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NUTRITIONAL VALUE, FOOD APPLICATIONS AND COMMERCIAL PROSPECTS OF MULBERRY PRODUCTS AND SILKWORM PUPAE IN INDIA

Rimjim Borah

Department of Commerce, Gauhati University, Gopinath Bordoloi Nagar, Guwahati, Assam 781014, India.,Email: rimjimborah456@gmail.com

Abstract

India has a large sericulture sector, but economic value is still concentrated mainly in silk fibre. Mulberry leaves, mulberry fruits and silkworm pupae can support a wider nutrition-oriented value chain because they contain proteins, fibre, minerals, unsaturated lipids and bioactive plant compounds. This narrative review explains the nutritional significance, food applications, safety requirements and commercial prospects of these sericulture-associated resources in language accessible to readers from commerce and social-science backgrounds. Mulberry leaves contain dietary fibre, protein, minerals, flavonoids, phenolic acids and 1-deoxynojirimycin (DNJ). Human studies indicate that standardized DNJ-containing products may reduce the rise in blood glucose after a meal, whereas many reported antioxidant, anti-inflammatory, anti-obesity and anticancer effects are based mainly on laboratory or animal studies. Mulberry fruits provide sugars, organic acids, vitamins, minerals and anthocyanins and have been developed into juices, wines, jams, jellies, bakery products, natural colourants and fermented foods. Silkworm pupae are nutrient-dense by-products containing protein, essential amino acids, lipids, minerals, chitin and potentially useful peptides. They can be processed into whole foods, protein meal, oil, feed ingredients and value-added co-products. Commercial use, however, requires control of allergens, microorganisms, chemical residues and lipid oxidation. In India, promising pathways include standardized mulberry-leaf products, regional mulberry-fruit foods, pupal meal and oil, and integrated recovery of protein, lipid and chitin. Market development must combine nutritional evidence with consumer research, regulatory approval, quality standards, traceability, processing economics and fair value sharing within the sericulture chain.

Keywords: Alternative Protein; Circular Bioeconomy; Functional Foods; Mulberry; Nutrition; Rural Enterprise; Sericulture; Silkworm Pupae; Value Addition.

Highlights

- Sericulture can generate nutritional and commercial value beyond the production of silk fibre.
- Mulberry leaves and fruits provide nutrients and phytochemicals, while silkworm pupae provide concentrated protein and lipids.
- Most disease-related claims remain preclinical; human evidence is strongest for the postprandial glycaemic effect of standardized mulberry-leaf products.

- Food safety, consumer acceptance, product standards, regulation and business feasibility determine whether nutritional potential becomes a viable market.

1. Introduction

Sericulture is the organized cultivation of silkworm host plants, rearing of silkworms, production of cocoons and conversion of silk filaments into yarn and fabric. India is distinctive because it produces the four major commercial silks; mulberry, eri, tasar and muga and the activity supports rural employment and small enterprises (Dutta and Nanavaty, 2007; Buhroo *et al.,* 2018). According to official data for 2021–2022, India produced 34,903 metric tonnes of raw silk, including 25,818 metric tonnes of mulberry silk. These figures indicate the scale of the biological and commercial value chain considered in this review (Central Silk Board, 2021-22).

The economic discussion around sericulture usually ends with silk. In practice, the same system generates several materials that may have value in food, feed, health products and industry. Mulberry plants produce leaves and fruits, while cocoon processing leaves behind silkworm pupae. These materials are not identical: leaves are plant-based ingredients rich in fibre and phytochemicals, fruits are naturally sweet and rich in pigments, and pupae are animal-derived ingredients rich in protein and lipids.

The domesticated mulberry silkworm Bombyx mori has a long history of human use and is now studied not only for silk but also as food, feed and a biological production system (Yang et al., 2014; Meng et al., 2017; Xu et al., 2019). Silkworm pupae are traditionally consumed in parts of India and several Asian countries, but modern commercialization exposes a larger and more diverse population and therefore requires formal safety and quality controls (Mishra *et al.*, 2003; Mitsuhashi, 1997; Yhoung-Aree *et al.*, 1997; Han *et al.*, 2017).

