodegradability and functional surface chemistry has inspired a range of applications (Chen *et al.*, 2019; Pardo-Ibáñez *et al.*, 2014; Mihalca *et al.*, 2021). CFF and keratin-based biocomposites have been developed as biodegradable cushion packaging, thermally insulating boards and foam-like materials for protective packaging and building insulation, where moderate mechanical strength is acceptable but low weight, thermal insulation and end-of-life degradability are paramount (Kurien *et al.*, 2022a, 2022b; Khan *et al.*, 2022; Dutta *et al.*, 2024; Strnad *et al.*, 2025). Keratin/thermoplastic films and keratin–cellulose nanocrystal biofilms show enhanced tensile strength, barrier properties and controlled biodegradation, making them candidates for sustainable food or cosmetic packaging, although sensitivity to moisture and processing cost remain obstacles (Pardo-Ibáñez *et al.*, 2014; Mosnáčková *et al.*, 2021; Chen *et al.*, 2019). Eggshell-reinforced starch and PLA films, as well as more recent composite films based on eggshell-derived $CaCO_3$, demonstrate improved tensile strength, elongation and water-barrier performance, as well as UV-blocking capability, suggesting uses in nonfood packaging, flower wraps and UV-sensitive product protection (Homavand and Yari, 2024; Athanasopoulou *et al.*, 2024; Chen *et al.*, 2019). The main challenges here are ensuring hygienic sourcing, overcoming possible odour or contamination concerns and tailoring barrier properties and durability to specific packaging lifetimes (Chen *et al.*, 2019; Khan *et al.*, 2022; Dutta *et al.*, 2024).

10.3 Biomedical and health-care applications

Biomedical and health-care applications form one of the most intensively researched areas for animal-based biocomposites, owing to the intrinsic biocompatibility and bioactivity of proteins such as silk fibroin, collagen and keratin (Li *et al.*, 2023; Ma *et al.*, 2024; Donato and Mija, 2019). Silk-fiber-reinforced polymers and silk-based scaffolds have been explored for bone fixation devices, ligament and tendon repair, dental fiber-reinforced composites and load-bearing tissue scaffolds, leveraging silk's high strength, controlled degradability and favorable cell interactions (Purnomo *et al.*, 2018; Mandal *et al.*, 2012; Sun *et al.*, 2021; Ma *et al.*, 2024). Keratin-based materials – ranging from fibers and films to hydrogels and nanofibers – have been investigated for wound dressings, drug delivery carriers, oral and nerve tissue engineering, and cell-culture scaffolds, often showing good cell adhesion and the ability to incorporate bioactive cues (Donato and Mija, 2019; Mosnáčková *et al.*, 2021; Popescu *et al.*, 2024). Eggshell-derived hydroxyapatite or $CaCO_3$ has been used as a bone substitute and as a reinforcement in PMMA and other dental resins to improve stiffness and radiopacity, though maintaining toughness and fatigue resistance remains challenging (Kattimani *et al.*, 2014; Opriș *et al.*, 2020; Yerou *et al.*, 2025). Key findings across this field underscore the importance of tuning degradation rate, mechanical strength and bioactivity simultaneously – particularly in load-bearing implants where premature degradation or insufficient stiffness could compromise function (Li *et al.*, 2023; Ma *et al.*, 2024; Popescu *et al.*, 2024). Regulatory approval, sterilization compatibility and reproducibility of animal-derived materials are central challenges limiting rapid clinical translation (Opriș *et al.*, 2020; Li *et al.*, 2023).

