Review Article

Revolutionizing Sericulture: New Trends in Biotechnological Applications and By-product Utilization

ABSTRACT

Sericulture, the cultivation of silkworms for silk production, is evolving with significant advancements in sustainability and technology. This review deals with recent trends and innovations in S~~s~~ericulture, highlighting the potential of sericulture by-products in regenerative medicine, tissue engineering and biofuel production. The application of biotechnological methods, including genetic engineering and bio-nanotechnology, has revolutionized silk production, enhancing silk quality and yield. The integration of advanced techniques and the diversification of silk applications, including pharmaceuticals, cosmetics and agriculture, promise to enhance the economic viability of sericulture. The review emphasizes the need for comprehensive research on by-product utilization and ~~the~~ development of sericulture models to boost ~~industry~~ sustainability and profitability of the industry. By balancing traditional practices with modern advancements, sericulture is poised for a sustainable and prosperous future.

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Keywords: Sericulture, biotechnology, sustainability, genetic engineering, eco-friendly practices and by-product utilization

1. INTRODUCTION

Sericulture, ~~the~~ anancient practice of rearing silkworms for silk production, has evolved significantly over millennia, establishing itself as a crucial global industry ~~globally~~. Originating in China around 2700 BCE, the art of silk produc transcended geographical and cultural boundaries, shaping trade routes and influencing economies worldwide. Today, sericulture remains vital to many economies, particularly in developing countries where it supports millions of livelihoods and contributes to both local and global markets. In the contemporary context, India stands second-largest producer of silk in the world, contributing to a global industry that is predominantly concentrated in Asia. India's diverse silk production encompasses four primary types: Mulberry (79.23%), Eri (13.32%), Tasar (6.8%) and Muga (0.54%) (Savithri *et al*., 2013). Each type has unique characteristics and applications, reflecting on Indian rich sericultural heritage and its role in global silk markets. Assam~~, for example,~~ is renowned for its Muga silk, a distinct and valuable product unique to the region (Gogoi *et al*., 2017). The practice of sericulture involves several intricate processes including the cultivation of host plants, rearing of silkworms and ~~the~~extraction of silk yarn. The primary host plant for silkworms is the mulberry ~~tree, whose leaves are crucial for the silkworm nourishment~~leaves. Additionally, other plants like castor are also utilized, particularly silkworm rearing~~production~~ (Ganga & Chetty, 2017). The silkworm *Bombyx mori* is predominantly used for silk proc

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but sericulture practices extend to other silkworm species as well. The sericulture industry is not only significant for its primary product, s~~S~~ilk fibre, but also for the valuable by-products it generates. These include sericin, a protein with antioxidant properties, which finds applications in cosmetics and medicine due to its benefits such as wound healing and UV protection (Aramwit&Sangcakul, 2007; Sasaki *et al*., 2000). Additionally, pupae from the silkworms are rich in protein and fat, making them suitable for use in animal feed and nutritional supplements. The potential of sericulture by-products extends to areas such as biofuels and sustainable practices, highlighting their economic and environmental significance (Buhroo*et al*., 2018; Kunz *et al*., 2016; Zhang *et al*., 2015) (Fig.1). Despite its advantages, sericulture faces several challenges majorly including~~. These include~~pest and disease management in host plants and silkworms, such as pebrine and muscardine, which can impact silk production quality and yield (Kovarova*et al*., 2021).

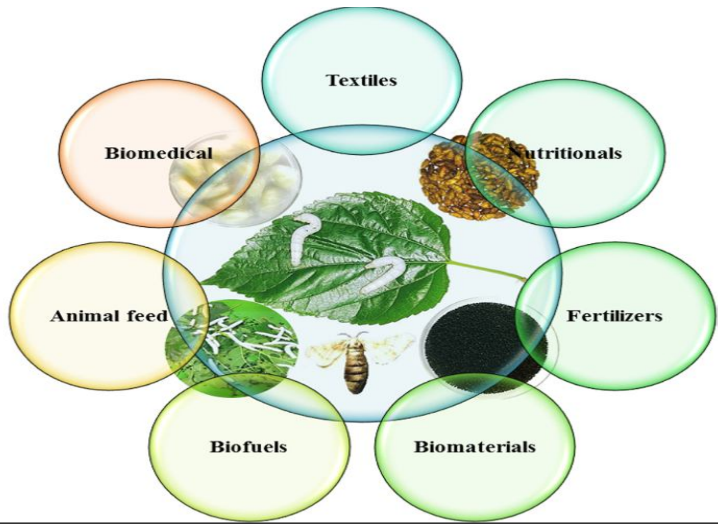

Fig.1 Schematic representation of sericulture in various field of applications.

