World Journal of Pharmacy and Medical Science

ISSN: 3049-3501
Impact Factor: 5.157
CODEN (USA): WJPMAA

Review Article
2026 Volume 2, Issue 9

Page No.: 24-32

ANIMAL FIBRES: BIOLOGICAL SOURCES, STRUCTURE, PRODUCTION, ECONOMIC IMPORTANCE AND SUSTAINABLE UTILIZATION-A REVIEW

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Article Received: 16 July 2026 Article Review: 06 August 2026 Article Accepted: 26 August 2026

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DOI: https://doi.org/10.5281/zenodo.22161599

How to cite this Article: Manish Sachan (2026). ANIMAL FIBRES: BIOLOGICAL SOURCES, STRUCTURE, PRODUCTION, ECONOMIC IMPORTANCE AND SUSTAINABLE UTILIZATION-A REVIEW. World Journal of Pharmacy and Medical Science, 2(9): 24-32.

ABSTRACT
Animal fibres are natural fibrous materials obtained from a wide variety of domesticated and wild animals and represent an important component of biological and economic resources. Unlike plant fibres, which are primarily composed of cellulose, most animal fibres are proteinaceous in nature and are mainly constituted by keratin or fibroin. Wool obtained from sheep, cashmere and mohair from goats, angora from rabbits, camel and yak fibres from their respective mammals, and silk from silkworms are among the most important animal fibres used by humans. From a zoological perspective, the production of animal fibres is closely associated with animal taxonomy, morphology, physiology, genetics, nutrition, reproductive biology, environmental adaptation and management practices. Fibre characteristics such as diameter, length, crimp, strength, colour and thermal insulation vary considerably among species and breeds and are influenced by both genetic and environmental factors. Animal fibres also possess considerable ecological and economic significance because they are renewable, biodegradable and often obtained as part of sustainable livestock and sericulture systems. However, challenges including climate change, animal diseases, nutritional limitations, intensive production systems, processing waste and animal welfare concerns can affect the sustainability of fibre production. Recent advances in genetics, breeding, biotechnology and improved animal-management practices provide opportunities for enhancing fibre quality and productivity while maintaining animal health and welfare. This review discusses the major biological sources of animal fibres, their classification, structure, growth and production, factors affecting fibre characteristics, economic and ecological importance, animal welfare considerations, and emerging approaches for sustainable utilization of animal fibres.

KEYWORDS: Animal fibres, Wool, Silk, Keratin, Fibroin, Fibre-producing animals, Sericulture, Livestock, Animal welfare, Sustainable production.

1. INTRODUCTION
Animal fibres constitute an important group of naturally occurring biomaterials that have been utilized by humans for thousands of years. They are primarily derived from the integumentary structures of animals or from specialized secretions produced by certain invertebrates. Historically, animal fibres played a fundamental role in the development of clothing, shelter and other forms of material culture. Even with the rapid expansion of synthetic fibres, natural animal fibres continue to occupy an important position because of their unique combination of physical, biological and functional properties.

From a zoological perspective, animal fibres are particularly interesting because their production is directly related to the biology of the animals from which they originate. The quality and quantity of fibre are influenced by species, breed, genetic constitution, age, sex, physiological condition, nutrition and environmental conditions. In mammals, fibres such as wool, hair and cashmere develop from specialized structures of the skin known as hair follicles. Their formation is associated with a complex process of cellular proliferation and differentiation. In contrast, silk is produced by specialized glands of insects, particularly the larvae of silkworms, and therefore represents a distinctly different biological mechanism of fibre production.

Among mammalian fibres, sheep wool is one of the most extensively produced and commercially important. Wool is predominantly composed of keratin and possesses characteristic crimp, elasticity, moisture-absorbing capacity and thermal insulation properties. Goats produce specialized fibres such as cashmere and mohair, while rabbits are important sources of angora fibre. Camelids such as camels, alpacas and llamas provide fibres that are particularly valued for their softness, thermal properties and adaptation to extreme climatic conditions. Yak fibre and musk ox fibre are also recognized for their excellent insulating properties.

Silk represents another major category of animal fibre. The domesticated silkworm, *Bombyx mori*, produces silk through specialized silk glands during the larval stage. The principal structural protein of silk is fibroin, which is surrounded by a sericin coating. The biological process of silk production is closely associated with the life cycle, feeding behaviour, growth and metamorphosis of the silkworm. Consequently, sericulture provides an important example of the relationship between insect biology and economic production.

