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Silkworm pupae protein: A sustainable food innovation

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Abstract
Silkworm pupae (*Bombyx mori*), a by-product of the sericulture industry, are emerging as a sustainable functional food due to their high protein content, essential amino acids, healthy fatty acids, vitamins, and bioactive compounds. They exhibit antioxidant, antimicrobial, anticancer, and antihypertensive properties, making them valuable for food, nutraceutical, pharmaceutical, and cosmetic applications. Advanced extraction methods have enhanced their utilization in protein-enriched products such as cookies and ice cream. Despite challenges related to allergenicity, perishability, and consumer acceptance, silkworm pupae possess strong potential as an eco-friendly and nutritious alternative protein source for future food systems.

Keywords: Silkworm pupae, Functional food, Sustainable protein, *Bombyx mori*, Bioactive compounds

Introduction
The growing global population is leading to steady increase in the demand for food and animal protein, which in turn raises the costs of traditional feed ingredients such as soybean meal, fish meal and corn. This situation highlights the growing necessity to investigate and assess alternative protein sources. Silkworm pupae (*Bombyx mori*), a by-product of the sericulture industry, offer a promising alternative. Silkworms, scientifically classified under the phylum Arthropoda, class Insecta, and order Lepidoptera, belong to the family Bombycidae and genus *Bombyx*. The silkworm life cycle lasts about seven weeks and has four stages of egg, larva, pupa and adult moth (Sangha *et al.,* 2024) [11]. Silkworm pupae (*Bombyx mori* L.), have been considered a waste material in silk production However, in recent years, studies on its use in different applications have begun to appear. The pupae, which make up approximately 60% of the dry weight of the cocoon, are a rich, high-quality protein source and widely utilized in food, feed, pharmaceutical and cosmetic applications (Rodríguez-Ortiz *et al.,* 2024) [9].

Cultural and Historical Usage
Historically, silkworm pupae have been consumed as food for over two thousand years, with records tracing back to ancient Chinese dynasties. They are eaten in different forms across Asia for example boiled and seasoned as Beondegi in Korea, simmered in soy sauce as Tsukudani in Japan, cooked with bamboo shoots and spices in Northeast India, and fried or roasted as snacks in Vietnam and Thailand (Wu *et al.,* 2021) [14].

Global and Regional Market Overview
The global silkworm pupae protein market is valued at approximately USD 445.5 million in 2025, with the Asia Pacific region dominating the sector by holding 40.75% of the total market share. The regional market has witnessed rapid growth, rising from USD 126.25 million in 2021 to USD 181.54 million in 2025, representing a 69.54% increase. The industry is projected to further expand to USD 368.61 million by 2033, growing at a compound annual growth rate (CAGR) of 9.26% (Future Market Report, 2025) [2].

Functional Foods
Functional foods are defined as foods that provide benefits beyond basic nutrition by enhancing health and reducing disease risk.

They contain biologically active compounds that have positive effects on body functions. Examples include fortified dairy, omega-3 enriched foods, probiotic yogurt and plant-based proteins (Henry, 2010) [3]. Silkworm pupae are classified as functional foods due to their rich profile of essential nutrients and beneficial bioactive compounds.

Nutritional Composition

Silkworm pupae contain 18 amino acids, with particularly high concentrations of phenylalanine and proline compared to hen eggs. Their fatty acid profile is rich in polyunsaturated fatty acids, including omega-3 alpha-linolenic acid. Among vitamins, pupae are especially rich in vitamin E (tocopherol) and vitamin B5, along with smaller amounts of vitamins K1, K2, D1, and D2. The bioactive compounds identified in silkworm pupae include phenolic acids such as ferulic and cinnamic acid, flavonoids such as luteolin and quercetin, and bioactive peptides that show antimicrobial and antioxidant properties. Chitin and chitosan, also derived from pupal shells, have been noted for their immune-enhancing activities (Mahanta *et al.,* 2023) [5].

