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Sericulture Waste to Wealth: A Review of By-product Utilization and Sustainable Management

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Abstract— *Sericulture, an important component of the rural economy of Northeast India, offers considerable opportunities for sustainable development through the effective utilization of its by-products. Sericulture by-products represent valuable biological resources that can be transformed into economically useful products, contributing to sustainable production systems and a circular bioeconomy. Pupae, larval excreta, leftover host-plant resources, defective cocoons, silk fibre waste, and wastewater from silk processing are among the leftovers produced during silkworm rearing, cocoon processing, and silk manufacture that have the potential to contribute value. Silkworm pupae can be used in food and feed applications due to their high protein and lipid content, while host plant leftovers and larval excrement can be turned into compost and organic manure. Handicrafts, recycled textiles, and other value-added goods can make use of short silk fibres and defective cocoons. Moreover, protein recovery from wastewater from silk production has prospective uses in biomaterials, cosmetics, and related industries. However, limited processing infrastructure, poor technological advancement, difficulties with quality control, and a lack of market connections continue to limit the economic use of these by-products. The main by-products of eri sericulture, their possible uses, and the important factors related to their sustainable use are highlighted in this paper. Additionally, it highlights the necessity of species-specific research, economical processing methods, better waste management, and increased cooperation between government agencies, businesses, farmers, and researchers. By-product valorisation could be integrated into eri sericulture to reduce environmental pollution, increase resource efficiency, diversify farmers' sources of income, and create jobs in rural areas. All things considered, if suggested utilisation paths are both commercially and scientifically viable, a circular bioeconomy approach to eri sericulture can support sustainable silk production and enhance livelihoods in North-east India.*

Keywords— Sericulture; sericulture by-products; waste management; circular bioeconomy; sustainable development; Northeast India.

I. INTRODUCTION

India has a glorious sericulture tradition with the unique feature of producing all the different types of commercial silks, namely mulberry, tropical tasar, oak tasar, eri, and muga. Sericulture is a labour-intensive cottage industry that can be undertaken by rural farmers, entrepreneurs, and artisans with low investment and high returns. Sericulture provides income and employment opportunities to small and marginal farmers and economically weaker sections of society, giving a high benefit-cost ratio compared to other crops through raw silk production [1]. Besides silk production, other beneficial products are released whose economic values are less than the total cost involved; these are often termed "sericulture waste" or "seri-waste". The major wastes and by-products include plant waste (leaves, fruits, stems and barks), silkworm waste, pupal waste, protein waste (sericin and fibroin), post-silk extraction process, etc. With effective utilisation of these products, sericulture can emerge as a promising occupation in farmers' minds, generating additional income and benefiting their economy [2]. According to the annual report of the Central Silk Board, total raw silk production in India during 2024–25 was recorded at 41,121 metric tonnes, marking a 6% increase over the previous year's figures. The mulberry variety continued to hold its position at the top with 75.68% (31,119 metric tonnes), followed by the total raw silk production in the vanya variety, which comprised eri at 19.18%

(7,886 metric tonnes), tasar at 4.58% (1,884 metric tonnes), and muga at 0.56% (232 metric tonnes). Although tasar and eri varieties showed growth in raw silk production at 19% and 10%, respectively, the muga variety declined by 8%. Sericulture not only produces silk but also generates a wide range of valuable by-products that offer substantial economic and environmental benefits. These include silkworm pupae, silkworm litter, reeling waste, perforated cocoons, and mulberry biomass, all of which can be utilized in diverse sectors such as animal feed, bioenergy, cosmetics, pharmaceuticals, and biocomposites. Effective valorization of these by-products enhances the overall profitability of sericulture, supports waste minimization, and strengthens circular bioeconomy models that provide additional income opportunities and improved livelihoods for rural communities [3]. Effective processing methods are required to maximize the return from silk cocoon by-products within the sericulture industry.

TABLE 1
YEAR-WISE RAW SILK PRODUCTION DATA FOR INDIA BY THE FOUR MAJOR SILKWORM VARIETIES: MULBERRY, TASAR, ERI AND MUGA (2020–21 ONWARDS)

Financial year	Mulberry	Tasar	Eri	Muga	Total
2020–2021	23,896	2,689	6,946	239	33,770
2021–2022	25,818	1,466	7,364	255	34,903
2022–2023	27,654	1,318	7,349	261	36,582
2023–2024	29,892	1,586	7,183	252	38,913

Source: Central Silk Board, Ministry of Textiles, Government of India. Production in metric tonnes (MT).

