Silkworm *Bombyx mori*

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Among insects, the silkworm *Bombyx mori* occupies a special position, being an excellent lepidopteran species representative of numerous scientific investigations. *B. mori* was domesticated and developed by human-driven selection from a wild origin since ancient times. Many years ago, silkworm genetic stocks were conserved in research facilitie. The silkworm can be considered from the economic point of view to be one of the most significant insects. It has been providing important benefits to humans, and it has continued developing thanks to its many practical applications, including using it as a model organism for medical purposes.

Keywords: mulberry ; silkworm ; pupae ; silk ; economic ; biodiversity

1. Mulberry Sustainability by Its Applications

Mulberry (genus *Morus*, family *Moraceae*) is a significant economic component in sericulture, the starting point since the quality of the cocoon and the quantity of leaves produced per unit of area are strongly correlated.

The mulberry tree is a perennial plant with significant traits, including higher leaf production, a shorter gestation time, and a greater capacity to adapt to the environment [1][2]. Ninety percent of the world's raw silk output comes from silk from silkworm *B. mori* [3]. This considerably improves many people's lives worldwide. Moreover, it has been stated that the mulberry plant offers a range of nutritional and therapeutic benefits, including its use in livestock feed and well-recognized medical advantages [4].

The mulberry leaves, fruits, and wood push the limits of sustainable development through multiple applications from an economic standpoint. Firstly, mulberry leaves are well known for being the only nourishment source for feeding and raising *B. mori* silkworms, although artificial diets have been adopted [5]. According to Srivastava et al. [6], leaves powder contains key nutrients, such as protein (5–7.3%), fat (2–5%), ash (14.59–17.24%), carbohydrates (9.70–30%), and energy (113–224 kcal/100 g). Cai et al. [7] found condensed tannins, jasmonic acid, anthocyanins, flavonoids, stilbene, and terpenoids, as bioactive compounds required as well for physiological processes in the larva body (growing, reproduction, silk production). One metric tonne of mulberry leaves will yield approximately 25 to 30 kg of cocoons [8].

Mulberry fruits, rich in protein and vitamins, have long been consumed worldwide in human and animal diets. Mulberry products, including juice, tea, wine, and jam, are worthy of inclusion in human diets because of their rich composition in antioxidants, vitamin C, potassium, magnesium, iron, and vitamins K and E.

Several studies have recently investigated the antioxidant potential of extracts from various mulberry plant components, including the leaves, roots, and fruits [9][10]. Furthermore, numerous studies have shown antioxidant, antiviral, anti-inflammatory, hypolipidemic, anti-hyperglycaemic, neuroprotective, anti-HIV, antihypertensive, and cytotoxic properties for mulberry leaves [11][12].

In conventional and contemporary medicine, fruits and leaves are recognized for their antidiabetic properties [8][13]. Traditional Chinese medicine uses mulberry leaf tea with flavonoids and polyphenol antioxidants. The tea has anti-inflammatory properties and reduces cholesterol. Recent studies have also shown mulberry leaf tea has therapeutic benefits for treating diabetes by decreasing blood sugar and inhibiting carbohydrate absorption [14].

Ghosh et al. [2] provided a detailed description of mulberry's economic importance. Thus, the protein-rich mulberry leaves of *Morus alba* can be used successfully as animal feed and can help in lowering blood pressure and cholesterol levels in humans.

Although they were considered waste, the mulberry leaf stalks, and leftovers, such as twigs and shoots, can add value to ruminants and monogastric diets [15][16][17][18][19][20]. The trunks' wood is valuable for manufacturing paper, handicrafts, cabinetry, handles, and as a fuel source [8].

The main issues that affect the silkworm farmers include mulberry and silkworm rearing management practices, mulberry field area, low quality of silkworm breeds, inadequate infrastructure, a lack of room for raising silkworms, a lack of sufficient start-up equipment for farmers, and low acceptance of new technologies [21].

