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Mulberry byproducts: A new economic frontier: A review

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Abstract

Mulberry (*Morus* spp.), which is commonly grown for sericulture, has unrealized potential in its byproducts, which present chances for sustainability and economic diversification. This analysis examines the potential for value addition of mulberry byproducts, such as fruits, leaves, bark, roots, and wood, in a variety of sectors, including food, medicine, cosmetics, and bioenergy. Mulberry byproducts, which are rich in bioactive substances such flavonoids, polyphenols, and alkaloids, have anti-inflammatory, anti-microbial, and antioxidant qualities that make them appropriate for use in functional foods and nutraceuticals. Additionally, mulberry leftovers can be transformed into organic fertilizers, animal feed, and biofuels, all of which support the ideas of the circular economy. In order to fully exploit the economic potential of mulberry byproducts, the article highlights the necessity of market growth, legislative assistance, and innovative processing methods. By taking advantage of these chances, mulberry farming can evolve from a sericulture-focused endeavor to a diverse sector supporting sustainable development and rural livelihoods.

Keywords: Mulberry (*Morus* spp.), mulberry byproducts, economic diversification, sustainability, value addition

Introduction

India has a rich and complex history of silk production and trade that dates back to the fifteenth century. The sericulture industry in India provides employment to approximately 8.8 million individuals, primarily in rural and semi-urban areas. A significant portion of this workforce comes from economically disadvantaged groups. For farmers engaged in sericulture, the cultivation of silk cocoons serves as a crucial source of income. Moriculture, the agricultural practice of cultivating mulberry plants, is essential as mulberry leaves are the primary food source for silkworms, which produce the natural fibers. Among the more than 20 species of mulberry, four are commonly grown: *Morus alba*, *Morus indica*, *Morus serrata*, and *Morus latifolia*. The Central Sericultural Germplasm Resources Centre plays an active role in preserving mulberry germplasm, with 1,109 different accessions, including 845 native and 264 foreign varieties (Khurana & Checker, 2011) [11].

In India, around 350–400 kg of mulberry leaves are required to raise 20,000 silkworm eggs, which eventually produce natural silk fiber. These practices provide scientific insight into the phytotechnology used to cultivate higher-value products within the sericulture system. Cocoons, the primary product of sericulture, are vital raw materials for the textile industry. In addition to these, numerous byproducts are produced, which can be converted into valuable commercial goods. For instance, to raise 100 dfls (disease-free layings) of silkworms, approximately 1,000 kg of mulberry leaves are necessary, yielding about 300 kg of litter and 500 kg of leftover mulberry waste such as dried leaves, leaf veins, and stalks (Mala & Chandrashekhar, 2020) [23]. These byproducts, rich in nutrients, contribute to the sustenance of mulberry crops.

Furthermore, for every kilogram of raw silk produced, 8.014 kg of wet pupa and 2 kg of dry pupa are generated, which, although not usable in sericulture, find applications in the food industry. Sericin, a gummy protein extracted from the cocoon during degumming, is similarly discarded in textile production, but it holds potential for use in pharmaceuticals and cosmetics. India produces around 1,600 tons of silk annually, with approximately 250–300 tons of sericin left as waste (Rajput *et al*., 2015) [31].

Mulberry trees can thrive in both fertile, deep, permeable soils and nutrient-poor, arid soils. Research by Shi *et al.* (2005) [37] demonstrates that mulberry trees are effective in preventing soil erosion. Moreover, these trees have the ability to clean up contaminated soils by absorbing heavy metals such as cadmium and lead. According to Sharma and Madan, mulberries are fast-growing, perennial woody plants rich in cellulose (57.45%), hemicellulose (16.3%), and lignin (24.6%). Mulberries are increasingly being studied for their potential in agro-pharmaceutical, phytoregenerable, and agro-alimentary industries.

Mulberry trees, typically around 1 meter tall, can absorb about 4,162 kg of CO2 and release 3,064 kg of O2 annually, making them excellent carbon sink plants. Additionally, they are capable of absorbing air pollutants like hydrogen, chlorine, fluoride, and sulfur dioxide. Mulberry plants are also known for producing flavanics, a chemical with anti-cancer properties (Zhang *et al*., 2009) [52]. The latex from mulberry trees, which has toxic properties and a defense mechanism against herbivory, is being researched for its potential as an herbicide target.