To understand the value-added products produced in sericulture, it is important to identify the biological and industrial by-products generated at different stages of production and evaluate their potential from host plant cultivation to filament extraction. Based on existing literature on sericulture by-products, they are commonly classified as pre-cocoon, cocoon/grainage, and post-cocoon stages according to their origin. Within this value chain, pre-cocoon by-products include various organic wastes and secondary materials produced during host plant cultivation and silkworm rearing before cocoon formation. Wastes originating from host plant cultivation of mulberry (*Morus* spp.) and wild hosts like arjun (*Terminalia arjuna*) and sal (*Shorea robusta*), and silkworm-rearing activity include lignocellulosic and organic wastes. The various wastes include foliage waste, pruned woody biomass, surplus fruits, and rearing bed refuse, along with arjun bark and sal seeds, resin, and leaves. These materials are very rich in their bioactive and nutritional profiles and hence have tremendous scope for value-added applications [4]. Cocoon waste comprising pierced, damaged, or leftover cocoon husks represents a protein-rich product with 45–55% protein content and vital amino acids of high biotechnological and medical value [5]. Another exploitation of cocoons through crafts like "jewellery sets," "home decor," "stationery," and "silk coloured paper" with "silk leather" paint, which are used to decorate various materials, can also help create employment opportunities with a potential increase in post-cocoon income of up to 10–25% [6], [7]. A product that is highly nutritious and can be used as food for both humans and livestock is silkworm pupae. Their derivatives, including pupal oil, skin, and chitin, have applications in cosmetics, pharmaceuticals, and oleochemical industries. Silk proteins such as sericin and fibroin possess important biomedical properties, particularly in wound healing and bioactive textiles, while waste cocoons can be utilized for handicraft production [8]. A report on this silk industrial waste pupae, which is generated by reeling of the cocoons of *Bombyx mori*, *Antheraea mylitta*, and *Antheraea assamensis*, represents a very nutritious waste with a mean energy value of 466 kcal/100 g. Proximate analysis indicates that protein was highest in *B. mori* (55.87%), followed by *A. assamensis* (52.65%) and *A. mylitta* (50.82%), whereas fat content ranged between 23.45 and 28.66% in the above species. Methanolic extracts of these pupae are found to possess significant antioxidant activity, especially in *B. mori*. Thus, the waste pupae can be employed effectively as a natural antioxidant in protein-rich food materials for human food development and as a premium and profitable feed ingredient in animal nutrition [9]. On the other hand, sericin is a cocoon protein that is removed during the degumming process; it accounts for about 20–30% of total silk protein and is present around fibroin filaments, resulting in about 50,000 tons every year. Due to its antioxidant capacity, high water-holding capacity, and the capacity to interact with other molecules through cross-linking and copolymerization, it is an attractive biomaterial with various potential uses in food products, pharmaceuticals, cosmetics, medicine, textiles, and molecular biology. The increasing demand for biodegradable and biocompatible materials has led to an increased interest in non-textile uses of this protein [10]. Although primarily associated with textile production, it has been observed that a substantial quantity of by-products is generated during the process, contributing to the economy. Furthermore, sericulture wastes have recently attracted attention for their sustainable utilization in biofuel production. Overall, traditional sericulture practices show significant potential for expansion into diverse and emerging fields of commercial importance,

including the development of biorefinery-based applications [11]. Efficient utilization and management of these by-products in the production of compost, medicine for humans, handicrafts, and cosmetics can increase the value of the silk industry by up to 40% by converting the by-products into high-value organic manure [6]. Studies have found that the economic benefits of sericulture increase by about 30–40% due to the utilization of various by-products in various fields [3], [12].

The considerable amounts of wastes and by-products generated during silk production hold promising potential for use in various sectors, leading to the development of the sericulture industry. Although the potential for the wastes is being explored extensively, their large-scale utilization and commercialization are yet to reach the desired level with the information available in different published articles. The objective of this review is to bring together existing data on mulberry and non-mulberry sericulture sectors, with special emphasis on recent developments in waste management techniques that are useful in improving the efficiency and growth of sericulture as a whole.