Mulberry, particularly Morus alba, has also been used in traditional food systems. Its leaves, fruits and processing residues have been studied for nutritional composition, food formulation and biological activity (Srivastava *et al.*, 2003; Yuan and Zhao, 2017; Dhiman *et al.*, 2020). However, scientific papers often mix results from leaves, fruits, roots and bark or present cell and animal experiments as if they were proven human benefits. This review avoids that problem by separating nutritional composition, food technology, preclinical evidence and human evidence.

The central argument of this paper is that nutritional potential alone does not create a successful product. Commercial success also depends on reliable raw-material supply, processing cost, product quality, regulatory classification, consumer trust, branding, distribution and a fair business model. This combined scientific and commercial perspective is particularly relevant for India, where sericulture already has an institutional base.

1.1 Aim and Scope of the Review

This review aims to: (i) explain the nutritional composition of mulberry leaves, mulberry fruits and silkworm pupae; (ii) summarize their food, feed and value-added applications; (iii) distinguish established human evidence from laboratory and animal findings; (iv) discuss safety, quality and regulatory requirements; and (v) evaluate practical commercial opportunities and barriers in India. The discussion is intentionally written in straightforward language so that readers from commerce, management and rural-development backgrounds can understand the science needed for responsible market analysis.

2. Review Methodology

The paper follows a structured narrative-review approach. The literature and statistical data covered research up to and including 2022. Scientific articles and reviews were identified from the literature listed in the original manuscript and supplemented with relevant systematic reviews and official Indian sources published by that date. Priority was given to studies on nutritional composition, food processing, human dietary response, food safety, industrial use and commercialization. Government sources were used for sericulture statistics and the Indian regulatory context. The evidence was organized into four levels. First, compositional studies explain what nutrients or compounds are present. Second, food technology-based studies test whether an ingredient can be processed into an acceptable product. Third, preclinical studies use chemical assays, cultured cells or experimental animals to explore possible biological mechanisms. Fourth, human studies examine effects in people. These levels are not interchangeable: a compound that neutralizes a free radical in a test tube is not automatically proven to prevent disease in humans.

The review does not present a formal meta-analysis because the studies differ widely in species, cultivar, plant part, extraction method, silkworm strain, processing condition, dose and outcome. Market prospects are assessed qualitatively because transparent Indian data on sales, consumer demand, processing costs and recoverable pupal volumes are limited.

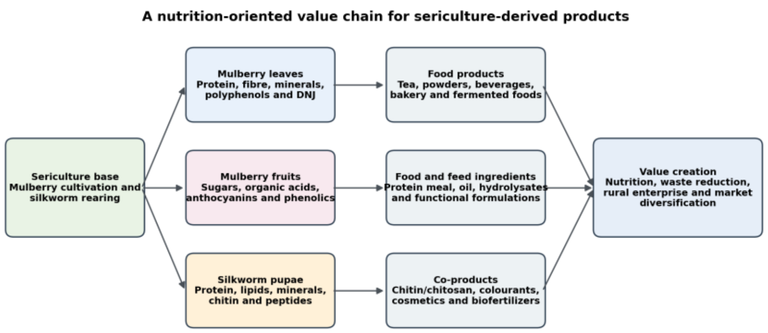

Figure 1. A nutrition-oriented value chain for mulberry products and silkworm pupae.

3. Nutritional Resources Generated by Sericulture

3.1 Mulberry Leaves

Mulberry leaves are primarily cultivated as silkworm feed, but they also contain nutrients relevant to human food. On a dry basis, they can provide protein, dietary fibre, minerals and small amounts of lipids. Their exact composition changes with species, variety, leaf age, season, soil, fertilizer, climate and drying method; therefore, published values should be treated as ranges rather than fixed numbers (Srivastava *et al.,* 2003; Yu *et al.,* 2018; Dhiman *et al.,* 2020).

The leaves also contain polyphenols and flavonoids. These are plant compounds that can participate in oxidation-reduction reactions and may influence biological pathways. Important examples include chlorogenic acid, rutin, quercetin derivatives and moracins (Thabti *et al*., 2014; Tu *et al*., 2019). Mulberry leaves also contain DNJ, an iminosugar that can inhibit alpha-glucosidase enzymes involved in the digestion of carbohydrates (Hansawasdi and Kawabata, 2006; Asai *et al.,* 2011). In simple terms, DNJ can slow the conversion of complex carbohydrates into absorbable glucose. Whole-leaf powder and concentrated extracts are different products. Whole-leaf powder retains fibre and a broad mixture of nutrients, whereas an extract may contain a higher concentration of selected compounds. A commercial label should therefore specify the plant species, plant part, extraction method, serving size and marker compound. Without such information, products called “mulberry leaf extract” cannot be compared reliably.

