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Sericulture by-products: A comprehensive review on utilization and sustainable development

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Abstract
Sericulture, the cultivation of silkworms for silk production, generates a wide range of by-products at various stages, from mulberry cultivation to post-cocoon processing. In the pre-cocoon stage, mulberry plant residues such as pruned branches, stems, roots, unfit leaves, and fallen fruits are produced in large quantities. These materials can be utilized for compost, vermicompost, livestock feed, herbal teas, nutraceutical extracts, and the preparation of value-added mulberry fruit-based products. During silkworm rearing, substantial quantities of waste are generated in the form of leftover mulberry leaves, rearing bed refuse, and larval litter. These wastes are rich in organic matter and can be converted into organic manure, biofertilizers, and soil conditioners through composting and vermiculture techniques. Silkworm faecal matter, an abundant by-product of the larval stage, contains undigested phytochemicals, dietary fibers, and bioactive compounds from mulberry leaves. It has applications in traditional medicine, pharmaceutical preparations, and as a potent organic fertilizer. After silk reeling, the silkworm pupae emerge as one of the most valuable by-products, being rich in protein, essential amino acids, and lipids. They are used as a food source in certain cultures, processed into poultry and aquaculture feed, and serve as raw material for pupal oil extraction, biodiesel production, and cosmetic formulations. Chrysalis and moth bodies obtained from grainage operations contain chitin, chitosan, and pigments, which have applications in biomedical industries, water purification, and the production of biodegradable materials. The grainage process also yields pierced or cut cocoons, which are unsuitable for reeling but valuable for handicrafts, decorative art, spun silk production, and the manufacture of composite materials. Silk reeling and spinning generate waste such as floss silk, noil, and short fibres, which are repurposed into spun yarn, nonwoven fabrics, upholstery, and insulation materials. Seri-industrial wastewater from degumming, dyeing, and finishing processes contains proteins, pigments, and organic compounds that can be recovered or treated through eco-friendly bioremediation techniques. Additionally, specialized protein extracts such as sericin and fibroin obtained from silk processing have gained commercial importance in cosmetics, pharmaceuticals, wound healing products, edible films, and tissue engineering scaffolds. Recognizing these outputs as valuable co-products rather than waste enhances the economic viability of sericulture, promotes resource efficiency, and supports environmental sustainability. With appropriate processing technologies and market development, sericulture by-products can contribute to a zero-waste industry model, creating opportunities for rural entrepreneurship, improving farmer income, and supporting the bio-circular economy.

Keywords: Sericulture by-products, silkworm pupae, pierced cocoons, mulberry residues, silk reeling waste, sericin, fibroin, chitin, chitosan, organic manure, handicrafts, biofertilizer, value addition, zero-waste sericulture, circular bioeconomy

1. Introduction
Sericulture, the practice of cultivating silkworms for silk production, is an ancient agro-based industry of great economic importance in countries such as India, China, Japan, and Thailand. While traditionally valued for producing high-quality silk, the industry also generates a wide spectrum of by-products during various stages of production, from mulberry cultivation to post-cocoon processing. These include mulberry plant residues, silkworm litter, pupae, pierced cocoons, reeling waste, sericin, fibroin, and seri-industrial wastewater, each of which holds significant potential for value addition. According to Qadir, proper utilization of sericulture by-products can contribute up to 30–40% additional value to the overall silk