II. MAJOR BY-PRODUCTS OF *BOMBYX MORI* SILK

Mulberry sericulture is an organized system comprising a number of activities, such as mulberry plant (*Morus* spp.) cultivation to produce cocoons by rearing the silkworm (*Bombyx mori*), which are then reeled to obtain the fine silk thread. This system is the backbone of silk production and holds immense importance in providing employment to rural areas [13]. With multiple economic and ecological benefits, moriculture is the foundation of rearing and offers a significant portion of mulberry waste. The biomass not consumed by silkworms also offers several applications, including leaves that are unsuitable for silkworms. Each mulberry plantation yields roughly 4 to 5 tonnes of dried pruned residues per hectare annually [14].

2.1 Mulberry leaves and leaf residue

The leaves of the mulberry plant contain a high content of bioactive compounds, among which alkaloids, flavonoids, polysaccharides, and polyphenols are the most important. Experimental evidence has shown that they exert specific regulation of blood glucose through complex molecular pathways, in addition to protecting pancreatic β-cells and reducing insulin resistance. Beyond this, they enhance lipid metabolism and mitigate oxidative stress, making mulberry leaves a promising therapeutic resource for the comprehensive management of diabetes mellitus [15]. In sheep, the addition of mulberry leaf powder (MLP) at the optimal level of 30% improved dry matter content and average daily gain, while organic matter digestibility, fibre digestibility, microbial protein production, and rumen papillae development increased linearly [16]. Supplementation with 45 g/day of mulberry leaf flavonoids (MLF) from mulberry residues relieved heat stress, increasing milk yield with higher milk protein, improved hormonal profile, and antioxidant activity (GSH-Px), and reduced oxidative stress (MDA), thereby proving to be a cost-effective supplement for increasing productivity under high THI (temperature-humidity index) conditions [17]. Abandoned mulberry tree branches also contain lignocellulose that can be used as a high-quality substrate to produce edible fungi, an important part of recycling in sericulture waste management, by reducing production costs. The process makes use of carbon dioxide that would have been emitted by burning the tree branches [18].

In India, green fodder cultivation covers only 4–5% of arable land, resulting in a 32% deficit of green fodder and 23% deficit of dry fodder for livestock, forcing reliance on low-nutritive crop residues like paddy straw that hinder productivity and health. Fodder trees like mulberry (*Morus* spp.), cultivable on boundaries, wastelands, and roadsides with minimal inputs, water, and labour, offer higher biomass yields per unit area and drought tolerance compared to annual crops. Mulberry leaves provide balanced nutrition with 5–10% crude protein, 9.9–13.85% crude fiber, 28.4% dry matter, energy of 69–86 kcal/100 g, and rich minerals (e.g., 380–786 mg/100 g calcium, 4.7–10.4 mg/100 g iron) alongside vitamins like ascorbic acid (160–280 mg/100 g) [18].

2.2 Mulberry twigs

Mulberry twigs, a sericulture by-product, are known to harbour bioactive compounds with potential health benefits. Researchers have found three flavonoids, namely kuwanon G, kuwanon H, and morusin, which exhibit potent butyrylcholinesterase inhibitory activity that may help prevent Alzheimer's disease. This indicates the effective utilization of mulberry twigs as a valuable resource for producing medicinal or functional materials [20]. Mulberry biomass production can be an important catalyst in the economic development of less-favoured regions, as it can provide supplementary income opportunities and improve the energy security of these areas. The optimal exploitation of the rapid-growing biomass can be an effective means to reduce the import dependency on fossil fuels and stimulate rural development sustainably [21]. Vermicomposting of sericulturally generated waste using *Eudrilus eugeniae* and *Eisenia foetida* earthworms generates a fertilizer rich in 1.8–2.0% nitrogen, 0.6–0.9% phosphorus, and 1.0–1.5% potassium, which is remarkably better than the 0.5%

nitrogen present in conventional farmyard manure (FYM) [22]. With a 60% biomass conversion ratio and a 1:2.3 costing ratio, the process is highly efficient, and even 7.5 MT/ha of the material can substitute the 20 MT/ha needs of FYM for leaf production while sustaining equal leaf yield levels of 48.6–50.4 MT/ha [23]. Practical implementation of the process shows higher production levels, and the V-1 variety mulberry yields are improved from 6.04 MT/ha to 7.23 MT/ha and average cocoon production levels increase from 58.42 kg to 62.46 kg [23]. This process, which improves soil organic matter and enhances soil fertility, decreases cultivation costs by 20% and increases yields by 25%.

