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SERICULTURE BEYOND SILK PRODUCTION: VALORIZATION OF BY–PRODUCTS AND PATHWAYS TOWARD A CIRCULAR AGRO–INDUSTRIAL SYSTEM

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Abstract: Sericulture represents a traditional agro–industrial system of significant economic and social importance which, in the current context of sustainable development, is undergoing a reorientation toward the full valorisation of resources and generated by–products. The present article aims to critically analyse recent scientific literature on silk production, global development trends in sericulture, and the valorisation potential of secondary streams such as silkworm pupae, sericin, and excreta. The methodology employed consists of a narrative review based on studies published between 2017 and 2025, selected from established international databases. The results highlight that sericulture by–products can be transformed into valuable sources of proteins, biopolymers, and bioactive compounds, with applications in the food, biomedical, cosmetic, and agricultural industries. At the same time, the limitations of the sericulture system are discussed, including the impact of environmental factors, the use of chemical substances, and biological risks affecting the health of silkworms.

Keywords: silkworm, sericulture, silkworm pupae, silk fibre

1. INTRODUCTION

Sericulture represents one of the oldest agro-industrial activities practiced by humankind, with documented origins in ancient China and an evolution closely linked to the economic, social, and cultural development of numerous regions of the world. Over time, this activity has been associated both with international trade exchanges and with traditional agricultural systems based on the efficient use of natural resources. At present, sericulture is recognized as a complex agro-industrial system that goes beyond the exclusive role of producing silk fiber and generates a wide range of biological by-products with valorization potential, such as pupae, sericin, and other secondary biomass streams. Due to its labor-intensive nature and the integration between mulberry cultivation and silkworm rearing, sericulture continues to play an important role in rural economies, especially in Asia, and is considered an activity with high development potential (Tzenov et al., 2025; Tasdeeq, U.I. et al., 2024).

However, silkworm rearing is accompanied by a number of limitations and disadvantages. Among these are the negative impact of climate change on mulberry leaf production, which is essential for feeding the larvae, as well as the intensive use of chemical substances (fertilizers and pesticides) in mulberry cultivation. The sericulture process involves a considerable amount of manual labor, as many stages are still carried out using traditional methods.

In addition, silkworm rearing and cocoon processing involve significant consumption of water, energy, and time, which contributes to increased production costs for both raw silk and silk fabrics, including expenses related to the maintenance of mulberry plantations. Another controversial aspect concerns the extraction of silk fiber, which involves the sacrifice of the larvae, raising ethical issues related to animal welfare.

Moreover, waste generated during the production process can have a negative impact on soil and water resources. Silkworms are susceptible to various diseases, and workers involved in this activity may develop respiratory conditions when working conditions are inadequate. Last but not least, as a product of animal origin, silk has a relatively high ecological footprint, associated with carbon monoxide emissions during the rearing process, compared to other natural fibers such as cotton or wool (Popescu A., et al., 2025).

Recent studies highlight silkworm pupae as an alternative protein source with promising functional properties for the food industry, especially when modern extraction and processing technologies are applied (Zeng, Y. et al., 2025). In parallel, the recovery of sericin from the wastewater generated during the degumming process is increasingly being addressed through “green” extraction methods, which allow both the reduction of environmental impact and the production of biopolymers with industrial and biomedical applications (Burgos Gomez, D.S. et al., 2025).

A significant volume of biomass is represented by silkworm excreta, long considered waste, but currently being investigated as a bioresource for animal feed, fertilizers, carbon-based materials, and the extraction of bioactive compounds, thereby contributing to resource cycle closure in sericulture (Xue, R. et al., 2025). However, the intensification of sericultural systems and the integration of alternative agricultural practices may introduce biological and chemical risks, particularly through the use of botanical insecticides, which have been shown to exert significant toxic effects on Bombyx mori larvae (Rattanapan, A. et al., 2025).

2. MATERIALS AND METHODS

The present article is a narrative review based on a critical analysis of recent scientific literature on sericulture, the valorisation of by-products, and the impact of environmental factors on silkworm health. The selection of studies was carried out using international scientific databases, including Web of Science, Scopus, and the MDPI platform, with primary consideration given to articles published during the 2017–2025 period.