10.4 Filtration, adsorption, agriculture, textiles and specialty use

Beyond structural and biomedical uses, animal-based biocomposites find applications in filtration, adsorption, agriculture, textiles and specialty functional surfaces (Khan *et al.*, 2022; Solís-Moreno *et al.*, 2021; Zahara *et al.*, 2021). CFF nonwovens and mats have been used as air-filtration media, heavy-metal and phenol sorbents, and oil-absorbent materials due to their high surface area, hydrophobicity and hollow morphology (Solís-Moreno *et al.*, 2021; Zahara *et al.*, 2021; Strnad *et al.*, 2025). Collagen–keratin biocomposites have been developed as pellicle-forming materials for seed coating and controlled release of nitrogen in agriculture, improving germination and early plant nutrition (Niculescu *et al.*, 2019). Feather fibers are increasingly explored as textile fibers in nonwovens and coatings for medical textiles and hygiene products, where their hypoallergenic character and biodegradability may reduce the environmental footprint of the textile industry (Khan *et al.*, 2022; Dutta *et al.*, 2024). Human hair and other keratin fibers have likewise been incorporated into polymer composites for low-cost, lightweight panels in construction and automotive interiors (Rahman *et al.*, 2023a, 2023b; Arinze *et al.*, 2022; Ali *et al.*, 2024). These niche applications often exploit specific properties (e.g. adsorption, acoustic damping and antibacterial activity) more than pure structural performance, but they still face common challenges: variability in waste streams, odour and contamination control and building consistent supply chains (Khan *et al.*, 2022; Dutta *et al.*, 2024; Niculescu *et al.*, 2019).

Current literature shows that animal-based reinforced biocomposites can deliver competitive or unique performance in many sectors, particularly when their natural functionalities – bioactivity, adsorption, flame retardancy and insulation – are harnessed alongside mechanical reinforcement (Khan *et al.*, 2022; Kurien *et al.*, 2022a, 2022b; Dutta *et al.*, 2024). However, the same features that make animal-derived materials attractive (biodegradability, rich chemistry and biological origin) also generate challenges in durability, regulatory acceptance and process control (Li *et al.*, 2023; Opriș *et al.*, 2020; Chen *et al.*, 2019). Continued progress will depend on integrating advanced processing (e.g. electrospinning and additive manufacturing), robust surface-modification strategies and standardized characterization with life-cycle and techno-economic assessment to position these materials realistically in the marketplace (Pardo-Ibáñez *et al.*, 2014; Ma *et al.*, 2024; Kaufmann *et al.*, 2025; Thimmegowda *et al.*, 2025).

11. Future outlooks

The future of animal-based reinforced bio-composites is both promising and multifaceted, offering avenues for material innovation, industrial diversification and meaningful progress toward circular-economy goals. As demonstrated throughout this review, animal-derived reinforcements are abundant, functionally rich and often undervalued. However, their successful integration into mainstream composite technologies will depend on overcoming several scientific and engineering challenges through targeted research. Looking ahead, the next decade of development in this field will likely be shaped by advances in four key domains: standardization and material consistency, process innovation, functional hybrid composites and application-driven performance optimization. A critical future direction lies in establishing standardized characterization protocols and quality benchmarks for animal fibers and mineral particles. Biological variability remains a core limitation that affects mechanical predictability and reliability. The development of material grading systems, similar to those used for plant fibers and synthetic reinforcements, would significantly improve reproducibility. The authors foresee a growing role for machine learning-assisted property prediction, where large data sets of natural fiber morphology, composition and processing history could be used to model mechanical performance and optimize formulation.

Another promising direction is the evolution of processing technologies specifically tailored to animal-based reinforcements. Future work must focus on low-temperature polymer processing, green solvent systems and precision cleaning/sanitization technologies that preserve the structural integrity of keratin, silk, collagen and mineral phases. Emerging techniques – such as reactive extrusion, microwave-assisted compounding, enzymatic surface modification and supercritical CO_2 treatments – hold potential for improving interfacial bonding without damaging the reinforcement. Additive manufacturing (three-dimensional and four-dimensional printing) of silk, keratin hydrogels and eggshell-based bioceramics presents a pathway for fabricating patient-specific biomedical implants and high-value functional components.