2. Silkworm Products—Economic Impact

Although there has been a noticeable improvement in silkworm breeding and the creation of new varieties, sericulture development still faces substantial challenges both upstream and downstream. The availability of high-quality eggs, efficiency of farms, health management, a lack or insufficiency of governmental support, unsustainable production, and competition from imported products are the predominant impediments to its development on both the upstream and downstream levels [22]. Sericulture's profitability can be boosted by legislation, investments, and cutting-edge procedures and methods.

Throughout the technological flux of growing silkworms, products (silk thread, pupae cake, pupae oil, larvae and excreta, moths, eggs) are generated at each phase with excellent application in various fields. This increases the incomes of silk farmers and from other related industries.

For instance, the manufacturing of silkworm silk thread (the main product considered a natural protein filament and finest yarns) had a considerable impact on economic development since it formed the basis of rural and urban economy areas of Asia, Europe, and American countries.

According to the FAO report, at the global scale, between 70,000 and 900,000 M.T. of silk is produced yearly, while the demand is rising by 5%. The need for silk will grow due to the population growth and the increased desire for attractive clothing items brought on by rapidly changing fashion trends in highly developed nations.

The high value of silk yarns explains why they have been a crucial part of cross-continental commerce for many generations. Major economic, social, and cultural contacts have resulted from these exchanges over shifting continental and marine routes, but their geopolitical and symbolic long-term significance is still obvious today. The silk production, processing, and trade also serve as the foundation for a tangible cultural heritage by aiding in the development of skills, work organization techniques, encouraging technical and technological transfers, and designing rural and urban landscape types. These traits of sericulture activities make them especially well-suited for addressing economically important topics from a global viewpoint.

Data Bridge Market Research [23] reports that the textile sector has experienced tremendous expansion, leading to the increased demand for silk. Producing silk does not require sophisticated machinery and equipment. These elements support the market's growth. The global silk market is anticipated to grow by USD 32.06 billion by 2029 with a Compound Annual Growth Rate (CAGR) of 8.30% from 2022 to 2029. According to Market Data Forecast [24], the CAGR is predicted to reach 11.32% from 2023 to 2028, while Mordor Intelligence [25] forecasted a CAGR of 5.5% for the 2018–2028 period. The Observatory of Economic Complexity (OEC) [26] reported the total silk transaction amount of USD 1.27 billion in 2020, which contributed to making silk the 96th most traded product in the world. Raw silk exports increased from USD 245 million in 2020 to USD 269 million in 2021.

According to OEC statistics, Romanian silk exports represented 2.07% of the total export value, while imports comprised 13.9%.

Silk fibrous proteins (sericin and fibroin) are beneficial compounds produced in the sericogenic glands of the silkworm through biosynthesis. Sericin, which makes up 25–30% of the protein, surrounds the fibroin fibre with a series of sticky layers that contribute to forming the cocoon. Sericin binds the silk threads around each other, ensuring the cohesiveness of the cocoon [27]. Biodegradable polymers that are favourable to the environment can be produced by mixing sericin with other resins. Sericin and fibroin can be used to create membranes for separation procedures [28].

According to Saric and Scheibel [28], researchers from several fields are looking into using recombinant silk proteins as green bio-polymers. Silk materials may also be macroscopically functionalized to create composite materials that offer remarkable versatility, such as for medical uses in diagnostics, biosensors, or tissue regeneration. Silk is also promising for various clinical and biological applications [29]. Similarly, Kundu et al. [29] highlighted fascinating technical progress made by using bioengineering in implantable optics, photonics, and electronics.

Silkworm pupa characteristics, nutritional value, and applications in different fields were detailed [11]. Thus, researchers focused on the excellent nutritional characteristics emphasizing fatty acids beneficial to health (omega-3 particularly) and wide applicability in human food and animal feed, medicine, and environmental impact reduction. The varied and intricate medicinal benefits, such as immunomodulatory, antibacterial, anticancer, antioxidant, hepatoprotective, antifatigue, and antiapoptotic actions, are also remarkable. Silkworm pupa bioactive compounds act by reducing plasma triglycerides. These bio-compounds act to treat wounds and control blood sugar levels, lower blood pressure, prevent thrombosis and arteriosclerosis, boost cell vitality, and enhance the body's defences in metabolic disorders [11][30][31].