The inclusion criteria targeted studies addressing:

- the use of primary and secondary resources in sericulture (cocoons, pupae, sericin, excreta),
- processing and extraction technologies with relevance to sustainability,
- food, industrial, or biomedical applications of derived products,
- biological and toxicological effects of chemical factors on Bombyx mori.

Studies with incomplete data, or those not directly relevant to the objectives of the review were excluded

The literature analysis was conducted using a comparative approach, aiming to identify current trends, methodological convergences, and limitations reported by different authors. Extracted information was organized thematically to avoid redundancy between sections and to allow an integrated interpretation of the available data. No original experiments were conducted, and all conclusions drawn are based exclusively on previously published data.

3. RESULTS

The reproductive process of the silkworm is cyclical and natural. The female moth emerges from the cocoon already carrying unfertilized eggs and awaits mating with the male for fertilization. After egg laying, the eggs hatch, resulting in larvae that feed on mulberry leaves until maturity. Subsequently, the larvae secrete the silk filament and construct the cocoon, inside which metamorphosis into the moth takes place. After approximately two weeks, the moth emerges from the cocoon, and the biological cycle resumes (Figure 1) (Gnabro, O.G., 2017).

Figure 1 – Stages of the silkworm's development (*Gnabro, O.G., 2017*)

The steady increase in demand has led to an intensification of silk production, which worldwide reached 94 thousand metric tons in 2023, registering an increase of 2.95% compared to the previous year (Figure 2) (*Popescu A., et al., 2025*). At the global level, China is the leading producer of silk, accounting for approximately 70% of world production, followed by India (≈17-18%), while Uzbekistan, Brazil, Thailand, and Vietnam each contribute less than 5%. Although silk represents less than 0.2% of the global textile market, production is distributed across more than 60 countries, with Asia supplying about 90% of mulberry silk and

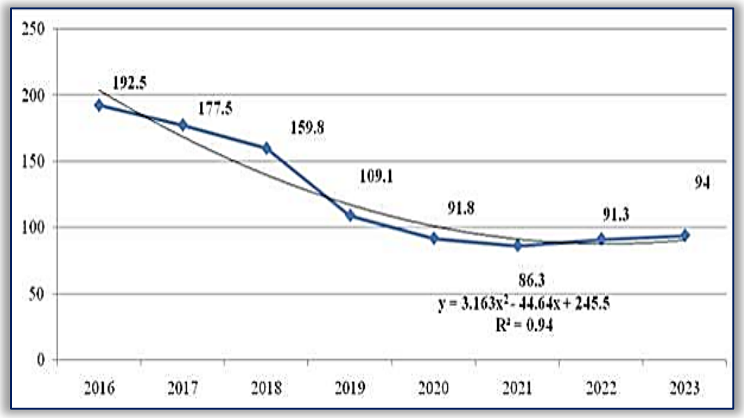

Figure 2 – Evolution of world silk production in the period 2016–2023 (thousands of metric tons) (Popescu A., et al., 2025)

nearly 100% of non-mulberry silk. Sericulture has a major socio-economic impact, providing employment for approximately 1 million people in China, 7.9 million in India, and around 20,000 weaving families in Thailand. It is also a low-investment activity that supports rural economies and helps limit migration to urban areas (*Tasdeeq, U.I. et al., 2024*).

Table 1. Global silk production (in metric tonnes) (*Tasdeeq, U.I. et al., 2024*)

	Countries	2016	2017	2018	2019	2020	2021	2022	2023
1	Bangladesh	44	41	41	41	41	41	41	41
2	Brazil	650	600	650	469	377	373	300	330
3	Bulgaria	9	10	10	10	10	9	7	7
4	China	1,58,400	1,42,000	1,20,000	68,600	53,359	46,700	50,000	50,000
5	Colombia	–	–	–	1	1	1	1	1
6	Egypt	1	1	1	2	2	2	1	1
7	Ethiopia	–	–	–	–	–	–	–	10
8	India	30,348	31,906	35,468	35,820	33,770	34,903	36,582	38,913
9	Indonesia	4	3	3	3	3	3	3	3
10	Iran	125	120	110	227	270	272	275	276
11	Japan	32	20	20	16	16	10	10	10
12	Madagascar	6	7	7	8	8	8	8	8
13	North Korea	365	365	350	370	370	370	370	370
14	Philippines	2	2	2	2	2	2	1	1
15	Romania	–	–	–	1	1	1	1	1
16	South Korea	1	1	1	1	1	1	1	1
17	Syria	0	0	0	1	1	1	1	1
18	Tajikistan	–	–	–	–	–	–	–	227
19	Thailand	712	680	680	700	520	503	435	291
20	Tunisia	2	2	2	2	2	2	1	1
21	Turkey	32	30	30	5	5	5	5	5
22	Uganda	–	–	–	3	3	3	3	3
23	Uzbekistan	1,256	1,200	1,800	2,037	2,037	2,037	2,037	2,037
24	Vietnam	523	520	680	795	969	1,067	1,236	1,448
	Total	1,92,512	1,77,507	1,59,855	1,09,111	91,765	86,311	91,319	93,986