production chain, thereby enhancing farmer income and promoting sustainable industry practices. Mulberry cultivation alone produces considerable quantities of by-products such as pruned branches, stems, roots, unfit leaves, and fallen fruits, which can be processed into compost, vermicompost, livestock feed, herbal teas, nutraceutical extracts, and mulberry fruit-based products (Rathore *et al*., 2018) [29]. During the silkworm rearing phase, large volumes of leftover mulberry leaves, bed refuse, and larval litter are generated, rich in organic matter and plant-derived bioactive compounds. These wastes have been effectively converted into organic manure and biofertilizers through composting and vermiculture methods, as demonstrated by Ahmed *et al*. (2020) [1], who reported that one hectare of mulberry cultivation yields approximately 15 metric tonnes of organic waste annually, supplying essential nutrients such as nitrogen, phosphorus, and potassium to agricultural soils. Silkworm faecal matter, another abundant by-product, contains undigested phytochemicals and dietary fibers from mulberry leaves and has found applications in traditional medicine, pharmaceutical formulations, and soil conditioners (Kim *et al*., 2011) [17]. Silkworm pupae, a protein-rich and lipid-rich resource, have been utilized as human food in several Asian countries, as well as in poultry and aquaculture feeds. Recent *in vitro* trials by Thangavel demonstrated that replacing soybean meal with up to 40% silkworm pupae in ruminant diets improved nutrient digestibility and reduced methane emissions by about 20%, indicating both nutritional and environmental benefits. In grainage operations, pierced or cut cocoons unsuitable for reeling are often discarded, yet they serve as raw materials for handicrafts, decorative art, spun silk production, and composite manufacturing (Kumaresan and Sannappa, 2013) [20]. Reeling and spinning processes generate silk waste such as floss, noil, and short fibers, which can be repurposed into spun yarn, nonwoven fabrics, upholstery, and insulation materials (Kumaresan *et al*., 2019) [21]. Furthermore, proteins such as sericin and fibroin extracted from silk have gained significant commercial value in cosmetics, pharmaceuticals, wound dressings, edible films, and tissue engineering scaffolds, as documented by Aramwit *et al*. (2012) [3]. Even seri-industrial wastewater from degumming and dyeing contains valuable proteins and pigments that can be recovered through eco-friendly bioremediation methods (Zhou *et al*., 2023) [40]. Recent reviews (Zhang *et al*., 2021; Kumar and Rajkhowa, 2019) [37, 18] emphasize that reclassifying these outputs as co-products rather than waste aligns with circular bioeconomy principles and supports rural entrepreneurship. By integrating traditional knowledge with emerging biotechnological applications, the sericulture sector can achieve a zero-waste model that enhances profitability, ensures environmental sustainability, and fosters innovation-driven growth.

2. Major By-Products from Sericulture

2.1 Silkworm Pupae

Silkworm pupae are one of the most valuable by-products of the silk industry, obtained after the reeling of silk from the cocoons. In commercial silk reeling, the cocoons are boiled to soften the sericin, and the continuous silk filament is unwound. Once the silk is extracted, the remaining pupae often constituting 50–55% of the cocoon's total weight are separated as a by-product (Kumar & Rajkhowa, 2019) [18]. Large-scale silk production results in substantial quantities of pupae; for example, India produces over 25,000 tonnes annually, much of which is still underutilized despite its nutritional and industrial value (Zhang *et al*., 2021) [37].

Composition

Silkworm pupae are rich in high-quality protein, typically ranging from 50–60% on a dry weight basis, with a balanced profile of essential amino acids such as lysine, methionine, leucine, and valine (Feng *et al*., 2020) [9]. The lipid fraction, accounting for 25–30% of dry matter, contains significant proportions of unsaturated fatty acids, including linoleic acid, oleic acid, and α-linolenic acid, which are beneficial for cardiovascular health (Zhang *et al*., 2021) [37]. Pupae are also abundant in micronutrients such as iron, magnesium, potassium, zinc, and selenium. Additionally, they contain bioactive compounds such as tocopherols (vitamin E), flavonoids, and peptides with antioxidant activity (Kim *et al*., 2011) [17]. The pupal oil has an iodine value indicative of semi-drying oil properties, making it suitable for both nutritional and industrial applications.

Applications

1. **Human Nutrition:** In several Asian countries, including China, Korea, Thailand, and Vietnam, silkworm pupae are consumed as traditional food, either boiled, fried, roasted, or processed into snacks, soups, and sauces (Rumpold & Schlüter, 2013) [30]. The high protein and unsaturated fatty acid content make pupae a sustainable alternative to conventional animal protein sources. Pupae powders are also incorporated into protein supplements, bakery products, and instant noodles to enhance nutritional value (Feng *et al*., 2020) [9]. Recent research has explored enzymatic hydrolysis of pupal proteins to produce bioactive peptides with antihypertensive, antioxidant, and immunomodulatory properties (Li *et al*., 2022) [22].
2. **Animal Feed:** Defatted silkworm pupae meal is an excellent protein supplement for livestock, poultry, and aquaculture. Studies show that replacing up to 40% of soybean meal with pupae meal in poultry diets results in similar growth performance while improving feed efficiency (Dong *et al*., 2018) [8]. In aquaculture, pupae meal supports fish growth, enhances feed digestibility, and improves flesh quality (Wang *et al*., 2020) [34]. Additionally, its lipid-rich composition provides a source of essential fatty acids for aquatic species.
3. **Industrial Uses:** Pupal oil, extracted through solvent or mechanical pressing, is a rich source of polyunsaturated fatty acids and has applications in cosmetics, skincare formulations, and soaps (Kumar & Rajkhowa, 2019) [18]. Due to its high energy density, pupal oil is also a viable feedstock for biodiesel production, with yields comparable to other insect oils (Zhou *et al*., 2020) [38]. Moreover, pupae-derived proteins and chitin can be utilized in biodegradable films, animal health supplements, and as nitrogen-rich fertilizer in organic farming.