Use of mulberry leaves:

In Chinese villages, mulberry leaves are often consumed as juice, owing to their high content of proteins, carbohydrates, sugars, starch, crude fiber, amino acids, vitamins A, B, and C, as well as essential minerals like calcium, magnesium, iron, and zinc, which contribute to human nutrition. Mulberry leaves also contain deoxy nojirimycin, a compound that inhibits the enzyme responsible for sugar breakdown. This property has been shown to be beneficial in managing AIDS and providing effective treatment for Alzheimer's disease, as highlighted by Suryanarayan. Furthermore, mulberry leaves, rich in protein and possessing neuroprotective properties, can be used to treat neurodegenerative conditions such as Alzheimer's and neuropathy (Buhroo *et al*., 2018) [4].

Research by Deepa and Priya (2012) [27] isolated a novel galactose-binding lectin from *Morus alba* leaves, which demonstrated cytotoxic effects against human breast cancer cells (Ic50 = 8.5 µg) and colon cancer cells (Ic50 = 16 µg). According to Venkatesh and Chauhan, mulberry leaf juice serves as a febrifuge, useful in treating amoebiasis, endemic malaria, colds, and diarrhea. Additionally, due to their high carotene content, mulberry leaves can provide a valuable source of vitamin A, which benefits the health of poultry birds and boosts their egg production (Buhroo *et al*., 2018) [4].

Mulberry leaves are also favored by sheep and goats because they are nutrient-dense, containing about 20% protein on a dry matter basis. In terms of biogas production, young mulberry leaves have a potential biogas yield of 60.6 ml/200 mg, with a degradation rate of 0.0703, while mature leaves yield 35.4 ml with a degradation rate of 0.0624.

Use of the mulberry tree's stem, twigs, and branches

Mulberry twigs and wood stems have diverse applications in various industries. They are used as fuel, for natural coloring or dye, alcohol enrichment, and in the paper and textile industries to produce what is known as "Artificial Cotton." Additionally, mulberry is utilized in cosmetics for hair lotions, skin moisturizers, and for wood processing in the production of furniture. The thicker mulberry stems are often used for making pens and serve as fuelwood in rural areas, thanks to their antiseptic properties. They are also used in the manufacture of sports goods, agricultural implements, and household articles.

Due to its strength, elasticity, flexibility, and durability, mulberry wood is ideal for making sports equipment such as hockey sticks, and tennis, badminton, and squash rackets. It is also used to produce low-quality plywood, which is employed for turning, carving, and constructing both small boats and large ships (Buhroo *et al*., 2018) [4]. Mulberry's soft, white fiber, extracted from its bleached and digested bark, is used in China and Europe for various applications, while its young, small pruned branches find use in the paper and textile industries.

Cotton-like fibers from phloem mulberry shoots are utilized as additives for making nets and ropes. Mulberry wood tannin extraction is also used for tanning and dyeing purposes. Phytochemical analysis of mulberry stem bark has led to the identification of compounds like Cathayanin and other cathayanons. The stem bark aggregates contain sugars, phytosterols, phosphoric acids, and cheryl fatty acids, which are used as stimulants and preservatives.

Use of mulberry root bark

Mulberry root systems play an important role in enhancing soil stability, particularly in purple soils, by increasing their shear strength and resistance to erosion. These root systems are capable of absorbing not only essential soil nutrients but also heavy metals such as lead (Pb), cadmium (Cd), and copper (Cu) (Jothimani *et al*., 2018) [10]. The root bark of *Morus alba* contains glycosides like 5 2'-dihydroxy flavanone-7 and 4'-di-o-D-glucose, which have been found to inhibit the proliferation of human ovarian cancer cells (HO-8910) (Zhang *et al*., 2009) [52].