Between 2016 and 2021, global silk production experienced a significant decline, reaching a minimum of 86.3 thousand metric tons in 2021, more than 55% lower than in 2016. Subsequently, production returned to an upward trend, increasing in 2022 and 2023. China and India remain the leading silk producers, together accounting for over 94% of global production; however, their trajectories differ: China experienced a sharp decline followed by a slight recovery, while India recorded steady growth throughout the entire period analyzed.

As sericulture evolves from a traditional industry focused exclusively on silk fiber production into a modern agro-industrial system, the importance of fully valorizing the resources and by-products generated along this value chain is becoming increasingly evident. Traditionally, many of these materials—such as silkworm pupae, reeling residues, or leftover mulberry leaves—have been regarded as low-value waste. Recently, however, the scientific literature has highlighted their economic and functional potential across a variety of applications, thereby promoting a circular economy model oriented toward sustainability and resource efficiency (*Lazăr, R.N., et al., 2025*).

Silk pupae, for example, are recognized for their high content of proteins, essential amino acids, and lipids, making them suitable for use as a nutritional source in human diets, animal feed, or even as raw material for oils, biodiesel, and cosmetic products. In addition, plant residues derived from mulberry cultivation and industrial waste generated during silk processing can be converted into compost, biofertilizers, cosmetic ingredients, or other value-added bioproducts, contributing to loss reduction and optimization of the value chain (*Menaka, S., et al., 2025*).

In addition, protein compounds and biopolymers extracted from silk—such as sericin and fibroin—are increasingly used in biomedical and cosmetic applications, as food ingredients, or in biodegradable materials, reflecting the potential of the "total resource valorisation" approach in sericulture (*Lazăr, R.N., et al., 2025; Mavilashaw, V.P. et al., 2025*).

In this context, Table 2 summarizes the main secondary resources identified in the recent literature, the associated processing methods, and their principal reported applications.

Pupal proteins: extraction technologies and optimization of functional properties

Recent literature highlights a growing interest in the extraction and modification of pupal proteins as ingredients for functional foods and industrial applications. Optimization of ultrasound-assisted

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extraction (UAE) has been reported as an effective strategy to increase yield and to tailor the structural characteristics of proteins, with a direct impact on their functionality (e.g., emulsifying and foaming properties) (*Zeng, Y., et al., 2025*). In more advanced processing studies, the use of multifrequency ultrasound has been associated with differentiated improvements in functional properties: certain frequency combinations enhance emulsification and stability, while others increase solubility and antioxidant capacity, suggesting that ultrasound "settings" can be tailored to the intended final application (*Ge, S. et al., 2022*).

Table 2. Resources derived from sericulture, processing methods and applications reported in recent literature

Sericultural resource	Processing method	Main reported outcomes	Application fields	Source
Silkworm pupae	Ultrasound–assisted extraction	Increased protein yield; improved solubility, emulsifying capacity, and foam stability	Functional foods, protein ingredients	(*Zeng, Y. et al., 2025*)
sericin	Optimized conventional extraction without aggressive chemical substances	Obtaining protein fractions with stable structure and high functionality; reduction of organic load in wastewater	Biomaterials, food applications, biomedical applications	(*Burgos Gomez, D.S.et al., 2025*)
Silkworm excreta	Fermentation, extraction, thermal conversion (biochar)	Reduction of biological risks; recovery of nutrients and bioactive compounds	Animal feed, organic fertilizers, carbon materials	(*Xue, R. et al., 2025*)
Silkworm larvae (*Bombyx mori*)	Exposure to botanical insecticides (neem extract)	Dose– and time–dependent mortality; disruption of detoxification enzymatic system	— (biological limitation)	(*Rattanapan, A. et al., 2025*)