The study of animal fibres therefore extends beyond their textile applications. It encompasses animal diversity, evolutionary adaptation, integumentary biology, genetics, physiology, nutrition, ecology, behaviour and economic zoology. Understanding these biological aspects is essential for improving fibre production while maintaining animal health and welfare.

In recent years, increasing attention has also been directed towards the sustainability of animal fibres. Their natural origin and biodegradability provide advantages over many petroleum-derived synthetic fibres. However, fibre production can also be associated with land use, water consumption, greenhouse-gas emissions, animal-management practices and processing waste. Therefore, sustainable animal-fibre production requires an integrated approach combining improved breeding, nutrition, animal health, welfare, resource management and environmentally responsible processing.

The present review provides a zoological perspective on animal fibres, emphasizing their biological sources, classification, structural characteristics, production mechanisms, factors affecting fibre yield and quality, economic importance, ecological significance, animal welfare and prospects for sustainable utilization.

2. Concept and Classification of Animal Fibres

Animal fibres are filamentous structures or protein-based materials produced naturally by animals and utilized by humans for textile, decorative, industrial and increasingly biomedical purposes. Based on their biological origin, animal fibres can broadly be divided into mammalian fibres and insect fibres. Mammalian fibres are generally derived from specialized skin structures, particularly hair follicles, whereas insect fibres are secreted by specialized glands.

2.1 Mammalian Fibres

Mammalian fibres are primarily composed of keratin, a fibrous structural protein rich in amino acids such as cysteine. The formation of keratin fibres occurs within hair follicles through coordinated processes of cell proliferation, differentiation and keratinization.
Important mammalian fibres include:

- Wool from sheep
- Cashmere from goats
- Mohair from Angora goats
- Angora fibre from rabbits
- Camel hair
- Yak fibre
- Alpaca fibre
- Llama fibre
- Qiviut from musk ox

These fibres differ considerably in diameter, length, crimp, colour, lustre, elasticity and thermal properties.

Figure 1: Major sources of animal fibres.

2.2 Insect Fibres

Insect fibres are primarily represented by silk, which is produced by specialized silk glands. The best-known commercial silk is obtained from the domesticated silkworm, *Bombyx mori*. Unlike mammalian fibres, silk is not produced by hair follicles. Instead, silk proteins are synthesized in specialized glands and extruded through the spinneret to form continuous filaments.

Silk mainly contains fibroin, a structural protein, and sericin, a gummy protein that surrounds and binds the fibroin filaments.

3. Major Fibre-Producing Animals

3.1 Sheep and Wool Production

The domestic sheep, *Ovis aries*, is one of the most important fibre-producing mammals. Sheep have been domesticated for thousands of years, and selective breeding has resulted in numerous breeds differing in body size, fleece characteristics, growth rate and fibre quality.

Sheep wool is produced by secondary hair follicles and is composed predominantly of keratin. The fleece generally consists of large numbers of fine fibres arranged in a characteristic crimped structure. Fibre diameter is one of the most important parameters determining wool quality.

From a zoological perspective, wool production is influenced by:

- breed and genetic constitution,
- age of the animal,
- nutritional status,
- seasonal changes,
- reproductive condition,
- environmental temperature,
- disease and parasite burden.

Fine wool is particularly valuable because of its softness and suitability for high-quality clothing. Coarser wool is commonly used for carpets, blankets and other products.

3.1.1 Biological Significance of Wool

The natural wool coat provides sheep with protection against:

- low environmental temperature,
- solar radiation,
- mechanical injury,
- moisture,
- fluctuations in environmental conditions.

Thus, wool should not be considered merely an economic product; it is also an important component of the animal's integumentary system and contributes to thermoregulation and environmental adaptation.

3.2 Goats and Specialized Animal Fibres

Goats are important producers of several high-value animal fibres. Two commercially important fibres are cashmere and mohair.

3.2.1 Cashmere

Cashmere is obtained primarily from specialized fine undercoat fibres of cashmere goats. These fibres are exceptionally fine and provide excellent thermal insulation. The development of the cashmere coat is strongly influenced by seasonal photoperiodic changes. During colder seasons, goats develop a dense undercoat that protects them against low temperatures. This seasonal biology is important in determining both the quantity and quality of harvested cashmere.