3.2 Mulberry Fruits and Fruit-Processing Residues

Mulberry fruits are relevant to a broader sericulture-based food economy because the same perennial plant can provide fruit in addition to leaves. White, red and black mulberries differ in colour, sugar-acid balance, vitamin content and phenolic composition (Ercisli and Orhan, 2007; Gungor and Sengul, 2008; Imran *et al*., 2010; Gundogdu *et al*., 2011; Aljane and Sdiri, 2016). Black and red fruits are generally valued for anthocyanins, the water-soluble pigments responsible for red, purple and blue colours (Du et al., 2008; Özgen *et al.,* 2009; Aramwit *et al*., 2010; Veberic *et al.,* 2015).

Fruit composition varies with genotype, maturity, growing region and post-harvest handling (Jalikopa *et al*., 2011; Eyduran *et al*., 2015; Jiang and Nie, 2015; Krishna *et al*., 2020). Reported components include glucose and fructose, organic acids, vitamin C, minerals, fibre and phenolic compounds (Akbulut and Özcan, 2009; Koca *et al*., 2008; Isabelle *et al*., 2008; Natić *et al*., 2015). Because fresh mulberries are soft and highly perishable, processing is essential for reducing losses and extending market reach. Pomace and other fruit residues can retain pigments and phenolics. Their use in colourants, bakery ingredients or encapsulated formulations can create additional value, although extraction cost, solvent choice and stability must be considered (Zhang *et al*., 2011; Gültekin-Özgüven *et al*., 2016).

3.3 Silkworm Pupae

Silkworm pupae remain after the cocoon has been stifled and reeled. They are commonly described as by products rather than waste because they can already be used as food, feed, oil source, fertilizer or raw material. Their composition varies with silkworm species, strain, sex, diet, developmental stage, stifling method, drying method and whether the sample is full-fat or defatted (Mishra *et al*., 2003; Wu et al., 2021; Tassoni *et al*., 2022).

Dried Bombyx mori pupae commonly contains a high proportion of crude protein and substantial lipid. The protein includes essential amino acids, while the lipid fraction commonly contains oleic, linoleic and alpha-linolenic acids (Hu *et al.,* 2017). A technical caution is necessary common nitrogen-based methods may overestimate "true protein" because chitin and other non-protein compounds also contain nitrogen. Amino-acid analysis and digestibility testing are therefore important for nutrition claims. Pupal lipids can be separated as oil, and defatting increases the protein concentration of the remaining meal. The unsaturated-fatty-acid profile is nutritionally interesting, but it also makes the oil vulnerable to oxidation, which produces a rancid smell and taste. Packaging, light, temperature, oxygen and storage time therefore have direct business importance because they determine shelf life. The remaining chitin-rich material may be converted into chitosan or other technical products. Protein hydrolysates and peptides have also been studied for antioxidants, antihypertensive and other functions, but most evidence remains laboratory-based (Ratcliffe et al., 2011; Wu *et al*., 2021; Tassoni *et al.,* 2022).

Table 1. Main nutritional components and their practical significance.

Resource	**Major nutritional or functional components**	**Simple scientific interpretation**	**Commercial relevance**
Mulberry leaves	Protein, fibre, minerals, flavonoids, phenolic acids and DNJ	A nutrient-containing plant ingredient; DNJ can reduce carbohydrate-digesting enzyme activity.	Tea, powder, seasoning, bakery ingredient, beverages and standardized extracts.
Mulberry fruits	Natural sugars, organic acids, vitamin C, minerals, fibre and anthocyanins	A perishable fruit with colour, flavour and antioxidant compounds; composition differs among species and maturity stages.	Juice, syrup, jam, jelly, wine, vinegar, colourant, bakery and fermented products.
Silkworm pupae	Protein, essential amino acids, lipids, minerals, chitin and peptides	A nutrient-dense animal-derived ingredient; composition depends strongly on processing and analytical basis.	Whole foods, protein meal, oil, feed ingredient, hydrolysates and chitin/chitosan.

