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Review Article

Bioconversion of Sericulture Waste into High-Value Products: A Sustainable Bioeconomic Approach

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ABSTRACT

Sericulture is one of the most important agro-based cottage industries in India, providing employment to rural families, particularly women. However, along with silk production, substantial quantities of organic waste are generated at different stages such as mulberry cultivation, silkworm rearing, reeling, and post-reeling processes. These wastes include silkworm pupae, sericin-rich reeling effluents, silkworm litter (frass), mulberry pruning residues, and defective cocoons. Traditionally, much of this waste is discarded or underutilized, resulting in environmental pollution and economic loss. The present study focuses on sustainable bioconversion strategies to transform sericulture waste into valuable products such as protein-rich feed, bioactive compounds, biofertilizers, biopolymers, and bioenergy. The research integrates biochemical extraction, microbial fermentation, composting, and circular bioeconomy principles to develop a zero-waste sericulture model. Economic feasibility, environmental benefits, and opportunities for rural entrepreneurship especially women led enterprises are also discussed. The study highlights how scientific waste utilization can significantly enhance sustainability, profitability, and resource efficiency in sericulture systems.

1. Introduction

Sericulture plays a vital role in rural livelihood security in India, especially in states like Telangana, Karnataka, and Andhra Pradesh. It is a labour-intensive industry that supports small and marginal farmers. However, for every kilogram of silk produced, a considerable amount of by-products and waste materials are generated. In recent years, sustainable agriculture and circular bioeconomy concepts have gained importance. Instead of treating waste as a disposal problem, it can be viewed as a resource for generating new products. Scientific bioconversion methods allow organic waste to be transformed into useful materials with economic value [1-8]. This study explores how sericulture waste can be efficiently utilized to reduce environmental burden while increasing income opportunities for farmers and entrepreneurs.

2. Types and Quantification of Sericulture Waste generated at different stages:

Sericulture waste is generated at multiple stages:

2.1 Silkworm Pupae and its uses:

After reeling, silkworm pupae remain as a major by-product. The Northeastern people eat 200 kinds of edible foods including silkworm pupae which has all three calorigenic nutrients. Pupae are rich in protein (50–60%), lipids (25–30%), and micronutrients. In many cases, they are discarded or used only as low-value poultry feed. The silkworm pupae have high protein content of 55,6 % of dry weight. except Eri silkworm pupae, all mulberry and non-mulberry pupae have 18 amino acids and 8 out of these amino acids satisfy WHO, FAO and UNO guidelines [9-12].

Silkworm pupae contain 25 distinct kinds of minerals and low sodium and potassium. Silkworm pupae once considered as by product which was a banded are emerging as a valuable resource with multiple applications. Silkworm pupae which are rich in high quality proteins (up to 76%) fatty acids like linoleic and alpha linoleic acid provides an important to alternate protein source for human consumption in places like Northeast India, the extracted chrysalis oil for cosmetic and medication while poultry and aquaculture. While the bioactive compounds that includes antioxidant like lutein and hex xanthin that benefitting human health and enhancing the cattle productivity. The pupal oil is second abundant substance in silkworm pupae with highest oil content of 26.2% in silkworms. The oil contains high concentration of polyunsaturated fatty acids which make