The increasing environmental and industrial demands have led to interest in silkworm pupae, an important by-product of silk production from *Bombyx mori*. They have shown considerable potential in human and animal nutrition and pharmaceuticals based on their antioxidant compounds and high unsaturated fatty acid content, such as α-linolenic acid, which has been reported to have cardioprotective, anti-inflammatory, antioxidant, anti-obesity, and neuroprotective properties [24].

2.3 Sericin

Sericin is a biodegradable biomaterial with strong moisturizing and healing effects, making it a perfect candidate for cosmeceuticals. The fact that it is derived from waste materials in the silk industry means that it is a product of the circular economy and a sign of a paradigm shift in the management of natural resources. Despite the scalability and regulatory hurdles, progress in its extraction and testing is increasing its adoption. It is a high-performance natural ingredient for modern skincare due to consumer demand for bioactive ingredients [25]. Sericin, a water-soluble protein of silk that is discarded during the degumming process, has been identified as a potential biomaterial for use in the food industry. With the increasing concern about plastic waste, sericin has been recognized as a biodegradable and valuable material because of its high content of amino acids and bioactivities such as antioxidant and antibacterial activities. Its hydrophilic and biocompatible properties make it even more functional, especially in film formation. Sericin can be used as a potential material in the preparation of biodegradable films when mixed with other biopolymers [26].

TABLE 2
MAJOR BY-PRODUCTS OF *BOMBYX MORI* AND THEIR UTILIZATION

By-product	Source	Potential uses	Critical considerations	References
Mulberry leaves & leaf residue	Unsuitable, excess, or leftover leaves	Livestock fodder, compost and extraction of bioactive compounds	Leaves suitable for silkworm feeding should be prioritized for cocoon production; fodder quality varies with leaf maturity and season.	[27]
Mulberry pruning and woody residues	Branches, stems and shoots removed during pruning	Compost, biomass, extraction of bioactive compounds and potential biochar production	Correct processing of woody residues is required; performance of biochar is dependent on properties and production conditions.	[27], [28]
Mulberry fruits	Fruits harvested or left unused	Juice, jam, dried fruit and other food products	Processing and storage are needed to manage perishability and maintain product quality.	[29]
Silkworm litter and rearing-bed waste	Faeces, leftover leaves and shed material from silkworm rearing	Compost, vermicompost, organic manure and possible biochar applications	Waste may contain pathogens or contaminants; treatment and safe handling are necessary before agricultural reuse.	[24], [27]
Silkworm pupae	Residue after silk reeling	Protein-rich feed ingredients, pupal oil and potential food or industrial ingredients	Processing, storage, microbial safety and allergen management are important.	[27]
Defective cocoons and silk waste	Unreelable cocoons, broken fibres and processing residues	Spun silk, silk-derived materials and biomaterial applications	Fibre quality and the economics of recovery determine commercial feasibility.	[27]
Sericin-rich reeling wastewater	Water generated during cocoon cooking and silk reeling	Recovery of sericin for potential biomaterial, cosmetic and other industrial uses	Recovery technologies and wastewater treatment are required to avoid environmental pollution.	[27]

III. MAJOR BY-PRODUCT OF TASAR

Apart from its most important task as a host for silkworm, the tasar host plant (*Terminalia arjuna* and *T. tomentosa*) is a powerhouse of utility for the phyto-pharmaceutical as well as phyto-industrial sectors. Residual parts of the tasar host plant possess a tremendous amount of bioactive ingredients. Hence, it is regarded as a very commercially important host plant. *Terminalia arjuna* (TA) is a clinically important medicinal plant known for its wide range of medicinal properties, including its application in alleviating ischemic complications, acting as an antioxidant and in cancer treatment, and also showing antimicrobial activity—all because of its flavonoid, triterpenoid, and phenolic contents. While its application in medicine is noteworthy and beneficial, its extracts also present an alternative green chemistry-based approach to producing stable gold and silver nanoparticles while gaining mechanistic advantages over their conventionally used reagents; however, their application is hindered by challenges involving their bioavailability and requirement for appropriate safety standards to allow their pharmaceutical application and usage in the near future. Future approaches toward resolving challenges in its application would require explorations in the application of nanotechnology and hydrogels while using "omics"- and toxicity-based approaches [29].