4. Food, Feed and Product Applications

4.1 Mulberry-Leaf Products

Mulberry leaves can be dried and used in tea, powder, capsules, seasoning mixtures, noodles, bakery products and beverages. Drying is a critical step because excessive heat can damage colour and heat-sensitive compounds, whereas insufficient drying allows microbial growth. Product developers must balance nutritional retention, safety, taste and cost.

Leaf extracts have shown alpha-glucosidase inhibition in laboratory systems and effects on postprandial glucose in small human studies (Hansawasdi and Kawabata, 2006; Asai *et al.*, 2011). Animal studies have also reported changes in glucose metabolism, lipid metabolism, obesity-related markers and liver outcomes (Andallu and Varadacharyulu, 2003; Miyahara *et al*., 2004; Liu *et al*., 2009; Sharma *et al*., 2010; Tanabe *et al*., 2011; Li *et al.*, 2013; Tsuduki *et al.,* 2013; Hu *et al*., 2019; Lee *et al*., 2020). These findings support further study but do not justify claims that ordinary mulberry tea can treat diabetes, obesity or liver disease.

Fermentation may change flavour and bioactive composition. Mulberry leaves have been used in experimental rice-wine production, and leaf silage has been explored as a source of lactic-acid bacteria (Tan and Li, 2013; Shokryazdan *et al.,* 2015). These are examples of product innovation rather than evidence of medical benefit.

4.2 Mulberry-Fruit Foods

Fruit processing is the most mature area of mulberry food development. Stabilized juice has been produced by controlling suspended solids and hydrocolloids, while syrup, squash, pekmez, jams and jellies extend shelf life and create products that are easier to transport (Sengül *et al.,* 2005; Oktay, 2013; Akkarachaneeyakorn and Tinrat, 2015; Thakur and Thakur, 2017; Quang Trung *et al*., 2018; Wongchalat and Chatthongpisut, 2016).

Mulberry fruits have also been used in wine and other fermented products. Fermentation changes sugar, acids, aroma and phenolic composition; quality therefore depends on fruit maturity, yeast, temperature and process control (Darias-Martín *et al*., 2003; Feng *et al.*, 2015; Wang *et al*., 2015; Yadav *et al*., 2017). Vinegar and other fermented products can provide additional market channels (Karaagac *et al*., 2016).

Food fortification studies include muesli, chocolate, pastry, pasta, yoghurt, jelly and meat products. In these applications, mulberry ingredients may contribute colour, fibre, flavour or phenolic compounds (Kobus-Cisowska *et al*., 2013; Byamukama *et al.*, 2014; Gültekin-Özgüven *et al*., 2016; Komolka *et al.*, 2016; Yazdankhah *et al.*, 2019; On-Nom *et al.*, 2020). Mulberry polyphenols and juice concentrates have also been tested for limiting oxidation in processed meat (Cheng *et al*., 2018; Cheng *et al.,* 2020). Commercial interpretation should remain practical. A technically successful formulation is not automatically a profitable product. Consumer liking, raw-material seasonality, processing yield, packaging, storage, retail price and competition from established fruit products must also be evaluated.

4.3 Silkworm Pupae as Food and Feed

Silkworm pupae are consumed roasted, boiled, fried, seasoned or incorporated into pastes and other dishes in several Asian food cultures (Mitsuhashi, 1997; Yhoung-Aree *et al.*, 1997; Mishra *et al.*, 2003). For wider commercial use, they may be dried and milled into a powder, defatted to produce a protein-rich meal, or hydrolysed to improve solubility and functionality. In feed markets, pupal meals can contribute protein and energy to poultry, aquaculture and other formulations. The commercial decision should be based on digestible amino acids, feed-conversion response, safety, oxidation stability and price relative to fishmeal, soybean meal and other ingredients. The fact that a material has a high crude-protein percentage does not by itself prove that it is economical or nutritionally superior.