3.2.2 Mohair

Mohair is obtained from Angora goats. It is characterized by:

- relatively high lustre,
- smooth surface,
- good tensile strength,
- resilience,
- relatively low felting tendency.

The biological characteristics of the Angora goat, including age, nutrition and genetic background, influence mohair production.

3.3 Rabbit as a Fibre-Producing Animal

The domestic rabbit, *Oryctolagus cuniculus*, is an important source of Angora fibre. Unlike ordinary rabbit hair, Angora fibre is exceptionally long, fine and soft. Angora rabbits possess a dense coat containing large quantities of fine fibres. Fibre production depends on breed, genetic selection, nutrition, age and management practices. The rabbit's rapid reproductive rate makes it biologically attractive for fibre production. However, intensive Angora production requires careful attention to:

- nutrition,
- grooming,
- skin health,
- parasite control,
- temperature regulation,
- prevention of fibre-related health problems.

3.4 Camelids and Their Fibres

Camelids represent an important group of fibre-producing mammals adapted to harsh environmental conditions.

3.4.1 Camel

Camels belonging to the genus *Camelus* produce a valuable fibre characterized by softness, insulation and relatively low weight. Camel fibre is particularly important in regions with arid and semi-arid climates. The camel's fibre coat represents an important adaptation to extreme thermal conditions. It helps reduce heat gain during the day while providing insulation during cold periods.

3.4.2 Alpaca

The alpaca, *Vicugna pacos*, is a South American camelid valued for its fine and soft fibre. Alpaca fibre is available in several natural colours and is widely used in premium textile products. Its biological characteristics include:

- fine fibre diameter,
- good thermal insulation,
- low lanolin content compared with sheep wool,
- natural colour diversity.

3.4.3 Llama

The llama, *Lama glama*, is another South American camelid that produces usable fibre. Llama fibre generally contains both fine undercoat fibres and coarser guard hairs. Selective processing allows the finer component to be used in textile applications.

3.4.4 Yak Fibre

The yak, *Bos grunniens*, is a cold-adapted bovine species associated primarily with high-altitude regions of Central and South Asia. Yaks possess a characteristic coat containing relatively coarse outer hairs and a fine, dense undercoat. The undercoat provides excellent insulation against extremely low temperatures. Yak fibre is valued for:

- softness,
- thermal insulation,
- lightweight nature,
- durability.

From a zoological perspective, yak fibre represents an excellent example of structural adaptation to high-altitude and cold environments.

4. Biological Basis and Structure of Animal Fibres

Animal fibres are closely associated with specialized biological structures and developmental processes in animals. In mammals, most fibres originate from hair follicles, which are complex epidermal structures embedded within the dermis. In insects such as silkworms, fibres are produced by specialized secretory glands. Therefore, the biological mechanism of fibre production differs considerably between mammals and insects. A typical mammalian hair or wool fibre consists of three major structural regions:

4.1 Cuticle

The cuticle is the outermost layer of the fibre. It consists of overlapping scale-like cells that protect the inner portions of the fibre from mechanical and environmental damage. The arrangement and characteristics of cuticular scales influence:

- fibre surface characteristics,
- friction,
- lustre,
- felting behaviour,
- resistance to mechanical damage.

In wool, the distinctive scale structure of the cuticle contributes to its characteristic felting properties.

4.2 Cortex

The cortex forms the major internal portion of most mammalian fibres. It consists of elongated, keratinized cells arranged predominantly along the longitudinal axis of the fibre. The cortex contributes significantly to:

- tensile strength,
- flexibility,
- elasticity,
- mechanical stability.

Differences in cortical cell organization are responsible for some of the variation in fibre characteristics among animal species and breeds.

4.3 Medulla

The medulla is the central region of the fibre and may be continuous, discontinuous or absent depending on species and fibre type. Fine wool fibres generally have little or no prominent medulla, whereas many coarse hairs contain a well-developed medulla. The presence of a medulla can influence fibre density, mechanical behaviour and thermal properties.

5. Hair Follicle and Fibre Formation

The hair follicle is the fundamental biological unit responsible for the production of mammalian fibres. A typical follicle contains several important components:

- hair bulb,
- dermal papilla,
- matrix cells,
- inner root sheath,
- outer root sheath,
- sebaceous gland,
- blood supply and associated connective tissue.

The hair bulb contains rapidly dividing matrix cells. These cells proliferate and subsequently differentiate into the various structural components of the fibre. The dermal papilla provides important signals and nutritional support required for follicular growth. Interactions between epithelial and mesenchymal cells regulate the development and activity of the follicle. Thus, fibre production is a highly coordinated biological process rather than simple secretion of a material.