2.2. Pierced / Cut Cocoons

Pierced or cut cocoons are obtained primarily from grainage operations, where silkworms are allowed to emerge as moths for breeding purposes. Unlike intact cocoons used for reeling, these are damaged by the emergence hole created by the moth, breaking the continuous silk filament. As a result, they cannot be reeled into raw silk but remain rich in silk fibroin and sericin, making them valuable for various applications (Kumaresan & Sannappa, 2013) [20]. In India alone, thousands of kilograms of pierced cocoons are generated annually, much of which is still sold to spun silk industries at very low prices, despite their potential for value addition (Rathore *et al*., 2018) [29].

Composition

Pierced cocoons consist primarily of silk fibroin (70–75%) and sericin (20–25%) along with pigments in the case of colored silk varieties. Fibroin is a structural protein with exceptional tensile strength and biocompatibility, while sericin is a bioactive protein with moisturizing, antioxidant, and antibacterial properties (Aramwit *et al*., 2012) [3]. The physical structure of pierced cocoons makes them suitable for direct use in crafts or as raw material for further processing into silk fiber products.

Applications

1. **Handicrafts and Decorative Items:** Pierced cocoons are widely used in cottage industries to create handicrafts such as artificial flowers, bouquets, garlands, greeting cards, decorative ornaments, jewelry, and wall hangings. Cocoon-based crafts have a growing niche market in home décor and souvenirs due to their natural texture, aesthetic appeal, and lightweight properties (Nandini *et al*., 2020) [25]. Training women's self-help groups (SHGs) in cocoon crafting has proven to enhance rural employment opportunities and empower artisans economically.
2. **Spun Silk Production:** Although unsuitable for reeling, pierced cocoons can be processed into spun silk. The process involves degumming, carding, and spinning to produce silk yarn for weaving or knitting. Spun silk has a softer texture compared to reeled silk and is used in fabrics, upholstery, and blended textiles (Kumaresan *et al*., 2019) [18].
3. **Composite and Industrial Materials:** Fibroin extracted from pierced cocoons is increasingly used in making biocomposites, medical sutures, and scaffolds for tissue engineering. Additionally, sericin recovered from degumming liquor has applications in cosmetics, hair care products, and biomedical dressings (Aramwit *et al*., 2012) [3].
4. **Educational and Promotional Uses:** Pierced cocoons are also used for educational displays in sericulture training programs and as natural packaging material for eco-friendly promotional products.

2.3. Silk Reeling Waste

Silk reeling waste refers to the fibrous residues generated during the reeling of silk filaments from cocoons in reeling units. This category includes floss silk, pelade, pierced or cut cocoons, reeling noil, and short fibers that cannot be reeled into continuous yarn. It also comprises the unreelable portions of the cocoon, silk threads broken during reeling, and residual gum waste from the degumming process (Kumaresan *et al*., 2019) [21]. In commercial silk production, reeling waste can constitute up to 25–30% of the total cocoon weight (Zhou *et al*., 2020) [38].

Composition

Silk reeling waste is composed primarily of fibroin (around 70–75%) and sericin (20–25%), the two major silk proteins. Fibroin is a fibrous protein with high tensile strength, elasticity, and biocompatibility, while sericin is an amorphous protein with hydrophilic, antioxidant, and antibacterial properties (Aramwit *et al*., 2012) [3]. Small amounts of pigments, wax, and minerals are also present depending on the silkworm variety and reeling process.