3.1 Host-plant residues

Beyond serving as the primary host plant for the tasar silkworm (*Antheraea mylitta*), *Terminalia arjuna* (Combretaceae) has been a key component of Ayurvedic medicine for over 3,000 years. Modern pharmacological research confirms that bark constituents such as triterpenoids, glycosides, and flavonoids exhibit strong inotropic, anti-ischemic, antioxidant, and hypolipidemic activities, underscoring its pharmaceutical importance [30]. Comprehensive evaluations by Vishaka et al. (2021) and Dash et al. (2025) collectively highlight the extensive utilization potential of tasar sericulture co-products, including the use of *T. arjuna* leaves as cattle fodder, vermicompost substrate, and herbal tea due to their rich phenolic and flavonoid content, as well as the exploitation of branches and stems for sports goods, agricultural implements, plywood, household décor, and biomass briquettes [31], [32].

Tasar silkworm (*Antheraea mylitta*) rearing and grainage generate substantial waste, including leftover leaves, pruned branches, larval litter, clipped moth wings, dead moths, pierced cocoons, and discarded eggs. Host plant residues from *Terminalia arjuna* and *T. tomentosa* can be used as cattle fodder, vermicompost, and herbal tea due to their rich phenolics, flavonoids, and antioxidants, while woody biomass is suitable for sports goods, plywood, décor, and biomass briquettes. Larval litter and muddle, comprising faeces, exuviae, and leaf debris, can serve as substrates for mushroom cultivation, sources of chlorophyllin and triacontanol for plant growth, and even pillow filling. Silkworm larvae and pupae are also used as bioreactors for biomolecules and recombinant proteins [31].

3.2 Grainage residues

Grainage by-products such as moth wings, dead moths, and eggs can be processed for natural dyes, compost, animal feed, medicinal wine, and nutritionally enriched foods. Pierced and cut-open cocoons are used in biocrafts such as greeting cards, wall hangings, garlands, and bouquets [33], [34].

3.3 Spent silkworm pupae and silk fibroin

Silk reeling generates floss, basin refuse, reeling water, and dead pupae, which are nutritionally rich. Silkworm pupae contain high levels of proteins, fats, α-linolenic acid, vitamins, and minerals, making them an excellent edible protein source. Pupal oil is applied in cosmetics and has bioactive properties, including regulating blood sugar, lipids, liver fat storage, and inflammatory mediators. Pupal chitin supports wound healing due to its antibacterial, antifungal, antiviral, anti-ulcer, and biocompatible properties. Pupae are also used for cultivating *Cordyceps militaris*, which enhances immunity and treats anaemia, insomnia, and respiratory weakness. Silk proteins fibroin and sericin derived from reeling waste are biocompatible, biodegradable, and thermally stable; fibroin is applied in tissue engineering, and sericin is used in cosmetics, pharmaceuticals, and drug/cell delivery [32], [35]. India produced 2,819 MT of tasar silk during 2015–16, which produces about 845.7 to 1,127.6 MT of tasar silk fibre waste. Fibre wastes are used for producing spun silk and fabrics [36], [37].

Overall, these co-products demonstrate that tasar silkworm rearing, grainage, and silk processing wastes can be converted into high-value nutritional, medicinal, cosmetic, agricultural, and biotechnological resources, supporting sustainable and profitable sericulture.