Pupal oil can be separated before protein processing. Microwave-assisted extraction and other methods influence yield, quality and oxidation (Hu *et al.*, 2017). A cascade process - oil first, protein second and chitin-rich material third, may create more total value than selling whole dried pupae, but it also requires greater investment, process control and reliable markets for each fraction (Wu et al., 2021; Tassoni et al., 2022). The international edible-insect sector shows that regulation, consumer perception, pricing and marketing are as important as nutrition (Zhang and Zhang, 2001; Han *et al.*, 2017). Products that hide insect identity may be more acceptable to some consumers, but transparent labelling remains essential, especially because of allergy risk.

Table 2. Representative product pathways and the evidence they provide.

Product pathway	Representative literature	What the studies mainly demonstrate	What remains to be established
Mulberry-leaf tea, powder or extract	Srivastava et al. (2003); Asai et al. (2011); Yu *et al.* (2018)	Nutrient composition, possible glycaemic function and suitability as a food material.	Standardization, sensory acceptance, long-term safety, shelf life and permitted claims.
Juice, syrup, jam, jelly and concentrated fruit products	Akkarachaneeyakorn and Tinrat (2015); Thakur and Thakur (2017); On-Nom *et al.* (2020)	Processing feasibility, stability, sensory quality and retention of pigments.	Indian supply-chain economics, packaging cost, demand and product differentiation.
Wine, vinegar and fermented foods	Darias-Martín *et al.* (2003); Feng *et al.* (2015); Wang et al. (2015)	Fermentation behaviour, aroma and phenolic changes.	Scale-up, regulatory category, alcohol policy and consistent raw-material quality.
Bakery, pasta, chocolate and colourants	Gültekin-Özgüven *et al.* (2016); Komolka *et al.* (2016); Yazdankhah *et al.* (2019)	Ingredient functionality, colour, fibre and sensory effects.	Bioavailability, cost-in-use, consumer willingness to pay and claim substantiation.
Whole pupae, pupal powder and protein meal	Mishra et al. (2003); Wu *et al.* (2021); Tassoni *et al.* (2022)	Nutritional composition and traditional consumption.	Allergen control, microbiological criteria, digestibility, national approval and acceptance.
Pupal oil, hydrolysates and chitin products	Hu *et al.* (2017); Wu *et al.* (2021); Tassoni *et al.* (2022)	Fractionation and potential higher value uses.	Pilot economics, product purity, oxidation control, wastewater and reliable buyers.

5. Health Relevance: What Is Supported and What Is Not

5.1 Glycaemic Response

The most credible human evidence for mulberry leaf concerns postprandial glycaemia, meaning the rise in blood glucose after eating. DNJ inhibits carbohydrate-digesting enzymes, and controlled studies have reported a reduced post-meal glucose response after standardized mulberry-leaf products (Asai *et al.*, 2011). This is a specific and limited finding. It does not mean that all mulberry-leaf products have the same DNJ content, nor does it establish that they cure diabetes. Laboratory and animal studies support possible mechanisms involving alpha-glucosidase inhibition, glucose absorption, insulin signalling and gut microbiota (Hansawasdi and Kawabata, 2006; Hu *et al.,* 2019; Li *et al*., 2013). These studies help explain how an effect might occur, but clinical recommendations require larger human trials with defined products, doses and safety monitoring.

5.2 Antioxidant and Anti-Inflammatory Findings

Mulberry leaves and fruits contain phenolic compounds that show antioxidant activity in chemical assays (Gungor and Sengul, 2008; Isabelle et al., 2008; Imran *et al.,* 2010; Yang and Lee, 2012; Thabti *et al.,* 2014; Wang *et al*., 2018; Tu *et al*., 2019). "Antioxidant activity" in a laboratory assay means that an extract can react with selected oxidants under controlled conditions. It should not be translated directly into claims that food prevents cancer, heart disease or ageing.

Cell and animal studies report anti-inflammatory, lipid-lowering, anti-obesity, neuroprotective and other effects (Kim *et al*., 2010; Shih *et al*., 2010; Yang *et al.,* 2010; Peng *et al*., 2011; Park *et al*., 2013; Wang *et al*., 2013; Jiao *et al*., 2017). These results are scientifically useful but remain preclinical. The dose used in an animal experiment may be much higher than the amount present in normal food, and the human body may absorb and metabolize the compounds differently.