Applications

1. **Spun Silk Yarn Production:** The most common use of silk reeling waste is in spun silk manufacturing. The waste is first degummed to remove sericin, then carded and spun into short-staple silk yarn. Spun silk, while less lustrous than reeled silk, is softer, warmer, and more affordable, making it suitable for apparel, upholstery, scarves, and blended fabrics (Kumaresan & Sannappa, 2013) [20].
2. **Nonwoven Fabrics and Insulation Materials:** Silk waste fibers are processed into nonwoven fabrics for applications in filters, thermal insulation, and padding materials. Their light weight, moisture-wicking ability, and biodegradability make them valuable for eco-friendly textile products (Mondal *et al*., 2020) [24].
3. **Protein Extraction for Industrial and Biomedical Uses:** Fibroin extracted from reeling waste is used in biomedical applications such as surgical sutures, wound dressings, drug delivery systems, and tissue engineering scaffolds due to its biocompatibility and mechanical properties (Vepari & Kaplan, 2007) [33]. Sericin recovered from degumming liquor has applications in cosmetics, hair conditioners, moisturizers, and as an additive in biodegradable films (Aramwit *et al*., 2012) [3].
4. **Composites and Reinforcement Materials:** Reeling waste fibers are incorporated into biocomposites with polymers for the production of eco-friendly boards, panels, and molded products. The fibroin's tensile strength and flexibility enhance the mechanical performance of such composites (Rajkhowa *et al*., 2013) [27].
5. **Fertilizer and Soil Conditioner:** After degumming, the residue can be composted to produce nitrogen-rich organic fertilizer, benefiting soil health in sericulture and other agricultural systems (Rathore *et al*., 2018) [29].

2.4. Mulberry Plant Residues

Mulberry (*Morus* spp.) is the primary host plant for silkworms (*Bombyx mori*), and its cultivation generates a variety of plant residues during routine management and harvesting operations. These residues include pruned branches, stems, roots, bark, unfit or diseased leaves, leaf midribs, fallen leaves, and overripe or dropped fruits. Seasonal pruning for canopy management, removal of senescent leaves, and orchard maintenance produce large amounts of lignocellulosic biomass, while unutilized fruits and damaged foliage add to the residue load (Kandari *et al*., 2019) [12]. It is estimated that one hectare of mulberry plantation can yield 4–5 tonnes of dry pruned biomass annually (Rathore *et al*., 2018) [29].

Composition

Mulberry plant residues are rich in lignocellulosic materials such as cellulose, hemicellulose, and lignin, along with secondary metabolites like flavonoids, alkaloids, and phenolic acids. The leaves are particularly rich in protein (15–28% dry weight), vitamins (A, C, E, K), minerals (calcium, potassium, magnesium, iron, zinc), and bioactive compounds such as rutin, quercetin, and chlorogenic acid (Zhang *et al*., 2018) [36]. Mulberry fruits are notable for their anthocyanin content, particularly cyanidin-3-glucoside, and have strong antioxidant activity (Zhou *et al*., 2021) [39]. The bark and roots contain compounds like mulberroside A, kuwanon G, and morin, which have antimicrobial and anti-inflammatory properties (Luo *et al*., 2020) [23].

Applications

1. **Organic Manure and Biofertilizer:** Pruned mulberry branches and leaf litter are shredded and composted to produce nutrient-rich organic manure. Incorporation of

mulberry biomass into vermicomposting systems improves nitrogen, phosphorus, and potassium availability, enhancing soil fertility and structure (Ahmed *et al*., 2020) [1].

2. **Livestock and Poultry Feed:** Mulberry leaves, even those unsuitable for silkworm feeding, can be processed as fodder for ruminants, rabbits, and poultry. Dried leaf meal serves as a protein-rich feed supplement, improving weight gain and milk yield in livestock (Benavides *et al*., 2012) [5].
3. **Mulberry Fruit Processing:** Fallen and excess mulberry fruits are used in value-added products such as jams, juices, wines, vinegar, and dried fruit snacks. They are also processed for natural colorants and nutraceutical powders rich in anthocyanins (Guan *et al*., 2024) [11].
4. **Medicinal and Nutraceutical Products:** Extracts from mulberry leaves, bark, and roots are used in herbal formulations for antidiabetic, antihypertensive, and anti-inflammatory purposes. Leaf tea is a popular nutraceutical beverage due to its ability to modulate blood glucose levels (Choi *et al*., 2016) [6].
5. **Industrial Uses:** Lignocellulosic biomass from pruned branches can be converted into biochar, particle boards, and pulp for paper production. Mulberry wood is also used in handicrafts and musical instrument making due to its fine grain and durability (Kandari *et al*., 2019) [12].

2.5. Silkworm Faecal Matter

Silkworm faecal matter, also known as silkworm excreta or litter, is a major by-product generated during the larval rearing phase. It consists of undigested mulberry leaf residues, plant cell wall fragments, and associated microbial biomass. Large-scale silkworm rearing produces considerable amounts of faecal matter, with estimates ranging from 60–70 kg per 100 disease-free layings (DFLs) (Ahmed *et al*., 2020) [1]. Traditionally discarded or used in a limited capacity as manure, silkworm faecal matter is now recognized as a valuable resource in agriculture, pharmaceuticals, and bioresource utilization.