Among the benefits of silkworm proteins and hydrolysed peptides are increased immunity and anticancer and antioxidant properties [32].

From a dietary perspective, the larvae and pupae are edible parts of the silkworms and are eaten by the inhabitants of China, Japan, Korea, Thailand, and Northeast India [33]. Due to their high protein content, silkworm pupae have been sold for centuries in various marketplaces and are regarded as an economically viable commodity [34].

Sericulture focuses on many methods that might boost the farms' incomes by manufacturing cocoons. Small-scale farmers need to identify new revenue streams, including the sale of cocoons and other applications of by-products. Silkworm rearing allows for a cheap supply of biomass, which is potentially a beneficial source for biogas generation [35]. In a study in 2019, Łochyńska and Frankowski [36] presented an option with encouraging results of fertilizer organic hemp culture (*Cannabis sativa* L.) with larva excrements.

Traditional Asian medicine has employed excreta therapeutically to treat various diseases [35]. Since it contains a lot of flavonoids, chlorophyll, alkaloids, carotenoids, and lutein, silkworm excreta may have considerable antioxidant action [11].

The litter of silkworms (leftover leaves and faeces) can be used as organic manure [37].

Over time, due to concerns about animal welfare, scientists have been obliged to restrict the number of vertebrates used as experimental animal models. Consequently, other animal models that do not need ethics committee approval have been considered. A richness of genetic resources, an evident genetic pedigree, and a short generation period with a 25–30-day larval stage are some traits that make using silkworms a more favourable, simpler, and less expensive model for studies [38]. Kodama et al. [39], quoted by Meng et al. [38], developed the first silkworm larva viral infection model for medication therapy. The findings of injecting the virus into the silkworm's haemolymph showed that nalidixic acid might suppress the growth of the flacherie virus and nuclear polyhedrosis virus (BmNPV) and shield silkworms against infection with related viruses.

Due to their great susceptibility to pesticides, antibiotics, pathogenic fungi, and germs that are harmful to humans, silkworms have become a paradigm for natural immune activation, drug screening and kinetic testing [38]. In addition, research on the pathophysiology and human microorganism toxicity has rapidly improved in recent decades. It was discovered that the chitosan isolated from silkworm pupae improved economic parameters. Hence, efficient pupa reutilization might be employed to produce a high-potential raw material for numerous biomedical processes by turning it into beneficial bioproducts [40].

In contemporary research, the silkworm is used as a model organism to investigate human tumours, degenerative diseases, and metabolic diseases.

Epigenetics investigates genetic variation at the chromatin and DNA alteration levels without variations in gene sequence [41]. In cutting-edge research and technology, it is a crucial information carrier. Sericulture research advanced in 2010 by creating the first silkworm methylation map (as an epigenetics marker).

Aznar-Cervantes et al. [42] showed that it was possible to use the silkworm to assess the hypoglycaemic activity of various products originating from sericulture by dietary addition after promoting glucose or sucrose-induced hyperglycaemia.

Future directions and targets may be established and investigated as science continuously develops.

3. Edible Silkworm—Mentality and Perspectives

3.1. Silkworm as a Source of Food

A 60% increase in the requirement for food is anticipated by 2050 [43][44]. Since the Novel Food Regulation was enacted on 1 January 2018, EFSA [45] has received many applications covering various novel and traditional food sources. They include foods made from algae, non-indigenous fruits, herbal compounds derived from plants, and different edible insect species. Silkworms *B. mori* have been considered as a suitable insect for human consumption as a substitute for animal protein, but did not yet receive official authorization as edible insects.

Edible insects are a distinct food ingredient that continues to gain value in improving global food security and providing an attractive alternative to meat. Insects can contribute to food production and reduce the adverse effects of climate change [46]. More than 2000 edible insect species, including silkworms, are consumed globally [44] in raw or processed form [46].