In addition, studies published in food science journals show that assisted methods (UAE/MAE and combinations with freeze-thaw treatments or enzymes) can modify secondary structure, particle size, and interfacial behavior of proteins, thereby supporting their incorporation into food matrices (emulsions, protein beverages, baked products) (*Phuangjit, U. et al., 2023*).

Sericin: recovery and uses in materials and functional applications

Another important stream is sericin, with emphasis on its recovery in the context of reducing the organic load of wastewater and its valorization as a biopolymer. In the literature addressing the transition of the silk industry toward circularity, sericin is explicitly mentioned as a valorisable "waste stream" (alongside low-quality cocoons, plant residues, and litter), being redirected toward materials, fertilizers, or other value-added applications (*Hassan, R. et al., 2025*). In sustainability-oriented reviews, sericulture is described as a system with multidirectional potential, in which biomaterials (fibroin/sericin) support applications in the medical and cosmetic fields, reinforcing the concept of an extended value chain (*Lazăr, R.N., et al., 2025*).

Silkworm excreta: valuable composition and directions for utilization

Silkworm excreta (frass) have shifted from being regarded as waste to being recognized as a bioresource. A recent review describes their use as a source of raw materials through extraction processes (e.g., chlorophyll, pectin, flavonoids, lutein, β-carotene), as well as their application as substrates for the production of value-added products, including uses in the chemical industry, materials science, and microbial bioproduction (*Xue, R. et al., 2025; Hassan, R. et al., 2025*).

Conversion of residues into carbon-based materials: biochar and adsorbents

In addition to agricultural uses, the literature shows that residues from the silk value chain can be converted into biochar and adsorbent materials. An open-access study available on PMC reports the production of biochar derived from silk cocoons and evaluates its performance in contaminant adsorption (both organic and inorganic), using BET/SEM analyses and adsorption/loading parameters (*Marszałek, A. et al., 2025*).

Table 3. Valorization of excreta and residues: target compounds and reported applications

Secondary stream	Target compounds/products	Typical method	Applications	Sursa
Excreta (frass)	Chlorophyll, pectin, flavonoids, lutein, β–carotene	Extraction/fractionation	Repurposing in circular models	(Xue, R. et al., 2025)
Excreta → biochar	Functional biochar	Thermal conversion	Repurposing in circular models	(Jiang, Y. et al., 2025)
Cocoons→biochar adsorbent	Adsorbent for contaminants	Pyrolysis + characterization (BET/SEM)	Repurposing in circular models	(Marszałek, A. et al., 2025)
Litter / mulberry residues / low–grade cocoons / sericin	Various reusable products	Repurposing in circular models	Fertilizers, materials, value–added products	(Hassan, R. et al., 2025)

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There are also studies examining biochar derived from silkworm excreta in agricultural contexts (e.g., effects on soil properties), suggesting that these materials may serve a dual role: residue stabilization and soil amendment functionality (*Jiang, Y. et al., 2025*).

4. CONCLUSIONS

The analysis of the specialized literature highlights that sericulture has now moved beyond its traditional role of silk fiber production, evolving into a complex agro-industrial system with multiple resource valorisation pathways. Although global silk production has experienced significant fluctuations in recent years, China and India remain the main players, and the socio-economic importance of this activity for rural areas is undeniable.

An essential aspect emphasized by recent studies is the high potential of sericultural by-products—pupae, sericin, and excreta—which were previously considered waste but can be transformed into valuable sources of proteins, biopolymers, and functional materials. Modern extraction and processing technologies, particularly ultrasound-assisted and other "green" methods, contribute both to increased efficiency and to a reduced environmental impact.

Nevertheless, sericulture faces major challenges related to high resource consumption, the use of chemical substances, and the biological sensitivity of silkworms to toxic factors. In this context, the adoption of sustainable practices and the integration of circular economy principles represent essential conditions for the long-term development of the sericulture sector.

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