The integration of modern technologies and biotechnological advancements is transforming sericulture practices. Innovations such as automation in the reeling process, advanced breeding techniques and genome editing have significantly enhance~~d~~ silk production efficiency and sustainability. For instance, the application of piggyBac transposon-based and RNA-guided genome editing techniques has improved the understanding of *Bombyx mori* and its applications in producing valuable proteins and biomaterials (Kovarova*et al*., 2021).

Recent trends also indicate the utilization of sericulture by-products for functional foods, nutraceuticals and biofuels represents a significant opportunity for enhancing the industries' profitability and addressing health and environmental concerns (Majumder, 1997; Singhal *et al*., 2005). In addition, the expansion of sericulture into new markets, particularly in Africa and Latin America, presents opportunities for further growth and development. As global economic shifts create new opportunities, sericulture's future potential appears promising, with ongoing research and technological innovations poised to drive the industry forward (Kim *et al*., 2010).

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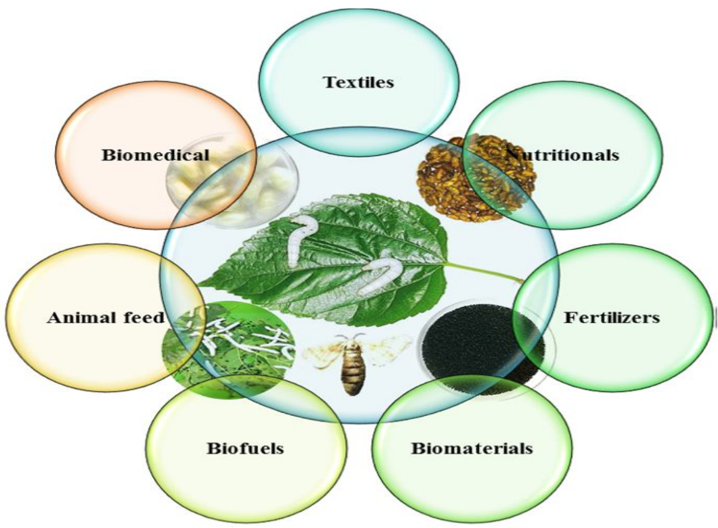

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Fig.1 Schematic representation of sericulture in various field of applications.

Characteristics and advantages of the structure of natural silk fibres

Silk protein~~,~~ derived from silkworms, consists primarily of silk fibroin (SF) and silk sericin (SS) (Kundu *et al*., 2012). The SF forms the core of ~~the~~ silk structure, providing strength and load-bearing capabilities, while SS acts as a gumming agent.The SS, which makes up 25-30% (w/w) of the cocoon, is a category of water-soluble glycoproteins (Rockwood *et al*., 2011). The functional diversity of silk depends on factors such as the silkworm's feeding region, nutritional attributes and environmental conditions including humidity and temperature (Rahmathulla, 2012). Variations in SF amino acid composition and the presence of flavonoids or carotenoids in SS are the key determinants of these functional differences (Bandyopadhyay *et al*., 2019).

Silk fibres exhibit beneficial mechanical properties, although their heterogeneity can be problematic. For example, the cross-sectional shape of silk fibres is not circular and varies along the length, complicating measurement. Despite this, silk fibres offer competitive modulus and tensile strength compared to synthetic fibres. Silks superior deformation characteristics also contribute to its fascinating deformability (Jauzein and Colomban, 2009).

There is growing interest in silk as a sustainable material, not only for traditional textiles but also for various technological and biomedical applications. Silk has been utilized in parachute cords, canopies, cables and suture materials (Altman *et al*., 2003). In biomedical fields, regenerated silk is used in forms such as electro spun fibres, foams, or sheets, which can be reinforced through encapsulation or coating. The application of biotechnology to modify silk further expands its potential (Grenier *et al*., 2004; Royer *et al*., 2005).