Composition

Silkworm faecal matter is rich in organic carbon, nitrogen, phosphorus, and potassium, making it an effective organic fertilizer. The nitrogen content ranges from 2.5–3.5%, phosphorus from 1.2–1.8%, and potassium from 1.8–2.2% on a dry weight basis (Ramesh *et al*., 2014) [28]. It also contains crude protein (15–20%), crude fiber (20–25%), chlorophyll derivatives, polyphenols, and bioactive compounds derived from mulberry leaves (Kim *et al*., 2011) [17]. Additionally, certain antimicrobial phytochemicals, flavonoids, and chlorogenic acids are retained in the excreta due to incomplete digestion by silkworms (Kato *et al*., 2009) [15].

Applications

1. **Organic Fertilizer and Soil Conditioner:** Silkworm faecal matter is widely applied to agricultural fields as a slow-release organic fertilizer, improving soil structure, water retention, and microbial diversity (Ahmed *et al*., 2020) [1]. Its high nutrient content promotes plant growth and increases crop yields in vegetables, cereals, and horticultural crops.
2. **Vermicomposting:** When combined with other organic wastes, silkworm faecal matter serves as an excellent feedstock for earthworms in vermicomposting systems. The resulting vermicompost is rich in humic substances and beneficial microbial populations, enhancing soil fertility and suppressing plant pathogens (Kumar *et al*., 2013) [19].
3. **Pharmaceutical and Nutraceutical Uses:** Bioactive compounds in silkworm faecal matter have shown potential in traditional medicine, particularly in East Asia, where it is used as an ingredient in herbal preparations for digestive health and detoxification (Kato *et al*., 2009) [15]. Extracts have demonstrated antioxidant, antimicrobial, and anti-inflammatory properties, attributed to residual polyphenols and flavonoids.
4. **Aquaculture Feed Additive:** Dried and powdered silkworm faecal matter has been tested as a feed supplement in aquaculture, providing plant-derived nutrients and improving water quality by stimulating beneficial microbial activity (Subramanian *et al*., 2012) [32].

2.6. Chrysalis and Moth Bodies

Chrysalis (pupal casing) and moth bodies are sericulture by-products obtained mainly from seed production (grainage) operations, where silkworms are allowed to complete their life cycle and emerge as adults. After mating and oviposition, the spent moths are discarded, while in certain cases the empty pupal cases are separated from grainage waste. These materials, often overlooked, are rich in biopolymers and bioactive compounds with potential industrial, pharmaceutical, and agricultural applications (Rajkhowa *et al*., 2013) [27].

Composition

The chrysalis casing is primarily composed of silk fibroin remnants, chitin, and small amounts of proteinaceous matter. Moth bodies contain chitin, chitosan, cuticular proteins, lipids, pigments (ommochromes, melanin), and trace minerals (Park *et al*., 2020) [26]. Chitin is a polysaccharide with structural and functional uses, while chitosan its deacetylated derivative is valued for its antimicrobial, biocompatible, and biodegradable properties (Kaur & Dhillon, 2014) [16]. Moth bodies may also contain residual lipids and pigments that can be extracted for specialized uses.

Applications

1. **Chitin and Chitosan Production**
   Both chrysalis casings and moth exoskeletons are viable sources of chitin, which can be chemically or enzymatically processed into chitosan. Chitosan has extensive applications in biomedical fields (wound dressings, drug delivery systems), water purification (heavy metal removal, flocculation), food preservation, and agriculture (seed coating, plant growth promoters) (Kaur & Dhillon, 2014) [16].

2. **Pigment Extraction**
   Moth bodies contain natural pigments such as ommochromes, which have potential as eco-friendly dyes for textiles and as biochemical markers in research (Gandhi *et al*., 2013) [10].

3. **Organic Fertilizer**
   Powdered moth bodies and chrysalis residues, after suitable composting, provide a nitrogen-rich amendment for soil, enhancing fertility and promoting plant growth (Ahmed *et al*., 2020) [1].

4. **Animal Feed Supplement**
   Defatted moth body powder can be incorporated in poultry and fish feed formulations as a protein source, although it is less common than silkworm pupae meal due to smaller

volumes of availability (Park *et al*., 2020) [26].