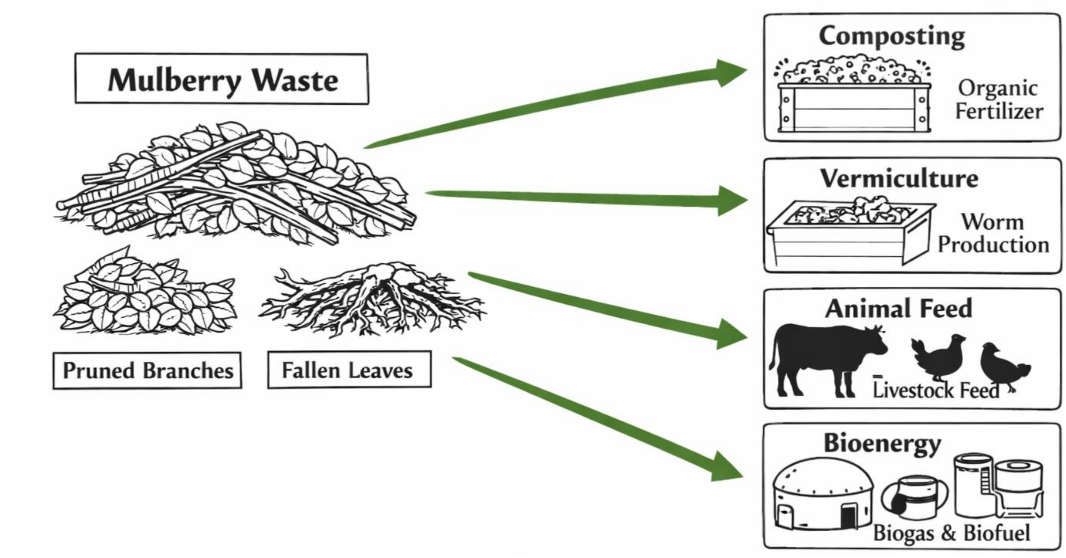

Figure-1. Line-art schematic diagram illustrating sustainable reuse pathways for mulberry cultivation waste

up to 44% of the total fatty acid profile. It's also rich in vitamins, flavonoids and poly phenols [13-16]. By utilizing the pupal waste, organic waste from silk industry is reduced and thereby benefitting the environment and thus contributing to circular bioeconomy. Hence silkworm pupae is called goldmine waste as it revolutionizes the food system, green technologies and bio medicines.

2.2 Sericin-Rich Effluents:

During cocoon boiling and silk reeling, sericin (a water-soluble silk protein) is removed from fibroin is not a highly useful biological material but has a lot of biological activity. The effluent water contains dissolved sericin which accounts for 15 to 35% and contributes to high biological oxygen demand (BOD) if discharged untreated. Sericin in coloured cocoons contains lutein, beta carotene and rare species of chlorophyll while sericin layer in a double cocoon contains flavonoids and their glycosides The layer close to fibroin is the innermost layer of sericin is secreted by the posterior cells of the middle silk gland, while the outermost layer which is soluble in hot water is secreted by the anterior cell s of the middle silk gland. The sericin is made up of 17 types of amino acids, majority of polar amino acids includes serine and aspartic acid [17].

2.3 Silkworm Frass (Litter)and its uses:

Silkworm litter, a by-product of sericulture comprises the larval excreta, uneaten mulberry leaves and rearing bed residues, the rearing waste constitutes about 61% of that contains 48.38% silkworm excreta, 40.43% of shoot waste and 11.18% of leaf waste which together constitute silkworm litter is produced from acre land by rearing 300 dlfs. silkworm litter is rich in flavonoids, chlorophyll, alkaloids, carotenoids and lutein compounds that shows high antioxidants activity [18-21].

Silkworm excreta mixed with leftover mulberry leaves accumulate in rearing houses. This material is rich in nitrogen and organic matter. Silkworm litter is a bio resource rich in organic matter and beneficial microbial populations making it a promising input for sustainable agriculture. Chlorophyll content in the litter is used in the food industry as a natural content. utilisation of these bioproducts reduces reliance on chemical fertilizers increase nutrients contents to agricultural fields contents to agricultural fields is an efficient method to decrease cadmium availability, fertilising trees with silkworm excrement which is an ideal example of a circular economy.

2.4 Mulberry Residues and uses:

Mulberry cultivation generates pruning waste, fallen leaves, and root residues, which are often burnt or left unused (Figure-1). If these wastes are not properly managed, they attract pests and creates unpleasant environment around the rearing houses. However, this waste material is rich in organic matter and makes them excellent raw material for composting and can also be converted into a valuable organic manure that not only improves the soil fertility but also supports sustainable plant cultivation. Mulberry residues which were considered as waste are now considered as valuable resources in circular economy as these residues are rich in proteins, dietary fibres and bioactive compounds. The sericultural waste is a mixture of leftover leaves, exuvial are utilised for Seri compost, in poultry and cattle feed and also as substrate for growing mushrooms thus helps in prevention of environmental pollution [22-26]. Figure-1 showing how mulberry cultivation produces pruning waste, fallen leaves, and root residues that are often burnt or left unused.

2.5 Reeling and Spun Silk Waste and their uses :

Defective cocoons, pierced cocoons, and thread waste are generated during reeling operations. Thread waste and spun waste are common by products generated during reeling, re reeling, twisting and fabric processing stages of sericulture which is sold at a low price though this waste possesses excellent mechanical strength, biocompatibility and biodegradability can be transformed into a high value textile waste like knubbs, bassinas and filature waste during different stages of fabric making. How ever due to its rich fibroin content, these silk waste possesses excellent mechanical strength can be made into a valuable raw material that can enhance economic value of the discarded waste material if used as a interlining material, ecofriendly packaging, decorative textile and insulation material. Quantifying these wastes helps in planning systematic utilization strategies and designing decentralized waste processing units. The chitin and chitosan from pupal skin helps in water purification, while the pupal oil which is rich in unsaturated fatty acid is used as a raw material in cosmetic industries. With silk powder which is prepared from silk waste