TABLE 3
MAJOR BY-PRODUCTS OF TASAR AND THEIR UTILIZATION

By-product	Source	Potential uses	Critical considerations	References
Tasar silk fibre waste	Deflossing, reeling and unreelable cocoon layers	Spun silk yarn, blended fabrics, sericin recovery and biomaterials	Fibre length and quality vary; processing technology affects recovery efficiency	[37]
Sericin protein	Cocoon cooking water and silk-processing waste	Cosmetics, antioxidant formulations, hydrogels and biomedical materials	Extraction, purification, stability and commercial-scale recovery require optimization	[38], [39]
Silk fibroin	Tasar silk fibre and discarded cocoon material	Biomaterials, films and pharmaceutical research	Extraction methods influence protein quality, purity and processing costs	[40]
Spent silkworm pupae	Cocoon stifling and silk reeling	Protein meal, animal feed, fish feed and pupal oil	Microbial safety, spoilage, drying requirements and feed regulations must be considered	[27], [33], [34]
Silkworm litter	Faeces and residual materials from silkworm rearing	Compost, vermicompost and organic manure	Nutrient composition, contamination and composting conditions influence suitability	[41]
Flimsy and cut cocoons	Cocoon sorting, grading and processing	Spun silk, handicrafts and decorative products	Suitability depends on cocoon condition, fibre quality and market demand	[40]
Moth wings, cuticle and insect residues	Grainage operations and adult moth handling	Chitin recovery, protein extraction and biomaterial research	Collection, purification, yield and economic feasibility require assessment	[40]
Pupal and larval exuviae	Insect moulting and development	Chitin-related materials and bioactive compound research	Composition varies; proposed biomedical uses need further validation	[27]
Cocoon cooking water	Cooking cocoons before silk reeling	Sericin recovery and protein-based products	High organic loads, wastewater treatment and recovery costs are important constraints	[42]
Host-plant residues	Pruning and maintenance of tasar host plants, including *Terminalia arjuna* and *Shorea robusta*	Compost, biomass and selected plant-extract applications	Sustainable harvesting, species identification and ecological impacts must be considered	[43]
Pupal oil	Oil extracted from spent silkworm pupae	Cosmetic, industrial and other value-added applications	Extraction yield, oxidation stability, purification and market acceptance require assessment	[27]
Cocoonase	Enzymatic secretions associated with moth emergence	Research into enzymatic cocoon softening and related applications	Enzyme activity, stability, collection and scale-up require further investigation	[40]

IV. MAJOR BY-PRODUCT OF ERI

Eri sericulture has various by-products of commercial value, apart from silk, such as protein- and fat-rich pupae, pupal oil, cocoon and spinning waste, chitinous exuviae, frass, and residues of host plants. These can be used to produce feed, food, cosmetics, medicines, fertilizers, and other bio-products, thereby making eri sericulture a robust bioeconomy model in vanya sericulture [44].

Leaves of castor (*Ricinus communis*) have 25% protein and 50% carbohydrates and are used in powdered form as natural repellents for aphids, mosquitoes, and termites; the fresh leaves are used to relieve body pain. Castor stem pulp is used in the production of wrapping paper and straw boards, and the stalks are used in biogas, vermicompost, and organic manure. The seeds have 40–55% oil, 20% protein, 20% carbohydrates, 5% sugars, and 2% ash. Castor oil is used as an industrial lubricant and in medicine as a lubricant mixture with mineral oil and wax. Tapioca (*Manihot esculenta*) tubers are a major source of food in Kerala and North-Eastern India, with 83% carbohydrates, 1.5% protein, and 25% starch (dry weight), and are primarily used in starch and glucose industries [5]. A biomass catalyst derived from the ash of *Heteropanax fragrans* was employed for the production of biodiesel from *Jatropha curcas* oil. The calcined catalyst at 550 °C possessed the highest basicity and activity, producing 97.75% yield in 65 minutes under optimal conditions (12:1 methanol:oil, 7 wt% catalyst, 65 °C). The catalyst could be recycled for three cycles (~90% yield), possessed an activation energy of 32.31 kJ mol^{-1}, and produced biodiesel that conforms to international standards [45].

Eri silkworm (*Samia ricini*), traditionally used as food in Northeast India, is a good source of protein and contains 16% protein, 8% fat, and good quantities of minerals. The protein is of very high quality, with amino acid scores of 99–100, leucine being the limiting amino acid, NPU of 41, and PDCAAS value of 86. Defatted eri silkworm meal has a protein content of approximately 75% with 44% essential amino acids and is useful for the preparation of high-quality protein concentrates for animal feed [46]. Comparative nutritional profiling of unspent and spent pupae of *Bombyx mori*, *Samia cynthia ricini*, and *Antheraea proylei* showed that silkworm pupae are nutritionally rich, particularly in protein and fat. Spent pupae of non-mulberry silkworms exhibited higher protein content, with *S. ricini* (41%) followed by *A. proylei* (40%), compared to *B. mori* (31%), while crude fat content ranged between 12–17%. This study also represents the first report on the nutritional composition of *A. proylei* pupae, highlighting the potential of spent pupal waste for value-added food and feed product development [47]. Another application of eri pupal powder as a by-product or as a substitute in broiler diets showed significantly higher body weight and weight gain of broiler chickens [48]. Eri silkworm pupae oil was evaluated for nutritional safety in an 18-week feeding study using Wistar NIN rats. Growth performance was comparable to sunflower oil–fed controls, with no histopathological evidence of toxicity. The oil significantly reduced serum cholesterol and triglycerides and increased HDL cholesterol ($P < 0.05$), attributed to its high α-linolenic acid content. These findings support its safety and potential as an alternative edible oil [46].