A comprehensive nutritional comparison between *B. mori* and meat from different species was provided by Orkusz et al. [44]. Accordingly, the energy value (kcal/100 g) of edible parts of *B. mori* ranges between 171.27 and 229, for horse meat it is 109, for pork shoulder 13.2, for beef shoulder 112, for rabbit carcass 123.24, for goose carcass 140.63, for duck carcass 199.04, for turkey breast 83, for chicken breast 98, and for chicken drumstick 125. Regarding protein level (g/100 g), the higher value was reported for *B. mori* (17.9–23.1), followed by chicken breast and horse meat (21.5%), while the lower value was found in the goose carcass. For the poor rural population especially, *B. mori* represents a source more attractive from the nutritional point of view than meat. The advantages include fast growth, more efficient feed conversion, and minimum resource requirement.

Although insects present many advantages, most consumers are wary of their safety in most developed nations and reluctant to include insects in their diets. However, the studies concerning edible insects are limited.

In Romania, similar to many Western countries, there is a strong mentality against consuming edible insects, despite the EU opinion and advice due to respect for culinary traditions, mentality, and lack of sufficient information. Zugravu et al. [47] pointed out the importance of knowledge as a determinant factor for accepting the intake of edible insects. The study of Zugravu et al. [47], including Romania, as part of a global investigation, used a questionnaire translated into Romanian to assess attitudes against eating insects and find modifiable factors associated with reluctance or aversion. Even though most people do not find insects appetizing, those who know more about them may be willing to try these novel food products because they relate them to protein or other nutrients content. Nonetheless, overcoming aversion will be crucial in accepting insect ingestion, as eating patterns change hesitantly and gradually.

As an argument, the FAO [48], cited by Zugravu et al. [47], reported that a significant portion of the population will not have enough water by 2025. Raising and processing insects requires less water. Certain insects, such as the yellow and smaller mealworms and silkworms, can withstand drought.

According to Wu et al. [32], 26 proteins from silkworm pupae have been identified as allergens. Phytate, phytic phosphorus, tannic acid, alkaloid, flavonoids, saponin, and oxalate are some of the antinutrients in silkworm pupae that have drawn the attention of several authors; however, their levels do not present a risk to humans [11][49][50].

The WHO and International Union of Immunological Societies (WHO/IUIS) Allergen Nomenclature Sub-Committee (www.allergen.org) [51] have not officially confirmed or registered any allergens of silkworm pupae aside from this arginine kinase (formally known as Bomb m 1). Therefore, a thorough risk evaluation of possible allergic risks is necessary before establishing silkworm pupae as a food source. Few studies evaluate silkworm pupa allergens, and most tend to base them on case reports rather than regularly using standardized tests. Although 26 silkworm pupa proteins have been identified as allergens, little is known about their immunological characteristics [32].

3.2. Silkworm, a Valuable Feedstuff for Animal Feeding

There is an increased interest in using silkworms in animal feeding due to their protein levels and protein digestibility (76–98%), lipids, and essential fatty acids [11], which emphasize their significance in the current trends in feed science and related sectors. The effects of using silkworm pupae in ruminants and monogastric species, including chickens, pigs, rabbits, and fish, were studied by many authors [52][53][54][55]. Silkworm pupae are the potential to replace soybean meal or fish meal in animal feeding. Silkworm pupa meal is a valuable and less expensive alternative protein source having a little lower quality than fish meal. The properties of hen eggs and yolk colour improved when silkworm pupae were used as a protein supplement [56]. In monogastric diets, silkworm pupae did not significantly impact growth and feed efficiency parameters.

The results demonstrated that silkworm pupae can stimulate rainbow trout’s immune system and cause some anaemia-related symptoms.

There is little information available about using silkworm pupae in pig diets. However, the pupal powder is advised for pig feeding due to its high protein content [57], albeit the increased oil content may cause an adverse reaction. Interestingly, the protein in pupae is superior to that in fish and soybean meal [56].

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