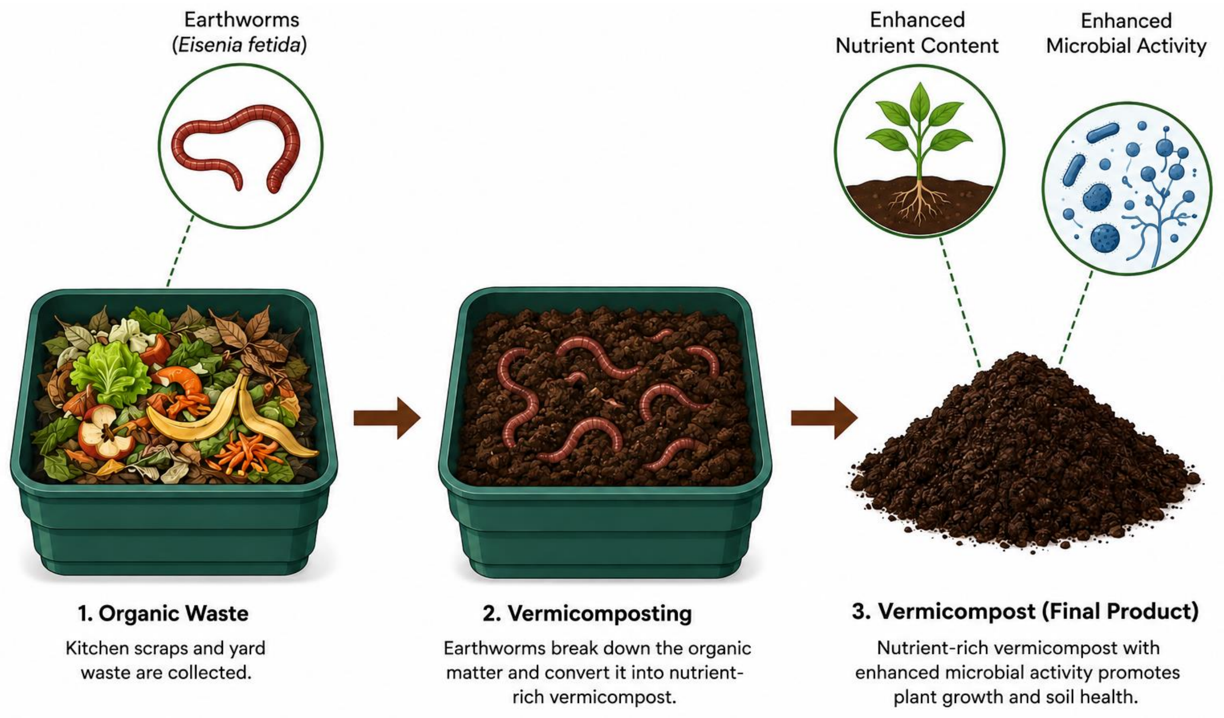

Figure-2. Schematic representation of vermicomposting using *Eisenia fetida*, illustrating the conversion of organic waste into nutrient-rich vermicompost with enhanced microbial activity

improves moisture retention and skin smoothness. Silk waste fibres can be incorporated into bio degradable plastic composites, a reinforced construction material and automative interior panels which with their enhanced tensile strength maintain light weight properties. With rise in price of fishmeal, the pupal meal which is protein rich is used as animal feed in poultry, dairy and aquaculture.

3. Bioconversion Technologies

Bioconversion refers to the use of biological processes such as microbial action, enzymatic treatment, and composting to convert organic waste into useful products.

3.1 Microbial Fermentation and its uses:

Microbial fermentation uses bacteria, fungi, or yeast to convert organic matter into valuable compounds. Silkworm pupae can be fermented to produce protein hydrolysates, amino acids, enzymes, and bioactive peptides. Fermented pupae meal has improved digestibility and can be used as high-quality animal feed. Silkworm pupae are not directly utilised because of poor digestibility, odour and rapid spoilage, hence microbial fermentation involves the biochemical transformation of silkworm pupae into high valve products with improved nutritional and functional properties. Bacteria, fungi and yeast enhanced the nutrient availability and produce beneficial metabolites. The collected fresh pupae are washed, dried, powered, sterilised to eliminate unwasted microbes and then fermented at controlled temperature (30 -37 centigrade<) for 3 days and converted to powdered form. Fermented pupae meal is used as a high protein feed ingredient to improve growth rate, feed conversion efficiency besides to provide the essential amino acids in poultry, dairy and pisciculture. the fermented pupae which is rich in nitrogen, phosphorus, potassium and amino acids improves the soil fertility and thereby maximizes the crop productivity. The fermented pupae serve as an alternative protein sources [27-28].

