

## Insect-Derived Biomaterials Including Chitin Silkworm and Beyond in Sustainable Applications

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Received 12 October 2025 | Revised 10 November 2025 | Accepted 17 December 2025 | Available Online January 12, 2026

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**Citation:** P. Yuvanthi, Mohammed Jawad Ahamed, N. B. R. Pravallika, and M Ashwini (2026). Insect-Derived Biomaterials Including Chitin Silkworm and Beyond in Sustainable Applications. *Biodiversity Reports An International Journal*.

DOI: <https://doi.org/10.51470/BDR.2026.05.01.22>

### Abstract

The growing demand for sustainable and biodegradable materials has intensified research into renewable biological resources as alternatives to petroleum-based products. Insect-derived biomaterials, including chitin, chitosan, and silk proteins obtained from silkworms and other insect species, have emerged as promising candidates due to their biocompatibility, biodegradability, and versatile functional properties. These materials demonstrate expanding applications in biomedical engineering, agriculture, food packaging, textiles, and environmental remediation. This review provides a comprehensive overview of major insect-derived biomaterials, their sources, extraction and processing approaches, and emerging sustainable applications. It also examines current challenges related to large-scale production, commercialization, and regulatory acceptance while highlighting future opportunities within circular bioeconomy frameworks. Advancements in processing technologies and increasing interest in eco-friendly materials position insect-based biomaterials as valuable components of sustainable industrial development and next-generation material innovations.

**Keywords:** insect biomaterials, chitin, chitosan, silkworm silk, bio-based materials, sustainable materials, circular bioeconomy.

### 1. Introduction

The increasing environmental burden caused by synthetic plastics and petroleum-based materials has led to a global search for renewable and environmentally friendly alternatives. Rapid industrialization and growing consumer demand for disposable products have intensified problems related to plastic waste accumulation, greenhouse gas emissions, and ecological degradation. Consequently, industries and research communities are actively exploring biodegradable and bio-based materials capable of replacing conventional non-renewable resources. Among the emerging solutions, biomaterials derived from insects have attracted considerable scientific and industrial interest [1]. Insects represent the most diverse and abundant group of organisms on Earth and possess unique biological structures that can serve as valuable material resources. Unlike many traditional livestock or plant-based raw materials, insect production requires comparatively low land area, water, and feed resources while generating fewer greenhouse gas emissions. Moreover, insects can be reared on agricultural by-products and organic waste, supporting circular bioeconomy principles by converting low-value waste streams into high-value biomaterials [2]. One of the most significant insect-derived materials is chitin, a naturally occurring polymer forming the structural component of insect exoskeletons. Chitin and its derivative chitosan possess properties such as biodegradability, antimicrobial activity, and biocompatibility,

making them useful across biomedical, agricultural, and industrial applications.

Similarly, silk fibers produced by silkworm larvae have been used for centuries in textile manufacturing, and modern research has expanded silk applications into advanced medical and technological fields. Recent advances in biotechnology, nanotechnology, and materials science have broadened the scope of insect-derived materials beyond traditional uses. Researchers are investigating new insect species as potential sources of proteins, waxes, and structural polymers suitable for sustainable materials. Additionally, increasing commercialization of insect farming for food and feed industries generates large quantities of insect biomass residues that can be utilized for biomaterial extraction, thereby enhancing resource efficiency [3-4]. As global industries move toward sustainable production models, insect-derived biomaterials offer promising solutions for biodegradable packaging, medical implants, environmental remediation, and agricultural sustainability. However, challenges related to processing technologies, market acceptance, and regulatory frameworks still require attention. This review aims to provide an overview of insect-derived biomaterials, focusing on chitin, silk, and emerging insect-based materials while examining their applications and future prospects in sustainable development.