The convergence of animal-derived materials with hybrid and multifunctional composite designs represents another frontier. Future research should explore synergistic reinforcement strategies that combine animal fibers with plant fibers, nanocellulose, graphene derivatives or mineral nanoparticles. Such hybrid systems may offer unprecedented combinations of toughness, bioactivity, fire resistance, adsorption capacity and electrical or thermal functionalities. The authors believe that hybridization will be central to designing next-generation bio-composites capable of matching or surpassing the multifunctional performance of synthetic fiber-reinforced polymers. From an application perspective, the future expansion of animal-based bio-composites will rely on application-driven design and regulatory integration. Biomedicine, filtration, environmental remediation, flexible electronics and smart packaging are areas where the intrinsic properties of animal derivatives – biocompatibility, antimicrobial activity and bioactivity – provide clear competitive advantages. However, scaling these applications will require robust sterilization protocols, regulatory compliance and long-term durability studies. Furthermore, LCA and techno-economic analyses must be incorporated into future research to demonstrate commercial viability and environmental superiority over existing solutions. Also, the future of animal-based reinforced bio-composites lies in advancing material standardization, developing specialized processing methods, exploring multifunctional hybrid systems and expanding into high-value application domains. By bridging biological insight with engineering innovation, future research can unlock the full potential of these materials, transforming animal wastes into functional, reliable and commercially competitive composite solutions. Ultimately, the future growth of this field depends on the establishment of sustainable value chains and industrial symbiosis. The authors anticipate that policy incentives, green manufacturing initiatives and global pressure to reduce plastic waste will further accelerate the industrial adoption of more bio-composites.

12. Conclusion

This review has comprehensively examined the diverse applications of animal-based reinforcement in bio-composites. The collective findings demonstrate that animal-derived reinforcements hold enormous but underexplored potential for sustainable composite development. Although plant-based fibers have dominated natural composite research, the literature clearly shows that animal-based materials possess unique structural and chemical features, including high protein content, hierarchical architectures, exceptional specific strength in the case of silk and mineral-rich phases such as $CaCO_3$ and hydroxyapatite in eggshells and bone. These attributes enable distinct mechanical, thermal and functional advantages that can be strategically harnessed in composite systems. Besides, animal-based materials are not seasonal like plants but are more readily available throughout the seasons annually. It was reaffirmed from the review that animal fibers can significantly enhance toughness, crack resistance, impact strength, thermal and acoustic insulation, and – in certain systems – flame retardancy. Mineral-based reinforcements derived from eggshells and bone contribute high stiffness, hardness and biocompatibility, particularly in biomedical and structural applications. When carefully processed and surface-modified, these materials can yield performance levels comparable to or exceeding many plant-based systems, highlighting the importance of optimizing interfacial adhesion, dispersion and thermal processing. The authors observe that animal-based materials also provide functional advantages beyond mechanical performance, such as adsorption capacity for filtration, antimicrobial activity in biomedical films, bioactivity in bone scaffolds and UV shielding in packaging films. These functionalities are difficult to replicate using synthetic reinforcements, demonstrating the broader value of animal waste streams. However, the paper highlights critical challenges that must be addressed for industrial adoption which include variability in fiber morphology, protein composition, mineral content and moisture behavior. These still remains major obstacle to consistency in composite design. Processing challenges – including thermal sensitivity, odor, hygiene issues and difficulties with uniform fiber dispersion – must be overcome through standardized pretreatment, improved compatibilization and process optimization tailored to the biological nature of the materials. Characterization methods must be adapted to account for hierarchical structures, overlapping thermal transitions and complex degradation mechanisms. These challenges underscore the need for interdisciplinary research that combines materials engineering, waste management, biotechnology and manufacturing science.

From the authors' standpoint, the industrial potential of animal-based reinforcements remains largely untapped. The global abundance of these wastes, especially from poultry, livestock and fisheries, presents an opportunity for large-scale waste valorization within a circular economy framework. Their integration into packaging, automotive interiors, building insulation, biomedical devices, agricultural films and filtration technologies promises environmental, economic and societal benefits. Yet, achieving these outcomes will require stronger efforts in developing standardized processing protocols, scalable fiber extraction and cleaning technologies, advanced hybridization strategies and rigorous long-term durability assessment. Thus, animal-based reinforced bio-composites represent a promising frontier in sustainable materials engineering. Their unique combination of lightweight structure, functional versatility and environmental relevance offers a compelling alternative to synthetic and plant-based reinforcements. As authors, we believe that strategically combining these animal-derived materials with innovative processing and hybrid composite designs will accelerate their adoption in high-value applications and contribute significantly to global circular-economy goals.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further reading

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