The root bark of *Morus alba* also contains a sanggenon alkaloid that, alongside glucosidase, is used to treat high blood pressure by inhibiting the production of plaque (Buhroo *et al*., 2018) [4]. Albanol A, a substance extracted from *Morus alba* root bark, has been shown to inhibit topoisomerase-II activity (IC50 = 22.8 µg) and exert significant cytotoxicity (IC50 = 1.7 µg) against HL60 human leukemia cells (Priya, 2012) [27].

Additionally, the roots of mulberry trees are rich in cudraflavone B, a compound that inhibits the activity of inflammatory mediators. Research by Lee *et al*. (2012) [22] revealed that morusinal, isolated from *Morus alba* root bark, inhibits collagen and arachidonic acid, which causes platelet aggregation, thus preventing arterial thrombosis and promoting recovery from transient strokes.

Morus alba also contains moracin, a new compound evaluated for its protective effects against hydrogen peroxide-induced stress in skin fibroblast cells (AH927) (Khayade *et al*., 2018) [12]. The ethanolic extract from the bark of *Morus alba* contains flavonoids such as morusin, mulberrofuran D, G, K, and kuwanon G, H. Among these, morusin and kuwanon H have shown positive activity against HIV (Shi *et al*., 2001) [37]. Finally, mulberry root juice possesses cathartic properties, making it effective in treating parasitic infections, including roundworm, tapeworm, and hookworm (Ramesh *et al*., 2003) [34].

Mulberry fruit use

Mulberry fruits are widely used in the cosmetic and pharmaceutical industries to treat a variety of ailments, including liver-kidney deficiencies, tinnitus, dizziness, rheumatic pain, premature gray hair, constipation, and diabetes. In addition to their medicinal uses, mulberries are commonly processed into jams, jellies, ice creams, and fruit tea. Unlike synthetic food colorings, which are often harmful to health, mulberry fruits provide a natural source of color and flavor. Approximately fifteen tons of mulberry drink, as well as red or purple anthocyanins, can be produced from mulberry fruits, which are used as coloring and flavoring agents (Malsiamani *et al*., 2008) [24].

It is believed that consuming a glass of mulberry wine daily can help eliminate toxins, lower cholesterol, and promote a slender and elegant physique, contributing to overall health improvement. Mulberry wine is made from overripe and sour fruits (Sinha, 2008) [38]. Additionally, the fruit of the *Morus nigra* plant is an ingredient in the Unani medication "Tut i-aswad," which is thought to have cancer-fighting properties (Ahmed *et al*., 1985) [2]. Mulberry leaves are also valuable for extracting "flavanics," which have anti-cancer properties (Zhang *et al*., 2009) [52].

Mulberry fruits are rich in polyphenolic compounds such as flavonoids, anthocyanins, benzoic acid, and hydroxycinnamic acid, which are believed to possess antioxidant, anti-diabetic, and anti-obesity effects (Yang *et al*., 2016) [51]. Resveratrol, found in dried mulberry fruits, is known to prevent the transformation of normal cells into cancerous ones, helping to avoid inflammation, chronic heart disease, and other health problems (Hou, 2003) [9]. One serving of mulberry fruit juice provides 10% of the daily recommended dietary fiber intake and has anti-aging properties (Rutuja *et al*., 2019) [35].

In the UK, a new fruit juice company called "Fair Juice" introduced a superfruit drink made from mulberry fruits, known for their high resveratrol content, which is beneficial for heart health and combating obesity (Fairjuice, 2008) [7]. Furthermore, Ayurvedic medicine benefits from the oil extracted from mulberry seeds, and both the food and pharmaceutical industries use mulberry fruit juice as a natural alcoholic extract additive. Habib reported that a multi-nutrient feed block made from mulberry fruits significantly boosted milk production in livestock by 30 to 50 percent, with minimal incidence of illness.

By-products of silkworm rearing: Silkworm rearing byproducts include leftover mulberry leaves and silkworm excrement in the rearing bed, which can be used in vermicomposting when combined with other agricultural waste, while silkworm litter by itself can be utilized in the pharmaceutical and biogas industries.