5. **Entomological and Educational Uses**
Preserved moth specimens and chrysalis casings are used in entomological collections, school displays, and training programs in sericulture to illustrate the insect's life cycle.

2.7. Seri-industrial Wastewater
Seri-industrial wastewater refers to the liquid effluents generated during various post-cocoon processing operations such as degumming, dyeing, bleaching, printing, and finishing in silk reeling and weaving units. The largest volume originates from the degumming process, where silk cocoons or waste silk are treated with hot alkaline or soap solutions to remove sericin. This wastewater is typically discharged in large quantities and contains dissolved silk proteins, dyes, pigments, detergents, and trace chemicals (Zhou *et al*., 2023) [40]. If untreated, it can cause environmental pollution; however, it is also a valuable source of recoverable biomolecules and bioactive compounds.

Composition
Degumming wastewater is rich in sericin, constituting up to 2–5 g/L, depending on the reeling or processing method (Aramwit *et al*., 2012) [3]. Sericin is a hydrophilic glycoprotein containing 18 amino acids, with high levels of serine, aspartic acid, and glycine, imparting antioxidant, antimicrobial, and UV-protective properties. Dyeing wastewater contains natural and synthetic dyes, pigments, mordants, and trace heavy metals, while bleaching wastewater may contain hydrogen peroxide residues and organic acids (Yuan *et al*., 2020) [35]. The biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are often high, indicating substantial organic load.

Applications
1. **Recovery of Sericin Protein**
Sericin extracted from degumming liquor is used in cosmetics (moisturizers, anti-aging creams, hair conditioners), pharmaceuticals (wound dressings, drug delivery systems), and biodegradable films. Its antioxidant and moisturizing properties make it suitable for skincare products (Aramwit *et al*., 2012) [3].

2. **Production of Biofertilizers**
Degumming wastewater, after appropriate treatment, can be used for irrigation or converted into biofertilizer due to its organic nitrogen content. The presence of amino acids and peptides supports plant growth and microbial activity in soils (Ahmed *et al*., 2020) [1].

3. **Biopolymer Synthesis and Coatings**
Sericin recovered from wastewater is incorporated into biopolymer blends for food packaging, edible coatings, and functional textiles with antimicrobial properties (Yuan *et al*., 2020) [35].

4. **Pigment and Dye Recovery**
Dye-containing wastewater can be processed to recover natural pigments such as anthraquinones from plant-based dyes or synthetic dyes for reuse, reducing the cost and environmental impact of textile processing (Kant, 2012) [13].

5. **Bioremediation Research**
Certain microorganisms, including *Bacillus* spp. and *Pseudomonas* spp., have been used to treat seri-industrial wastewater while simultaneously producing value-added products like biosurfactants or enzymes (Patil *et al*., 2015).

2.8. Sericin and Fibroin Extracts
Sericin and fibroin are the two major silk proteins obtained during post-cocoon processing. Fibroin forms the structural core of the silk fiber, while sericin is the gummy coating that binds fibroin filaments together. During silk reeling and degumming, sericin is solubilized in hot water or alkaline solutions, while fibroin remains as the main fiber component. Both proteins have been increasingly recognized as high-value biomaterials due to their unique physicochemical and biological properties (Vepari & Kaplan, 2007) [33].

Composition
Fibroin is a fibrous protein rich in glycine, alanine, and serine, organized into β-sheet structures that impart high tensile strength, elasticity, and thermal stability. It is biocompatible, biodegradable, and has tunable mechanical properties, making it suitable for a wide range of applications (Altman *et al*., 2003) [2]. Sericin is a globular glycoprotein with a high content of polar amino acids such as serine, aspartic acid, and glycine, giving it hydrophilic, antioxidant, and antimicrobial properties (Aramwit *et al*., 2012) [3]. It also exhibits UV-absorbing ability and acts as a natural moisturizer.

Applications
1. **Biomedical Applications**
Fibroin is widely used in tissue engineering as scaffolds for bone, cartilage, skin, and nerve regeneration due to its excellent biocompatibility and tunable degradation rate (Kundu *et al*., 2013). It is also employed in wound dressings, surgical sutures, and drug delivery systems. Sericin, with its bioactive properties, is incorporated into wound healing materials to enhance cell proliferation and collagen synthesis (Aramwit *et al*., 2010) [4].