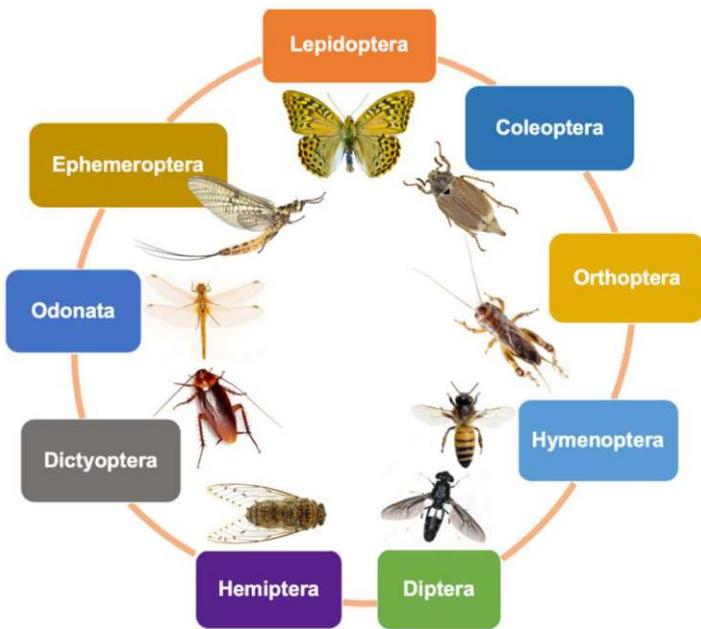


Figure 1 illustrates major insect orders that serve as potential sources of chitin and chitosan, including Lepidoptera, Coleoptera, Orthoptera, Hymenoptera, Diptera, Hemiptera, Dictyoptera, Odonata, and Ephemeroptera. These insects possess chitin-rich exoskeletons that can be utilized for biomaterial extraction after appropriate processing. Among these, beetles, flies, crickets, grasshoppers, and silkworms are particularly important due to their large biomass availability and feasibility of mass rearing. The growing practice of insect farming for food, feed, and waste conversion has further enhanced opportunities to recover chitin as a value-added byproduct, promoting circular bioeconomy principles. Efficient utilization of insect biomass not only reduces industrial waste but also provides sustainable raw materials for biomedical, agricultural, and packaging applications. Consequently, insect-derived chitin and chitosan are emerging as eco-friendly alternatives to conventional marine-based sources and is adopted from [3] copyright permission from MDPI common creative licence.

**2. Major Insect-Derived Biomaterials**

Insect-derived biomaterials originate mainly from structural components of insects as well as secreted substances that possess useful physical and biochemical properties.

Among these materials, chitin is the most abundant and widely studied polymer obtained from insect exoskeletons. Chitin is a polysaccharide structurally similar to cellulose and plays a crucial role in providing mechanical strength and protection to insects. It forms a composite structure along with proteins and minerals, creating a lightweight yet durable exoskeleton [5]. Through chemical or biological processing, chitin can be converted into chitosan, a more soluble and versatile polymer with extensive industrial and biomedical applications. Chitosan exhibits antimicrobial properties, film-forming capability, and excellent compatibility with biological tissues, making it valuable in wound healing, drug delivery, and food preservation. Insects such as crickets, beetles, mealworms, and black soldier flies serve as potential alternative sources of chitin, especially as insect farming expands globally.

Silkworm-derived biomaterials represent another important category. The domesticated silkworm, *Bombyx mori*, produces silk fibers during cocoon formation. Silk primarily consists of fibroin, which provides structural strength, and sericin, a protein that coats fibroin fibers. Silk fibroin has exceptional mechanical strength, elasticity, and biocompatibility, enabling applications in surgical sutures, tissue scaffolds, and regenerative medicine. Sericin, previously discarded during textile processing, is now recognized for its antioxidant and moisturizing properties and is used in cosmetics and pharmaceuticals [6]. Beyond silkworms, other insect species also contribute to biomaterial development. Honeybee products such as beeswax, propolis, and royal jelly have long been used in medicinal and cosmetic applications. Beeswax is used in biodegradable coatings, packaging materials, and pharmaceutical formulations. Propolis contains bioactive compounds with antimicrobial and anti-inflammatory properties, supporting its use in medical and health-related products [7]. Emerging insect farming industries focused on black soldier flies and mealworms generate large volumes of biomass residues after protein extraction for animal feed. These residues are rich in chitin and proteins, which can be processed into biopolymers and bio-based composites suitable for sustainable material production. Research is also exploring insect cuticular proteins and bio-inspired structural materials that mimic natural insect designs for engineering applications. The diversity of insect-derived biomaterials and their multifunctional properties provide opportunities for innovation across various sectors. Continued research into extraction efficiency, material modification, and scalable production technologies is expected to further expand their industrial applications in the coming years.