Rearing and Additional Agricultural Waste for Vermicomposting

Each year, approximately 15 metric tons (MT) of sericultural waste are generated from one hectare of mulberry farms, which includes silkworm rearing waste and other agricultural byproducts. This waste contains around 280–300 kg of nitrogen, 90–100 kg of phosphorus, and 150–200 kg of potash (Das *et al*., 1997) [5]. Using these byproducts as a foundation for vermicomposting leads to the production of organic manure, which not only reduces the cost of chemical fertilizers but also enhances soil health and improves the nutrient availability for mulberry plants, consequently improving leaf quality.

Venugopal *et al*. (2010) [43] found that vermicompost produced from sericultural farm residue, using a mixed culture of juvenile earthworms (*Eudrilus eugeniae*, *Eisenia foetida*, and *Perionyx excavatus*), contains 1.8–2.0 percent nitrogen, 0.6–0.9 percent phosphorus, and 1.0–1.5 percent potash. According to Dandin *et al*. (2006) [6], this vermicompost has been proven to be significantly superior to farmyard manure.

Silkworm Excreta as a Substrate for Biogas Production:

Biogas, an important energy source in rural and agricultural regions, is produced through anaerobic digestion of organic waste. Research has shown that the biogas generated from silkworm breeding waste and caterpillar excreta is comparable to biogas from other agricultural substrates, including cattle, pig, and chicken manure. Lochynska and Frankowski reported that fermenting silkworm breeding waste produces 256.59 m^3/Mg TS of methane and 489.24 m^3/Mg TS of biogas. In contrast, fermenting silkworm excreta under mesophilic conditions results in 167.32 m^3/Mg TS of methane and 331.97 m^3/Mg TS of biogas.

Silkworm excrement, often referred to as feces, is a significant byproduct of sericulture. It is cylindrical in shape, measuring 2-3 mm in length, and has a deep green color. Silkworm excreta has potential applications in both the pharmaceutical and food industries (Vimolmangkang *et al*., 2013) [44]. Historically, silkworm feces have been used in traditional Chinese, Korean, and other Eastern Asian medicines to treat various ailments such as headaches, stomachaches, and infectious disorders (Tulp & Bohlin, 2004) [45].

The chemical components of silkworm excreta include chlorophyll and its derivatives, xanthophylls, carotenoids, and flavonoids, which have been extensively documented (Park *et al*., 2011) [28]. From the excreta of *Bombyx mori* silkworms, chlorophyll derivatives such as CpD-A, B, -C, and -D have been isolated. CpD-A, in particular, has been widely studied for its role as a "photosensitizer" in *in vitro* photodynamic therapy (PDT) for cancer treatment (Lee *et al*., 1990) [20]. Additionally, three beneficial substances—lupeol, β-sitosterol, and 1-tritriacontanol—have been extracted from silkworm excrement. It is believed that 1-tritriacontanol is produced in the silkworm's intestine, while lupeol and β-sitosterol, which are derived from the mulberry leaves the silkworms consume, are expelled in their unaltered form and have anti-inflammatory properties (Vimolmangkang *et al*., 2013) [44]. Furthermore, silkworm excrement can also be utilized in the food industry as a natural coloring agent. Research by Vila *et al*. (2018) [46] demonstrated that silk and polyamide textiles could be easily dyed using a natural dye derived from silkworm feces, resulting in a yellowish-brown hue.

Byproducts of silk reeling

Silk Waste and Its Applications

In the silk industry, "silk waste" specifically refers to fibers that are too short or not continuous enough to be reeled into silk. During the reeling process, the pelade layer—the innermost layer of the cocoon—is discarded along with the pupa as basin waste. Additionally, during the degumming process, silk sericin is removed to enhance the value of silk as a textile fiber, but it is generally considered waste.