2. **Cosmetic and Personal Care Products**
Sericin is used in skin moisturizers, anti-aging creams, and hair conditioners due to its film-forming, hydration, and antioxidant properties. It helps improve skin elasticity, smoothness, and hair shine by forming a protective layer that retains moisture (Kato *et al*., 1998) [14].

3. **Food Industry**
Both fibroin and sericin have been used as edible coatings to prolong the shelf life of perishable foods. Sericin is incorporated into functional foods for its antioxidant activity, while fibroin films are explored as biodegradable packaging materials (Dash *et al*., 2008) [7].

4. **Pharmaceutical and Nutraceutical Applications**
Fibroin-based nanoparticles and microspheres are developed for controlled drug release, particularly for anticancer, antibiotic, and peptide drugs (Seib, 2018) [31]. Sericin is investigated for its cholesterol-lowering, anti-inflammatory, and neuroprotective effects in nutraceutical formulations (Li *et al*., 2022) [22].

5. **Textile Functionalization**
Sericin recovered from degumming wastewater is reapplied to fabrics to impart antimicrobial, UV-protective, and moisturizing properties, adding value to silk and blended textiles (Yuan *et al*., 2020) [35].

2.9. Specialty Extracts and Novel By-products

In addition to traditional by-products such as pupae, pierced cocoons, reeling waste, and sericin/fibroin proteins, sericulture yields a range of specialty extracts and emerging novel by-products that are gaining scientific and commercial interest. These include bioactive compounds, enzymes, pigments, and secondary metabolites derived from silkworms, mulberry plants, and silk-processing streams. With advances in biotechnology, nanotechnology, and green chemistry, these components are increasingly targeted for extraction and application in high-value industries such as pharmaceuticals, cosmetics, nutraceuticals, and materials science (Mondal *et al*., 2020) [24].

Composition

Specialty extracts may include silk-derived peptides, chitin and chitosan from insect exoskeletons, mulberry anthocyanins and flavonoids, sericin-based oligopeptides, fibroin-derived nanofibrils, and insect wax esters. Other novel components include mulberroside A and DNJ (1-deoxynojirimycin) from mulberry leaves and bark, with potent antidiabetic properties (Luo *et al*., 2020) [23]. Pigments such as ommochromes from moth bodies and carotenoids from mulberry fruits are also part of this category (Gandhi *et al*., 2013) [10].

Applications

1. **Bioactive Peptides and Functional Foods**
   Hydrolyzed silk proteins yield peptides with antioxidant, antihypertensive, and antimicrobial properties, suitable for incorporation into functional foods and dietary supplements (Li *et al*., 2022) [22].

2. **Enzyme Production**
   Certain microbial strains isolated from silkworm litter and rearing environments produce industrial enzymes such as cellulases, proteases, and lipases. These enzymes are explored for textile processing, food industry applications, and environmental bioremediation (Subramanian *et al*., 2012) [32].

3. **Natural Pigments**
   Ommochrome pigments from moth eyes and wings are investigated as eco-friendly dyes for textiles and inks (Gandhi *et al*., 2013) [10], while anthocyanins from mulberry fruits are used as natural food colorants and antioxidant additives (Zhou *et al*., 2021) [39].

4. **Nutraceutical Compounds**
   DNJ from mulberry leaves and bark acts as an α-glucosidase inhibitor, useful in managing type 2 diabetes. Mulberroside A from mulberry root bark exhibits anti-inflammatory, hepatoprotective, and skin-lightening effects, making it a candidate for herbal medicine and cosmeceuticals (Luo *et al*., 2020) [23].

5. **Nanomaterials and Advanced Composites**
   Fibroin nanofibrils and sericin nanoparticles are emerging as carriers for drugs, cosmetics, and active packaging systems. Chitosan extracted from moth and chrysalis bodies is applied in biodegradable films, nanocomposite coatings, and biomedical implants (Kaur & Dhillon, 2014) [16].

6. **Insect Wax and Lipids**
   Wax esters and neutral lipids extracted from certain sericulture by-products have potential in polishes, lubricants, cosmetics, and candle making (Mondal *et al*., 2020) [24].