Microbial fermentation of silkworm pupae helps in conversion of pupae into a valuable product that supports circular bioeconomy, supports sustainable development and value addition in silk industry.:

Mulberry residues can also undergo fermentation to produce organic acids, bioethanol, or single-cell protein. This technology is cost-effective and suitable for small-scale rural units. In moriculture, large quantities of residues can be converted into valuable products through fermentation wherein cellulose , proteins and sugars are converted into useful simpler substance by microbes like *Saccharomyces cerevisae,* Lactobacillus which enhance the nutritional value of the mulberry residues and produce by products ,these residues are rich in nitrogen, phosphorus and potassium which improves the soil fertility, by increasing the microbial activity to maximize the mulberry leaf yield for sustainable sericulture farming .Fermented fruit residues contains antioxidants like anthocyanins and polyphenols when converted into wines and functional beverages. The bioethanol helps to reduce greenhouse gas emissions, supports waste to wealth concepts in agriculture and sericulture thus promotes the sustainable farming.

3.2 Enzymatic Hydrolysis:

Enzymatic hydrolysis involves breaking down complex proteins and polysaccharides into simpler molecules using specific enzymes. Proteases can hydrolyse pupal proteins into bioactive peptides with antioxidant and antimicrobial properties. During hydrolysis of pupal proteins enzymes breaks the peptides bonds and converts large proteins molecules into small peptides. Protease hydrolysis produces peptides with several beneficial biological activities like

antioxidant, antimicrobial properties that makes silkworm pupal protein hydrolysates suitable as a functional and nutraceutical food formulation which are environmentally friendly. Chitin present in pupal shells can be converted into chitosan using chemical or enzymatic methods. Chitosan has applications in medicine, agriculture, and water purification.
This method enhances product quality and adds significant commercial value.

3.3 Composting and Vermicomposting:

Silkworm litter and mulberry waste are ideal substrates for composting. Composting converts organic waste into nutrient-rich manure through microbial decomposition. Vermicomposting, using earthworms such as *Eisenia fetida*, further enhances nutrient content and microbial activity (Figure-2). The resulting vermicompost improves soil fertility, water retention, and mulberry leaf yield. This supports sustainable mulberry cultivation and reduces dependence on chemical fertilizers. During sericulture activities a large quantity of organic residues causes unpleasant odour and environmental pollution though they are rich in organic matter. These materials when properly decomposed produce nutrient rich manures which are essential for healthy growth of mulberry thus the leaf protein content and palatability enhances the silkworm growth subsequently the economic traits.

3.4 Anaerobic Digestion:

Anaerobic digestion is a process where organic waste is decomposed in the absence of oxygen to produce biogas (methane + carbon dioxide). Silkworm litter and mulberry waste can be used in biogas plants. The generated biogas can be used for cooking or electricity generation, while the digestate serves as organic manure. This method contributes to renewable energy generation and reduces greenhouse gas emissions.

4. Future Prospects:

The integration of advanced bioconversion technologies with biotechnology and artificial intelligence has significant implication for sustainability and economic viability of the sericulture industry. These integrated approaches create new and diversified revenue streams for rural sericulturist by converting sericultural waste into value added products. The integration helps in improving the occupational and environmental health. Traditional disposal of sericultural waste, particularly sericin rich effluents, contributes to high BOD, leading to waste pollution, adoption of bioconversion processes significantly reduces BOD levels, thereby minimises the environmental hazards and improves working condition of the rearers and reelers in their respective sectors. Furthermore, the synergy between biotechnology and artificial intelligence ensure precise and efficient utilization of sericultural byproducts, transformation of waste into biomedical materials, nutraceuticals and ecofriendly industrial products, thus supports the development of a circular bioeconomy where waste is recycled into valuable resources. ultimately, this approach reinforces that concept that in a scientifically managed sericulture system “NOTHING IS WASTE”, Every seri by product generated can be effectively converted into economically.

5. Conclusion

Sericulture waste should no longer be considered as a disposal problem but a resource for valuable biological products through systematic bioconversion techniques. adoption of integrated waste management techniques can convert the sericulture waste into a value-added product which not only increases the farmers income but also ensures environmental sustainability. Hence there is always a need to carry out research on scaling technologies, improves extraction efficiency and promotes commercialization pathways.

Competing interests:

The authors declare that they have no competing interests

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