**Table 1. Major Insect-Derived Biomaterials and Their Sustainable Applications**

Biomaterial Source	Important Biomaterial Obtained	Important Properties	Major Sustainable Applications
Silkworm ( <i>Bombyx mori</i> )	Silk fibroin and sericin	High strength, biocompatibility, biodegradability	Textiles, tissue engineering, wound dressings, cosmetic products
Insect exoskeletons (crickets, beetles, mealworms)	Chitin and chitosan	Biodegradable, antimicrobial, film-forming ability	Biomedical products, biodegradable packaging, agriculture inputs
Black soldier fly larvae residues	Chitin and protein-rich biomaterials	Renewable, recyclable, waste conversion potential	Bioplastics, bio-composites, sustainable packaging
Honeybees	Beeswax and propolis	Antimicrobial, protective, biodegradable	Food coatings, pharmaceuticals, cosmetics, packaging
Mealworms and other farmed insects	Protein and polymeric biomaterials	Lightweight, biodegradable, bio-compatible	Composite materials, feed, packaging materials
Insect cuticular proteins	Structural biopolymers	Mechanical strength, bio-inspired structural potential	Bio-composite materials, engineering applications

### 3. Extraction and Processing Technologies

Efficient extraction and processing technologies are crucial for transforming insect biomass into usable biomaterials while maintaining sustainability and economic feasibility. The quality, purity, and performance of insect-derived materials largely depend on processing techniques used to separate structural polymers and proteins from insect tissues. Traditionally, extraction of chitin from insect exoskeletons involves chemical treatments using strong acids and alkalis to remove minerals, proteins, and pigments. While effective, these chemical processes may generate hazardous waste and increase environmental impact if not properly managed [8]. In recent years, research has increasingly focused on developing eco-friendly extraction methods that reduce chemical consumption and environmental risks. Biological and enzymatic extraction methods utilize microorganisms or enzymes to break down unwanted components while preserving the integrity of chitin and proteins. These green extraction methods not only reduce environmental pollution but also improve product quality and safety for biomedical applications [9]. Processing technologies also influence the physical form and usability of biomaterials. Chitin and chitosan can be converted into powders, films, fibers, hydrogels, or nanoparticles depending on intended applications. Nanotechnology has enabled development of chitosan nanoparticles used in drug delivery systems, water purification, and antimicrobial coatings. Such advanced materials exhibit improved performance due to increased surface area and enhanced functional properties.

Silk processing technologies have also advanced beyond traditional textile applications. Modern methods allow extraction of purified silk fibroin, which can be processed into films, sponges, hydrogels, and nanofibers for biomedical uses. Techniques such as electrospinning and 3D bioprinting enable fabrication of silk-based scaffolds suitable for tissue engineering and regenerative medicine [10]. Emerging technologies including biofabrication and composite material development combine insect-derived polymers with plant or synthetic materials to create biodegradable composites. Such innovations expand potential industrial applications of insect biomaterials while supporting sustainable material production systems.

### 4. Sustainable Applications of Insect-Derived Biomaterials

Insect-derived biomaterials demonstrate wide-ranging applications across multiple sectors due to their eco-friendly properties and functional versatility. One of the most promising areas of application is biomedical engineering, where chitosan and silk-based materials are used in wound dressings, tissue scaffolds, and drug delivery systems. Chitosan exhibits antimicrobial and hemostatic properties that promote faster wound healing, while silk-based scaffolds provide structural support for tissue regeneration [11]. In agriculture, insect-derived biomaterials are increasingly used as plant growth enhancers and biological crop protection agents.