Human fruit studies are fewer. Trials involving mulberry fruit jelly or fruit consumption have reported changes in post-meal cardiometabolic measures or lipid profiles, but sample sizes and products differ (Sirikanchanarod *et al.,* 2016; On-Nom *et al.,* 2020). These findings justify further study rather than broad therapeutic claims.

5.3 Antimicrobial, Anticancer and Other Claims

Mulberry compounds have inhibited microorganisms or cancer-cell growth in laboratory studies (Fukai *et al.,* 2005; Deepa *et al*., 2012; Lee *et al*., 2014). Such results identify potentially useful molecules or preservation systems, but they are not evidence that eating mulberry products treats infection or cancer. Product descriptions should use phrases such as "showed activity in vitro" rather than "has anticancer properties."

Similarly, pupal peptides and insect-derived compounds have been explored for biological activity and traditional medicine (Ratcliffe *et al*., 2011; Zimian *et al*., 1997; Aznar Cervantes *et al.,* 2021). Commercial healthcare products require compound identification, dose-response data, toxicity testing, bioavailability and human efficacy. These requirements are much more demanding than those for ordinary food.

Table 3. Evidence ladders for commonly discussed health effects.

Claim area	Current evidence	Appropriate conclusion
Postprandial glycaemic response	Mechanistic studies, animal studies and small human trials of standardized leaf products	DNJ-containing mulberry-leaf products may reduce the rise in glucose after carbohydrate-containing meals.
Antioxidant activity	Many chemical assays; some cell and animal studies	Mulberry contains phenolic compounds with measurable antioxidant activity in experimental systems.
Anti-inflammatory and lipid effects	Mainly cell and animal studies; limited human evidence	Promising preclinical findings that require product-specific clinical confirmation.
Anticancer activity	Primarily cultured cell and animal research	Potential molecules for further research; not a demonstrated food effect in humans.
Pupal bioactive peptides	Laboratory hydrolysate and peptide studies	Possible functional ingredients after safety, identity and efficacy are established.

6. Safety, Quality and Regulation

6.1 Silkworm-Pupae Safety

Allergy is the most important safety concern for silkworm-pupae food. Some pupal proteins are similar to allergens found in crustaceans, mites and other arthropods. A person with shrimp, crab, shellfish or mite allergy may therefore be at risk of cross-reaction. Heating does not reliably remove all allergenic proteins (Wu et al., 2021). Commercial products need clear ingredient identification, cross-contact control and an adverse-event plan.

Raw pupae may also carry microorganisms, including spore-forming bacteria. Cooking can reduce many vegetative cells but may not remove spores. Safe production requires controlled heating, rapid drying, low water activity, hygienic handling, appropriate packaging and microbiological shelf-life testing (EFSA Scientific Committee, 2015).

Chemical risks include pesticide residues from mulberry cultivation, cleaning chemicals and oxidation products. Because pupal oil contains unsaturated fatty acids, quality can deteriorate during storage. Peroxide value, free fatty acids, odour and packaging performance are therefore practical quality indicators.

6.2 Mulberry-Product Safety

Mulberry leaves grown for silkworm feeding are not automatically food-grade. Human-food products require verified botanical identity, approved agricultural inputs, washing or cleaning, microbial control, pesticide-residue testing, heavy-metal limits and standardized drying. Concentrated extracts may increase exposure to both desired compounds and contaminants.

Products containing DNJ may lower post-meal glucose. Consumers using glucose-lowering medicines may therefore need professional advice. Long-term high-dose use, pregnancy, lactation and use in children are not as well studied as ordinary dietary consumption.

6.3 Regulatory Position in India

In India, commercial development begins with product classification. A conventional food, proprietary food, nutraceutical, health supplement, animal feed, cosmetic ingredient and pharmaceutical product are not regulated in the same way. The composition, label, claims and evidence must match the selected category.

FSSAI regulations require prior approval for a non-specified food or food ingredient that is not standardized or otherwise permitted. A human-food product based on silkworm pupae should therefore receive a formal regulatory assessment before national marketing (Food Safety and Standards Authority of India, 2017). Traditional local consumption is important evidence of use but does not automatically settle the status of a new processed ingredient, extract or nationwide branded product.