3. Discussion and Future Prospects

The diverse range of sericulture by-products from mulberry plant residues and silkworm pupae to pierced cocoons, reeling waste, faecal matter, chitin sources, and seri-industrial wastewater illustrates the significant untapped potential within the silk value chain. Historically, these materials were regarded as waste and disposed of with little or no processing. However, recent research and industrial innovations have reframed them as co-products with high nutritional, medicinal, and industrial value (Mondal *et al*., 2020; Rathore *et al*., 2018) [24, 29]. By integrating advanced biotechnological, chemical, and mechanical processing methods, these by-products can be transformed into functional products such as nutraceuticals, biofertilizers, biopolymers, natural pigments, and biodegradable packaging materials. From an economic perspective, value addition to sericulture by-products offers substantial benefits to farmers, small-scale processors, and rural entrepreneurs. For instance, the conversion of silkworm pupae into high-protein feed ingredients or edible insect snacks provides additional income streams, while handicrafts from pierced cocoons support women's self-help groups in rural areas (Nandini *et al*., 2020) [25]. The application of mulberry residues in composting and livestock feed not only reduces waste but also lowers input costs for farming communities (Benavides *et al*., 2012) [5]. Such integrated resource use aligns with the principles of the circular bioeconomy**,** wherein waste from one process becomes the feedstock for another, minimizing resource loss and environmental impact.

Environmental sustainability is another key driver for enhanced utilization of sericulture by-products. Silk reeling waste, degumming wastewater, and dye effluents once major pollutants are now sources of valuable proteins, pigments, and bioactive molecules (Zhou *et al*., 2023) [40]. Green extraction techniques, enzymatic degumming, and microbial bioremediation are replacing conventional, chemically intensive processes, reducing chemical load and improving the eco-profile of the silk industry (Aramwit *et al*., 2012; Yuan *et al*., 2020) [3, 35]. This transition is not only crucial for meeting environmental regulations but also for aligning with consumer demand for eco-friendly and ethically sourced products.

In terms of market trends, the growing global interest in sustainable materials, edible insects, and natural bioactives presents a significant opportunity for sericulture by-product valorization. Functional foods enriched with silk-derived peptides, bio-based cosmetic ingredients like sericin, and biodegradable composites reinforced with silk fibroin are gaining traction in both domestic and export markets (Li *et al*., 2022; Kaur & Dhillon, 2014) [22, 16]. The development of such high-value applications requires collaboration between research institutions, industry stakeholders, and policymakers to establish processing standards, quality control protocols, and certification systems.

Future prospects in this domain depend heavily on technology adoption, policy support, and market development. Investment in decentralized processing units for by-products can create rural employment and reduce post-harvest losses. Capacity-building initiatives to train farmers and artisans in product development, branding, and marketing will be essential to fully realize the socio-economic potential of these resources. Moreover, integrating sericulture by-product utilization into national waste management and bioeconomy policies can accelerate its role in achieving Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production, climate action, and livelihood enhancement.

In conclusion, the holistic valorization of sericulture by-products represents a strategic pathway to transform the silk sector into a zero-waste, high-value, and environmentally sustainable industry. By combining traditional knowledge with modern technological interventions, it is possible to not only enhance resource efficiency but also create diversified income sources for rural communities, thereby strengthening the resilience and competitiveness of the sericulture industry in the 21st century.

4. Conclusion

Sericulture, long valued for its high-quality silk production, generates a diverse range of by-products across its pre-cocoon and post-cocoon stages. These materials once viewed as low-value waste are now recognized as valuable resources with applications in food, feed, pharmaceuticals, cosmetics, agriculture, textiles, and environmental management. From protein-rich silkworm pupae and bioactive sericin to nutrient-dense mulberry residues, natural pigments, chitin-based biopolymers, and recyclable reeling waste, each by-product offers multiple opportunities for value addition. The adoption of modern extraction, processing, and product development technologies has expanded their utility, aligning sericulture with principles of the circular bioeconomy and zero-waste manufacturing. The economic benefits of by-product valorization are particularly significant for rural communities and small-scale producers, offering new income streams, employment opportunities, and reduced dependence on external inputs. Environmentally, the recovery and reuse of silk-processing effluents, protein-rich residues, and biodegradable materials reduce industrial pollution, conserve resources, and contribute to sustainable production practices. However, realizing the full potential of these resources requires coordinated efforts in technology dissemination, infrastructure development, quality control, and market linkages. Looking ahead, the integration of sericulture by-product utilization into national policies on waste management, bio-based industries, and rural development can further accelerate the sector's transformation. With rising consumer demand for eco-friendly, functional, and health-promoting products, sericulture by-products are well-positioned to meet both domestic and international market needs. By bridging traditional sericultural practices with modern innovation, the industry can evolve into a model of sustainable, resource-efficient production that benefits both people and the planet.

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