Chitosan formulations stimulate plant immune responses and improve resistance against fungal and bacterial diseases, reducing dependency on chemical pesticides. Seed coatings and biodegradable films derived from chitosan also improve seed germination and crop establishment under stress conditions.

Food packaging industries are exploring biodegradable films made from chitosan and other insect-based polymers as alternatives to plastic packaging.

These materials possess antimicrobial properties that help extend shelf life of perishable food products. Adoption of biodegradable packaging materials contributes to reduction of plastic pollution and supports sustainable consumption patterns [12]. Textile and fashion industries continue to benefit from silk production, while research explores eco-friendly composite materials incorporating insect proteins for advanced fabric applications. Sustainable silk production practices further enhance environmental performance of textile industries. Environmental applications include water purification systems where chitosan acts as a bio-adsorbent capable of removing heavy metals, dyes, and pollutants from contaminated water. Insect farming also contributes to waste management by converting organic waste into valuable biomass that can be further processed into biomaterials. Such diversified applications demonstrate that insect-derived biomaterials can contribute significantly to sustainability goals across industrial sectors.

### 5. Challenges and Commercialization Barriers

Despite significant research progress and promising applications, commercialization of insect-derived biomaterials still faces several constraints. One major challenge is production cost, as extraction and purification processes can be expensive compared to conventional synthetic materials. Scaling up production while maintaining cost efficiency remains a key hurdle for industry adoption [13]. Standardization and quality control also pose challenges, as variations in insect species, feed sources, and processing methods can influence material quality. Establishing uniform production standards is necessary to ensure consistent product performance, especially in biomedical applications where safety requirements are stringent.

Regulatory frameworks governing insect-based materials vary across countries and are still evolving. Lack of clear regulatory guidelines may slow commercialization and limit industrial investment. Consumer perception and acceptance also influence market adoption, particularly in regions where insect-based products are unfamiliar [14]. Infrastructure limitations in insect farming and processing industries further constrain supply chain development. Investments in farming facilities, processing plants, and distribution systems are required to support large-scale production [15]. Addressing these challenges will require collaborative efforts among researchers, industry stakeholders, and policymakers. Technological innovation, supportive regulations, and increased public awareness can accelerate commercialization of insect-derived biomaterials in sustainable industries.

### 6. Future Perspectives and Opportunities

Future research in insect biomaterials is expected to focus on improving extraction efficiency, developing multifunctional materials, and integrating insect-based products into circular bioeconomy systems. Advances in biotechnology may enable genetic and metabolic optimization of insects for enhanced biomaterial production [16]. Growing demand for biodegradable materials in packaging, agriculture, and medicine offers significant opportunities for insect-derived products. Integration of insect farming with organic waste management systems further enhances sustainability [17-18]. Interdisciplinary collaboration among material scientists, biotechnologists, and industrial partners will accelerate innovation and commercialization of insect biomaterials in global markets.

## 7. Conclusion

Insect-derived biomaterials, including chitin, chitosan, silk proteins, and other bio-based compounds, are emerging as promising sustainable alternatives to conventional petroleum-based materials.

Their natural abundance, biodegradability, and multifunctional properties make them suitable for diverse applications across biomedical, agricultural, packaging, textile, and environmental sectors. Increasing interest in circular bioeconomy systems further strengthens the relevance of insects as renewable resources capable of converting organic waste into valuable biomaterials. Advancements in extraction technologies and material processing have expanded the scope of insect-derived materials beyond traditional uses, enabling development of innovative products such as biodegradable packaging, wound healing materials, water purification systems, and sustainable agricultural inputs. At the same time, challenges related to large-scale production, cost efficiency, quality standardization, and regulatory acceptance continue to influence commercialization prospects. Future progress will depend on continued research, technological innovation, and investment in sustainable insect farming and processing infrastructure. Strengthening collaboration among researchers, industries, and policymakers will help integrate insect-based biomaterials into mainstream markets. Harnessing the potential of insect-derived materials can play a significant role in reducing environmental impacts while supporting sustainable industrial development and resource-efficient production systems worldwide.

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