Internationally, EFSA has examined general risks associated with insects as food and feed, including microbiological, chemical and allergenic hazards (EFSA Scientific Committee, 2015). This should not be described as automatic approval of every insect species or product.

Table 4. Priority hazards and minimum business controls.

Hazard or quality issue	Mainly affects	Business consequence	Minimum control
Allergenicity and arthropod cross-reactivity	Pupae and pupal protein	Consumer injury, recall, legal and reputation risk	Allergen assessment, segregation, cleaning validation, clear labels and complaint monitoring.
Microorganisms and spores	Pupae; poorly dried leaves and fruits	Spoilage, foodborne illness and short shelf life	Validated heat treatment, rapid drying, water-activity target, hygiene and microbiological testing.
Pesticides and heavy metals	Leaves, fruits and pupae	Regulatory failure and loss of buyer confidence	Approved cultivation practices, supplier records and residue testing.
Lipid oxidation	Whole pupae,	Rancid flavour, nutrient loss	Oxygen/light-barrier packaging,

	meal and oil	and rejected stock	cool storage and oxidation specifications.
Batch-to-batch variation	All products	Unreliable nutrition label and inconsistent consumer experience	Raw-material grading, marker compounds, proximate analysis and written specifications.
Unsupported health claims	Foods and supplements	Regulatory action and consumer deception	Match wording to the evidence level; avoid treatment or cure claims.

7. Commercial Prospects in India

7.1 Resource and Value-Chain Opportunity

India already has mulberry farms, silkworm rearers, cocoon markets, reeling units, research institutes and government support (Sharma and Zote, 2010; Singhal *et al.*, 2010). This existing network reduces the need to build an entirely new supply chain. However, a commercial nutrition business needs information that silk statistics do not provide such as quantity of food-grade leaves and fruits, fresh and dry pupal volume, seasonal availability, current local uses, ownership of by-products and the distance between production and processing sites.

Value addition should not reduce the performance of the main silk business. High-quality leaves are required for silkworm growth; diverting them to human food may increase leaf price but reduce cocoon output. A sensible model may use surplus, pruned, grade-rejected or separately cultivated food-grade leaves rather than simply taking leaves away from rearing. Pupae are perishable and rich in fat. They must be stabilized soon after reeling. Small, decentralized units may handle collection and primary drying, while centralized facilities may be more suitable for defatting, protein processing and allergen-controlled production.

7.2 Consumer Acceptance and Market Positioning

Mulberry-leaf tea and fruit products are likely to face a lower psychological barrier than whole-insect foods because they fit familiar product categories. Their main market questions are taste, convenience, price, trust and evidence for claims. Branding should emphasize traceability and quality rather than exaggerated medicinal promises.

Silkworm pupae already have cultural acceptance in parts of Northeast India. This regional knowledge is a commercial advantage, but it should not be assumed that all Indian consumers will respond in the same way. Research should measure willingness to try, preferred product form, reaction to visible versus powdered insects, allergy information, acceptable price and the role of traditional identity.

Feed and pet-food markets may offer an earlier large-scale pathway because they avoid some of the consumer resistance associated with human insect foods. Even here, price, digestibility, oxidation stability, regulatory compliance and consistent supply remain decisive.

7.3 Product Opportunities

Table 5. Commercial-readiness assessment for India.

Opportunity	Indicative readiness	Why it is promising	Main barriers	Recommended next step
Mulberry-leaf tea	Medium to	Familiar plant	Taste, variable DNJ and	Develop standards,

and powder	high	product; relatively simple processing; can use planned food-grade leaf supply.	polyphenols, residue control and claim regulation.	sensory testing, shelf-life data and a clear positioning strategy.
Mulberry-fruit beverages, preserves and colourants	Medium to high in suitable regions	Uses perishable fruit and established food technologies.	Short harvest season, soft fruit, cold-chain need and competition from other berries.	Map regional supply, optimize processing yield and build local premium products.
Pupal meal for feed	Medium to high	Concentrated protein and energy; lower cultural barrier than human food.	Price competition, oxidation, digestibility and feed approval.	Run feeding and cost-per-digestible-protein studies with Indian material.
Pupal oil	Medium	Creates value before protein concentration; unsaturated-fatty-acid profile.	Rancidity, odour, refining cost and uncertain food-grade market.	Pilot extraction, refining, stability and buyer testing.
Pupal protein for human food	Low to medium	High protein density and possible functional properties.	Allergy, food approval, flavour, consumer acceptance and processing cost.	Begin with formal regulatory consultation and controlled regional product trials.
Chitin/chitosan and specialty fractions	Low to medium	Higher-value co-product in a cascade biorefinery.	Chemical processing, wastewater, purity standards and limited buyers.	Quantify mass balance, environmental burden, product quality and contracted demand.