Frass, which forms the bulk of eri-culture waste (60–65%), is a nutrient-dense waste rich in nitrogen, phosphorus, and potassium, added to which are several bioactive compounds such as chlorophyll derivatives and flavonoids [49]. Its high moisture content of 65–75% and the presence of probable pathogens in rearing bed refuse demand much care while handling, but its ideal C:N ratio makes it an ideal waste for composting and production of organic fertilizers. Moreover, research has pointed out that these wastes from sericulture could be used as superior nutritious substrates in the cultivation of oyster mushrooms (*Pleurotus* spp.), thus turning what would have been a waste disposal problem into one that helps solve food security [50]. Eri frass with agricultural residues generates a good quality organic fertilizer with 3.5–4.2%, 2.1–2.8%, and 2.8–3.5% NPK composition, respectively. The large area covered by eri in India also results in large quantities of organic waste in the form of frass, cocoon, and pupae, which are usually disposed of through detrimental methods to the environment. In the interest of promoting sustainable growth, some strategies convert this resource into a useful component. Of the total waste, 60–65% is frass, which is rich in nitrogen, phosphorus, and potassium, making it ideal as an organic fertilizer or vermicomposting, which expedites the process by 30–40%. It also generates 0.35–0.42 m^3/kg biogas. Another advantage is that 50–60% protein-rich spent pupae are useful as a substitute for 15–20% conventional protein uses in poultry feed, which also creates a healthcare industry with pharmaceutical-grade sericin and fibroin-rich cocoon wastes. Economic viability also supports the cause as the value added through processing 1 kg frass, 15 kg spent pupae, and 10 kg cocoon generates a revenue of 8–12/- per kg, besides reducing the sector's carbon footprint by 25–30%. Despite some challenges, this model also attracts 15–20% farmer income through adoption of these bio-refineries [51].

TABLE 4
MAJOR BY-PRODUCTS OF ERI SERICULTURE AND THEIR UTILIZATION

By-product	Source	Potential uses	Critical considerations	References
Eri silkworm pupae	Pupae remaining after cocoon harvesting and processing	Human food, animal feed, protein meal, oil extraction	Nutritional quality, hygiene, allergenicity, and safe processing	[52], [53]
Silkworm excreta (frass)	Excreta produced by larvae during feeding	Organic manure, compost, vermicompost, soil amendment	Nutrient variability, contamination, and safe composting	[54]
Host-plant residues	Unconsumed castor, kesseru, and other host-plant leaves and pruning residues	Compost, mulch, biogas, organic fertilizer	Pesticide residues, decomposition, and moisture management	[21]
Defective cocoons and cocoon waste	Damaged, pierced, stained, or irregular eri cocoons	Spun yarn, handicrafts, nonwoven textiles, silk-protein recovery	Fibre quality, processing cost, and market demand	[21]
Silk-processing wastewater	Wastewater from cocoon cooking, washing, and degumming where applicable	Sericin recovery, cosmetic ingredients, biomaterials, treated-water reuse	Protein recovery efficiency, chemical residues, high organic load, and treatment costs	[42]
Larval and rearing residues	Dead larvae, moulting skins, and other biological waste	Composting and nutrient recycling	Diseased larvae require appropriate biosecure disposal	[21]
Eri silk fibre and spinning waste	Short fibres, broken fibres, and yarn remnants	Recycled yarn, blended textiles, handicrafts, composite materials	Fibre length, cleanliness, strength, and processing cost	[21]
Pupal exoskeleton	Exoskeletal material discarded during pupal processing	Chitin and chitosan extraction; potential biodegradable coatings and fruit-preservation applications	Extraction chemicals, yield, product quality, and environmental impact	[55]

V. MAJOR BY-PRODUCT OF MUGA

5.1 Muga silkworm pupae

Muga silkworm pupae are generated when cocoons are processed for the extraction of the silk fibre. Their availability depends on production, the types of cocoon, and whether cocoons are used for reeling. Various studies on *Bombyx mori* pupae demonstrate their potential as sources of protein, lipid, and minerals. Their possible uses include protein supplement, insect oil, and animal feed [24].