6. Fibre Growth Cycle

Mammalian hair follicles undergo cyclic phases of activity. The three major phases are:

6.1 Anagen

Anagen is the active growth phase. During this stage, matrix cells undergo rapid proliferation and differentiation, resulting in continuous fibre production. The duration of anagen has a major influence on the final length of the fibre.

6.2 Catagen

Catagen is a transitional phase in which follicular activity decreases. Cell proliferation declines and structural changes occur within the follicle.

6.3 Telogen

Telogen represents the resting phase. Fibre growth is minimal or absent, and eventually the old fibre may be released from the follicle. The relative duration of these phases varies among species, breeds and body regions.

6.4 Biological significance

The regulation of the fibre-growth cycle is influenced by:

- genetics,
- hormones,
- photoperiod,
- nutrition,

- environmental temperature,
- physiological condition.

Seasonal changes in fibre growth are particularly important in animals living in cold climates.

7. Chemical and Biological Composition of Animal Fibres
Most mammalian animal fibres are composed predominantly of keratin, whereas silk is primarily composed of fibroin and sericin.

7.1 Keratin
Keratin is a structural protein rich in amino acids, particularly cysteine. Cysteine residues can form disulfide bonds, which contribute to the strength and structural stability of the fibre. The biological properties of keratin fibres are therefore strongly related to:
- amino-acid composition,
- disulfide bonding,
- hydrogen bonding,
- molecular organization,
- fibre morphology.

Wool, cashmere, mohair and many animal hairs are examples of keratin-based fibres.

Fibroin is the principal structural protein of silk and provides strength and structural stability. Sericin is a glue-like protein surrounding the fibroin filament and helps bind the silk filament during cocoon formation.

8. Factors Affecting Animal Fibre Production
Animal fibre production is a complex quantitative and qualitative trait controlled by multiple biological and environmental factors.

8.1 Genetic Factors
Genetic constitution is one of the most important determinants of fibre characteristics. Breed differences can influence:
- fibre diameter,
- fibre length,
- fibre density,
- crimp,
- colour,
- annual fibre yield.

Selective breeding has therefore played an important role in improving the productivity and quality of fibre-producing animals.

8.2 Age
Fibre characteristics may change with age. Young animals may produce fibres with different diameter and growth characteristics compared with mature animals. Age-related changes can also affect the overall quantity of fibre produced.

8.3 Sex
Sex-related differences may occur because of differences in hormonal status, body size and metabolism. In some species, males and females may show differences in fibre growth and production.

8.4 Nutrition
Nutrition is essential for normal fibre formation. Protein, energy, minerals and vitamins contribute to cellular proliferation and keratin synthesis. Inadequate nutrition may result in:
- reduced fibre growth,
- lower fibre strength,
- changes in fibre diameter,
- increased breakage,
- poor overall fleece quality.

Sulfur-containing amino acids are particularly important for keratin synthesis because of their role in disulfide-bond formation.

8.5 Environmental Conditions
Temperature, humidity, photoperiod and altitude can influence fibre production. Animals living in cold environments often develop dense insulating coats. This is clearly observed in:
- yak,
- camelids,
- sheep,
- musk ox.

Such adaptations demonstrate the close relationship between animal ecology and fibre characteristics.

9. Economic Importance of Animal Fibres
Animal fibres contribute significantly to rural livelihoods, livestock-based economies, handicrafts and textile industries. Fibre-producing animals can provide an additional source of income alongside meat, milk, hides and other livestock products. Important economic benefits include:
- Employment generation
- Rural livelihood support
- Value addition to livestock production
- Export potential
- Traditional handicraft development
- Support for sericulture and allied industries

High-value fibres such as cashmere, fine wool, alpaca and silk can have substantial economic importance because of their specialized characteristics and consumer demand.

10. Ecological Importance of Animal Fibres
Animal fibres are closely associated with the ecology and environmental adaptation of fibre-producing animals. In many species, the fibre coat performs important protective functions before it becomes an economically useful product.

Wool and hair provide insulation against low temperatures and help animals maintain thermal balance. In cold-adapted species such as yak, alpaca and musk ox, the dense undercoat is an important adaptation to extreme climatic conditions. Similarly, camel fibre contributes to adaptation to large fluctuations in temperature in arid environments.