7.4 Business-Model Considerations

A viable enterprise must calculate more than the selling price. Major cost items include collection, transport, drying energy, labour, equipment, extraction yield, packaging, quality testing, licensing, rejected batches, marketing and distribution. A product with excellent nutrition can fail if it requires expensive stabilization or has a short shelf life.

A cascade biorefinery can improve revenue by separating oil, protein and chitin-rich fractions, but complexity also increases capital investment and wastewater treatment. The preferred scale should be established through pilot trials and techno-economic analysis, not through nutritional composition alone.

Fair value sharing is important because farmers and reelers supply the raw material, while processors and brands may capture most of the final value. Cooperatives, farmer-producer organizations, women’s self-help groups and local enterprises may participate in collection, drying and simple food processing, while advanced extraction may require centralized facilities. Environmental claims should also be measured. Using a by-product can reduce disposal, but drying, solvents, transport and processing consume resources. Life-cycle assessment is needed before describing a product as automatically sustainable.

8. Research Gaps and Future Directions

- **National material-flow data:** India needs species-wise and region-wise estimates of leaves, fruits and pupae that are available for value addition after existing uses are considered.
- **Product standards:** food-grade specifications should define identity, moisture, protein basis, marker compounds, microbial limits, pesticide residues, metals, oxidation and allergens.

- **Human evidence:** standardized products require adequately powered trials that report dose, composition, safety and clinically meaningful outcomes.
- **Processing research:** pilot-scale studies should compare drying, defatting, extraction and fermentation on yield, nutrition, flavour, safety and cost.
- **Consumer and market research:** studies should examine regional differences, price sensitivity, product visibility, labels, trust and willingness to purchase.
- **Regulatory clarity:** developers need a transparent route for insect-derived food ingredients, feed products and nutraceutical claims.
- **Business and sustainability assessment:** techno-economic analysis, life-cycle assessment and value-chain governance should be integrated with food science.

9. Limitations of the Review

This is a narrative review and not a formal systematic review or meta-analysis. The cited literature differs in material, analytical method, extraction process, dose and experimental model. Some older product-development studies provide limited detail on modern quality requirements.

The commercial assessment is qualitative because Indian data on pupal volumes, processing yields, product sales, consumer willingness to pay and regulatory decisions are incomplete. The paper therefore identifies plausible opportunities and required evidence rather than claiming that all proposed products are already commercially viable.

10. Conclusion

Sericulture can support a nutrition and value-addition economy beyond silk, but the three main resources considered in this review must be understood separately. Mulberry leaves provide fibre, protein, minerals and phytochemicals; standardized DNJ-containing products have the clearest human evidence for moderating post-meal glucose response. Mulberry fruits provide sugars, acids, minerals and anthocyanins and can be converted into familiar food products that reduce post-harvest loss. Silkworm pupae provide concentrated protein and lipids and can be used in food, feed, oil and biorefinery applications.

The scientific opportunity is real, but broad labels such as “superfood” are less useful than product-specific evidence. Most antioxidant, anti-inflammatory, anti-obesity, anticancer and medicinal claims are still based on laboratory or animal studies. Commercial products must control allergens, microorganisms, residues, oxidation and batch variation. They must also satisfy Indian food or feed regulations and communicate benefits without misleading consumers. For India, the most practical early opportunities are standardized mulberry-leaf foods, regional mulberry-fruit products, pupal meal for feed, pupal oil and integrated fractionation of pupae. Progress will depend on cooperation among food scientists, sericulture specialists, economists, regulators, farmers, reelers and entrepreneurs. In this way, nutrition science can strengthen, not replace, the commercial and rural-development foundations of sericulture.

Declarations

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