5.2 Unreelable and flawed cocoons

Flawed, pierced, stained, damaged, or irregular cocoons may be unsuitable for the production of good-quality and continuous silk filament. Potential applications of these cocoons include spun silk, blended yarn, handicrafts, decorative textiles, and fibre-reinforced composite materials. The feasibility of each application depends on fibre length, strength, and processing cost. Silk-based materials have garnered significant research interest because silk protein can be processed into films, scaffolds, hydrogels, and other functional materials [56]. However, it is necessary to conduct experiments to determine whether defective muga cocoons are appropriate for each of these applications.

5.3 Silkworm litter and frass

Silkworm frass mainly consists of excreta, and it may also include other rearing leftover leaf material. The potential of silkworm feces from different species as a resource for industrial and agricultural use has been studied [57]. Appropriate litter and frass might be assessed for composting or used as a soil supplement in muga sericulture. The material should be examined for

microbiological contamination, compost maturity, nutritional content, carbon-to-nitrogen ratio, and possible phytotoxicity prior to application. Without testing, results from other silkworm species cannot prove that muga frass is suitable for agricultural use.

5.4 Host-plant residues

Som (*Persea bombycina*) and soalu (*Litsea monopetala*) are the two main host plants utilized in commercial muga silkworm rearing. Devi et al. (2021) studied the food plants and nutritional characteristics of *Antheraea assamensis* and discussed their significance and variety [58].

TABLE 5
MAJOR BY-PRODUCTS OF MUGA SERICULTURE AND POTENTIAL UTILIZATION

By-product	Potential applications	Research required	References
Muga pupae	Protein ingredients, insect oil, feed research	Proximate composition, amino acids, fatty acids and safety	[59], [60]
Defective cocoons	Spun silk, crafts and fibre composites	Fibre quality, mechanical properties and process feasibility	[61]
Short silk fibres	Yarn, nonwoven materials and blended textiles	Fibre length, strength and morphology	[61]
Sericin-containing residues	Protein recovery, films, hydrogels and cosmetics research	Extraction yield, molecular characteristics and biocompatibility	[62], [63]
Fibroin-containing residues	Silk-based films, scaffolds and composites	Protein recovery, structural and thermal characterization	[61]
Silkworm frass and litter	Compost and soil amendments	Nutrients, microbial quality and compost maturity	[64]
Som and soalu residues	Mulch, compost and biomass	Chemical composition and agricultural suitability	[64]
Empty cocoons	Handicrafts, decorative products and fibre recovery	Material quality and economic feasibility	[61]
Grainage residues	Composting and biochemical research	Composition, safety and suitable processing methods	[64]

VI. DISCUSSION AND CONCLUSION

The utilization of sericulture by-products offers a significant opportunity to promote sustainable, resource-efficient, and economically viable eri silk production. Major by-products of eri sericulture, including silkworm pupae, larval excreta, leftover host-plant materials, defective cocoons, silk fibre waste, and silk-processing wastewater, possess considerable potential for value addition. Eri silkworm pupae are valuable sources of protein and lipids, making them potential ingredients for food and feed applications. Meanwhile, larval excreta and host-plant residues can be utilized for composting and nutrient recycling, contributing to sustainable agricultural practices. Defective cocoons and short fibres may be used in handicrafts, recycled textiles, and other value-added products. Moreover, sericin-containing wastewater produced during the production of silk presents chances for the recovery of proteins and their uses in biomaterials, cosmetics, and other industrial fields.

Despite these advantages, poor processing technologies, low awareness, inadequate infrastructure, difficulties with quality control, and underdeveloped markets continue to hinder the efficient use of eri sericulture by-products. To assess the composition, safety, recovery effectiveness, and commercial viability of various by-products, comprehensive research is thus required. The development of affordable technology for the production of organic fertiliser, protein recovery, and the transformation of biological leftovers into products with added value should receive special emphasis. To develop suitable technologies and create sustainable value chains, research institutions, sericulture departments, businesses, and eri farmers must work together more closely.

Promoting by-product utilization in eri- and muga-producing regions of Northeast India could improve farmers' income, generate rural employment, reduce waste-disposal problems, and support circular bioeconomy initiatives. The nutritional value

of eri silkworm pupae and the potential recovery of silk proteins from processing wastewater provide useful starting points for developing such approaches. However, findings from conventional silk-processing systems should be adapted to eri silk only after species-specific and process-specific validation. Overall, transforming eri sericulture by-products into valuable products can contribute significantly to sustainable sericulture development, environmental protection, and improved rural livelihoods, provided that the proposed technologies are scientifically validated, environmentally sound, and economically feasible.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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