Animal fibres are also part of natural nutrient cycles. After shedding, naturally occurring fibres may undergo gradual degradation through physical, chemical and biological processes. Protein-based fibres can ultimately contribute nitrogen-containing organic material to ecosystems.

From a sustainability perspective, the biodegradable nature of protein-based fibres represents an important advantage over many persistent synthetic fibres. However, the overall environmental impact of animal-fibre production depends on animal husbandry, grazing systems, feed requirements, water use, transportation and fibre processing.

11. Animal Welfare and Ethical Considerations

Animal welfare is an increasingly important component of modern animal-fibre production. Fibre harvesting should be conducted in a manner that minimizes pain, injury, fear and unnecessary stress. Potential welfare concerns may arise from:

- inappropriate shearing,
- poor handling,
- skin injuries,
- parasitic infections,
- inadequate nutrition,
- extreme climatic exposure,
- overcrowding,
- inappropriate fibre-harvesting practices.

In sheep, timely shearing can be beneficial because excessive fleece accumulation may contribute to heat stress and hygiene problems. However, improper shearing can cause cuts and injuries.

Similarly, management of Angora rabbits requires careful attention because excessive matting of the coat may interfere with normal movement and skin health.

Ethical fibre production should therefore incorporate the principles of animal health, adequate nutrition, comfortable housing, appropriate handling and humane harvesting practices.

12. Sustainable Production of Animal Fibres

Sustainable animal-fibre production requires integration of animal biology, environmental management and economic considerations.

12.1 Genetic Improvement

Selective breeding can improve fibre yield and quality while maintaining desirable animal characteristics. Important breeding objectives include:

- increased fibre density,
- appropriate fibre diameter,
- improved fibre length,
- greater fibre strength,
- disease resistance,
- adaptation to local environments.

Modern genomic approaches can potentially accelerate the identification of animals carrying desirable fibre-related traits.

12.2 Nutritional Management

Balanced nutrition supports normal fibre growth and animal health. Adequate protein, energy, minerals and vitamins are essential for maintaining fibre production. Nutritional management should be species-specific because dietary requirements vary among sheep, goats, rabbits, camelids and other animals.

12.3 Improved Animal Health

Diseases and parasites can adversely affect both animal welfare and fibre quality. Regular veterinary care, parasite control and appropriate preventive-health programmes can improve productivity.

12.4 Sustainable Grazing

For grazing animals, appropriate pasture management is essential. Overgrazing can cause:

- soil degradation,
- vegetation loss,
- reduced biodiversity,
- erosion.

Rotational grazing and appropriate stocking densities can help reduce these effects.

13. Animal Fibres as Sustainable Biomaterials

The biological origin and proteinaceous nature of many animal fibres have attracted interest beyond conventional textiles. Keratin obtained from wool and other animal fibres has potential applications in:

- biodegradable materials,
- films and coatings,
- composites,
- tissue-engineering materials,
- drug-delivery systems,
- cosmetic formulations.

Silk fibroin has received considerable scientific attention because of its biocompatibility, mechanical properties and ability to be processed into different biomaterial forms.

Thus, animal fibres are increasingly being investigated as bio-based functional materials, expanding their importance beyond traditional economic zoology.

14. Challenges in Animal Fibre Production

Despite their economic and biological importance, animal-fibre systems face several challenges. Major challenges include:

- Climate change
- Animal diseases and parasites
- Feed and water availability
- Variability in fibre quality
- Labour-intensive production
- Processing costs
- Competition from synthetic fibres
- Environmental concerns associated with livestock production
- Animal welfare requirements
- Changing consumer preferences

Addressing these challenges requires multidisciplinary collaboration among zoologists, animal scientists, geneticists, veterinarians, environmental scientists and fibre-processing specialists.

15. Future Perspectives

The future of animal fibres is likely to depend on the integration of traditional animal husbandry with modern biological technologies. Future research should focus on:

- genomic selection for improved fibre traits,
- climate-resilient breeds,
- improved nutritional strategies,
- disease-resistant animals,
- non-invasive fibre-quality assessment,
- welfare-friendly harvesting techniques,
- waste minimization,
- biodegradable processing methods,
- recycling and value addition,
- development of novel biomaterials from animal proteins.

Greater emphasis should also be placed on conserving indigenous breeds and locally adapted fibre-producing animals. Such breeds may possess valuable genetic characteristics for adaptation to regional climates, disease resistance and efficient utilization of local resources.