Extraction Methods

To efficiently extract and preserve these valuable compounds, various modern techniques are employed. Acid-alkaline pH shift extraction involves altering the pH to solubilize and precipitate proteins at their isoelectric point (Niveditha *et al.*, 2020) [6]. Enzymatic extraction uses proteolytic enzymes such as alcalase, papain and trypsin to break down pupal biomass and release proteins and bioactive peptides in an eco-friendly manner. Microwave-assisted extraction utilizes microwave energy to disrupt cellular structures, increasing yield while preserving protein quality (Phuangjit *et al.,* 2024) [7]. Ultrasound-assisted extraction employs high-frequency sound waves to enhance the diffusion of intracellular compounds, yielding up to 68% protein (Ma *et al.,* 2023) [4]. Lastly, Freeze-thaw assisted extraction gently ruptures cells through repeated freezing and thawing cycles, maintaining native protein structures and enhancing solubility (Phuangjit *et al.,* 2024) [7].

Pharmacological Properties

Silkworm pupae proteins have demonstrated remarkable pharmacological properties. The anticancer potential is primarily linked to their protein hydrolysates and peptides, which induce apoptosis in cancer cells by altering mitochondrial pathways upregulating pro-apoptotic proteins (Bax) and downregulating anti-apoptotic proteins (Bcl-2). Antioxidant activity is achieved through the reduction of Reactive Oxygen Species (ROS) and enhancement of enzymatic defences like Superoxide Dismutase (SOD) and Glutathione (GSH). In addition, silkworm pupae extracts show antibacterial activity, particularly against *Staphylococcus sciuri*, due to chitin, chitosan, and pupal oil. They also exhibit antihypertensive effects by inhibiting Angiotensin-Converting Enzyme (ACE) and reducing post-meal blood glucose levels. Together, these bioactivities highlight the potential of silkworm pupae proteins as natural therapeutic agents (Wu *et al.,* 2023) [13]. The pupal oil has also shown potential for cardiovascular protection, immune regulation, and fatigue reduction (Zhou *et al.,* 2022) [15].

Applications

Silkworm pupae and their derived proteins hold immense promise across various industrial sectors. In the food industry, they are used in protein powders, snacks, and functional foods; in cosmetics and pharmaceuticals, their bioactive compounds contribute to formulations with antiaging, antioxidant and anti-inflammatory benefits (Priyadharshini and Swathiga, 2021) [8].

Laws and Regulations

Regulatory frameworks governing edible insects are evolving. According to the U.S. FDA (2016), insects can be considered safe food sources if they are produced under controlled, hygienic conditions. In the European Union, silkworm pupae fall under the "novel foods" category, regulated by EU Regulation 2015/2283, which ensures safety evaluation and traceability. These frameworks are essential for mainstreaming insect-based foods and expanding market accessibility (Zhou *et al.,* 2022) [15].

Disadvantages of using silkworm pupae as food

Despite the advantages, the use of silkworm pupae proteins faces several challenges. These include the risk of microbial contamination from improper handling, the presence of antinutritional factors that may affect nutrient bioavailability, complex and time-consuming extraction methods, and cultural resistance to insect consumption. Additionally, fresh pupae are highly perishable, requiring efficient processing and preservation technologies (Durgam and Reddy, 2024) [1].

Future Perspectives

Silkworm pupa protein (SPP) holds significant promise for future applications due to its high protein content, bioactive compounds, and versatility. It enables up to 76% protein concentration with beneficial acids and vitamins through advanced processing and is positioned as a sustainable food and feed ingredient. SPP also has potential roles in biotechnology and biomedical fields, such as recombinant protein production, vaccine delivery, and drug bioreactors. Future research should focus on large-scale commercialization, safety evaluations and product diversification to fully harness the potential of silkworm pupae protein as a sustainable and functional food ingredient (Wu *et al*., 2023) [13].

Conclusion

In conclusion, silkworm pupae protein represents a highly promising resource for addressing the global need for sustainable and nutritious food alternatives. Rich in protein, vitamins, minerals, and bioactive compounds, it offers diverse functional and health benefits. Its applications extended to the food, nutraceutical, pharmaceutical and other industrial sectors. As research and innovation continue to expand, silkworm pupae protein is poised to become a key component in the next generation of sustainable, health-promoting functional foods.

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