Silkworm Pupa in the Culinary and Medical Industries

After the reeling process, silkworm pupae are a direct byproduct of the silk industry. India produces over 40,000 metric tons (MT) of silkworm pupae annually on a dry weight basis (Priyadharshini *et al*., 2017) [29]. Silkworm pupae are rich in crude proteins (50–60%), lipids (25–35%), free amino acids (5-8%), carbohydrates (8–10%), and essential vitamins like E, B1, and B2, along with minerals such as calcium and phosphorus. A 100g serving of dried silkworm pupae can provide up to 75% of the daily protein requirements for an average individual (Singh & Suryanarayana, 2003) [39]. The pupae are particularly nutrient-dense due to minerals like calcium, selenium, and phosphorus, as well as vitamins such as pyridoxal, riboflavin, thiamine, ascorbic acid, folic acid, nicotinic acid, and pantothenic acid. The high-quality lipids found in silkworm pupae are also used in medicinal applications (Shanker *et al*., 2006) [40]. By stimulating apoproteins and lipid-metabolizing enzymes, silkworm pupae help regulate lipoprotein and plasma lipid levels in rats' serum, making them useful in treating hyperlipidemia. Additionally, silkworm pupae contain lecithin, which has antioxidant properties (Hu & Chen, 2011) [8]. In countries like China and Korea, silkworm pupae are widely used in nutritional supplements, medications, and animal feed. They are considered a premium source of animal protein and are the only insect food recognized in the Ministry of Health's list of Novel Food Resources (Kim *et al*., 2008) [15]. Silkworm pupae are consumed in various forms, including whole pupae, pupal oil, and pupal powder. Due to their high concentration of essential amino acids, silkworm proteins are considered complete proteins. According to the World Health Organization (WHO), silkworm pupae provide all the amino acids required by the human body in the correct proportions (Kohler *et al*., 2019) [16].

The unsaturated fatty acid content of silkworm pupae is approximately 70–80%, and the unsaponifiable substances in the oil, such as cholesterol, β-sitosterol, and campesterol, make up about 1%. In food applications, such as biscuits made with 7% powdered silkworm pupal waste, each serving contains 6.6 mg of iron, 114.5 mg of calcium, 79.3g of carbohydrates, 51.3g of fat, 16.6g of protein, and 854 kcal (Vishaka *et al*., 2020) [47].

Silkworm pupae in compost

Eight percent of nitrogen is present in dried silkworm pupae. Given that pupae are rich in protein and nitrogen as well as micronutrients including copper, magnesium, manganese, and zinc, there is a chance that pupal waste might be bioconverted into enriched compost and used as a source of nutrients (Mahesh *et al*., 2020) [25]. When combined with chemical fertilizers, the application of Silkworm pupae residual biocompost (SPRB) greatly improved mulberry growth and yield metrics (Mahesh *et al*., 2020) [25]. Using silkworm pupal waste, Karthikeyan and Sivakumar (2007) [17] mass-cultivated the biopesticide bacterium Bacillus thuringiensis. The viable spore count (VSC) was used as a measure to assess the pupal waste medium's effectiveness.

Using Silkworm Pupae as Animal Feed

Waste silkworm pupae are rich in nutrients that make them beneficial for various types of livestock. De-oiled pupae can enhance hens' egg-laying capacity, while fat-free pupae are particularly useful in aquaculture. When incorporated into fish feed, silkworm pupae help increase yields. According to Mahata *et al*. (1994) [26], fish that were fed a diet with approximately 38% of their total dietary protein replaced by silkworm pupal meal exhibited the fastest growth rates among silver barb fingerlings (*Barbonymus gonionotus*). In a polyculture system involving Indian carp (*Catla catla*) and mrigal carp (*Hypophthalmichthys molitrix*), fermented silkworm pupae silage or untreated fresh silkworm pupae paste was used to replace fish meal in carp feed formulations. The fish that were fed the fermented silkworm pupae silage showed higher survival rates, better feed conversion ratios, and improved specific growth rates compared to those fed with untreated silkworm pupae or fish meal (Rangacharyulu *et al*., 2003) [32]. Silkworm pupae are also used as feed for dogs, pigs, poultry, and in pisciculture due to their high protein and fatty acid content. The dried pupal meal has been shown to improve fish survival, feed conversion, and specific growth rates, as well as enhance the growth rate and egg quality in hens. Additionally, rabbits fed de-oiled pupae gained weight and fur more effectively.

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