16. Comparative Characteristics of Major Animal Fibres.

Table 1: Comparative Characteristics of Major Animal Fibres.

S. No.	Animal	Scientific name	Fibre	Major protein	Important characteristics	Major use
1	Sheep	*Ovis aries*	Wool	Keratin	Crimped, elastic, insulating	Clothing, carpets, blankets
2	Cashmere goat	*Capra hircus*	Cashmere	Keratin	Very fine, soft, warm	Luxury textiles
3	Angora goat	*Capra hircus*	Mohair	Keratin	Lustrous, smooth, durable	Premium textiles
4	Rabbit	*Oryctolagus cuniculus*	Angora	Keratin	Fine, soft, lightweight	Garments, textiles
5	Camel	*Camelus* spp.	Camel fibre	Keratin	Warm, lightweight, insulating	Clothing, blankets
6	Yak	*Bos grunniens*	Yak fibre	Keratin	Fine undercoat, highly insulating	Clothing, handicrafts
7	Alpaca	*Vicugna pacos*	Alpaca	Keratin	Soft, warm, lightweight	Premium clothing
8	Llama	*Lama glama*	Llama fibre	Keratin	Strong, relatively coarse	Textiles, carpets
9	Musk ox	*Ovibos moschatus*	Qiviut	Keratin	Extremely warm and fine	Luxury textiles
10	Silkworm	*Bombyx mori*	Silk	Fibroin	Strong, lustrous, continuous filament	Clothing, biomedical materials

17. Recent Research and Emerging Trends

Research on animal fibres has increasingly moved beyond conventional textile applications toward molecular biology, biotechnology, sustainability and advanced biomaterials. One important research direction is the molecular investigation of hair-follicle development and keratin formation. Understanding the genetic and cellular mechanisms responsible for fibre characteristics may facilitate more precise breeding strategies.

Another emerging area is the use of genomic and transcriptomic technologies to identify genes associated with fibre diameter, growth rate, follicle development and fibre quality. Such approaches may help improve fibre-producing animals without relying solely on conventional phenotypic selection.

Silk research has similarly expanded considerably. Silk fibroin is being investigated as a biomaterial because of its favourable mechanical properties and biological compatibility. This has created opportunities in tissue engineering, drug delivery and regenerative medicine.

There is also growing interest in converting animal-fibre waste into useful products. Keratin-rich waste generated during wool and fibre processing may potentially be recovered and transformed into value-added materials.

18. CONCLUSION

Animal fibres represent an important intersection of zoology, animal biology, ecology and economic development. They originate from diverse animal groups and exhibit considerable variation in their biological sources, structure, composition and functional properties. Mammalian fibres such as wool, cashmere, mohair, angora, camel, yak and alpaca fibres are primarily associated with specialized hair follicles and keratin production, whereas silk represents a distinct insect-derived fibre produced by specialized silk glands. The quantity and quality of animal fibres are determined by a complex interaction between genetics, age, sex, nutrition, physiology, environmental conditions and management practices. The fibre coat also performs essential biological functions, particularly thermal insulation and environmental protection, demonstrating that economically valuable animal products often originate from important adaptive features of animals. From an economic perspective, animal fibres support livestock farming, sericulture, rural employment and traditional industries. At the same time, growing concerns regarding climate change, environmental sustainability and animal welfare require more responsible production systems. Modern advances in genetics, genomics, nutrition and biotechnology offer significant opportunities for improving fibre production while maintaining animal health and ecological sustainability. Furthermore, the potential of keratin and silk proteins as biodegradable biomaterials has opened new research directions in biotechnology and biomedical science.

Overall, the future of animal fibres lies not simply in increasing production but in achieving a balance between animal welfare, biological productivity, environmental sustainability, economic value and technological innovation. A zoological understanding of fibre-producing animals is therefore essential for developing sustainable and scientifically informed animal-fibre systems.

19. CONFLICTS OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript.

20. ACKNOWLEDGEMENT

The author sincerely expresses profound gratitude to the Director, Higher Education, Uttar Pradesh, for providing valuable institutional support, encouragement, and academic motivation. The author also gratefully acknowledges to Dr. Pushpraj Singh, Assistant Professor, Department of Chemistry, Government Girls Degree College Chhibramau, Kannauj, Uttar Pradesh, for valuable guidance, continuous encouragement, and support during the preparation of this review article.

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