Silks versatility extends to applications in tissue engineering, including intra-articular ligaments (Bartow, 1916; Liu *et al*., 2007), cartilage and bone scaffolds (Meinel *et al*., 2004, 2005, 2006; Luan *et al*., 2006; Kirker-Head *et al*., 2007; Meechaisue*et al*., 2007), skin (Min *etal*., 2004), artificial blood vessels (Lovett *et al*., 2007; Priestley, 2007; Yang *et al*., 2007) and nerves (Wang *et al*., 2007). In the coming years, silk is expected to play an increasingly significant role in these advanced biomedical applications due to its unique properties and biocompatibility.

Improved Mulberry Cultivation Techniques

Mulberry leaves are the primary food source for silkworms, and advancements in mulberry cultivation have significantly impacted sericulture. Innovations in fertilization, irrigation and pest management have increased both the yield and quality of mulberry leaves. Additionally, the development of dwarf mulberry varieties and hydroponic cultivation methods allows for year-round production, mitigating the effects of seasonal fluctuations and ensuring a steady supply of feed for silkworms.

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Bioresources of Mulberry

The *Morus alba* or white mulberry, has a rich history of use especially in traditional Chinese medicine where it has been documented since A.D. 659. ~~This plant is particularly known for its role as the primary food source for silkworms, crucial to the sericulture industry.~~ Beyond its agricultural importance, *Morus alba* boosts a variety of medicinal and nutritional benefits, driven by its rich content of natural isoprenoid-substituted phenolic compounds and flavonoids. (Fig.2).

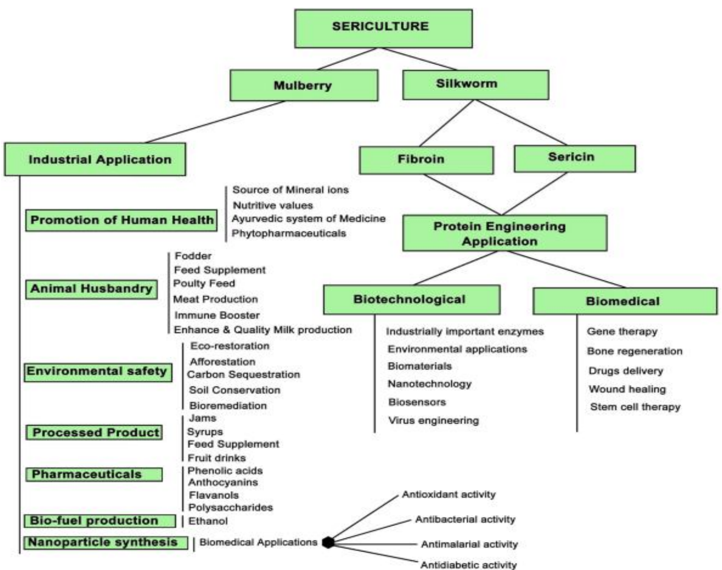

Fig.2 Schematic representation of Bioresources Applications of Sericulture.

Nutritional and Medicinal Properties

Morus alba is a significant source of flavonoids like quercetin, rutin and isoquercitrin, which exhibit strong antioxidant properties. These compounds help in scavenging free radicals, thereby protecting against oxidative stress and cardiovascular diseases by inhibiting LDL oxidation, which contributes to atherosclerosis. Additionally, the presence of prenylated flavonoids further enhances its antioxidant capabilities.

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Mulberry extracts

Mulberry extracts have shown anti-inflammatory, anti-pyretic and anti-exudative properties, making them beneficial for managing conditions such as inflammation and fever (Singh & Ghosh, 1992). Moreover, 1-deoxynojirimycin (DNJ) and

Moran 20K, found in mulberry are noted for their effectiveness against hyperglycaemia and lipid peroxidation, which are significant concerns in diabetes management.

Mulberry Leaves

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Mulberry leaves are utilized in various forms, including tea, juice and as forage. Mulberry tea, made from the decoction of leaves and is popular for its anti-diabetic and cholesterol-lowering effects. It is also used as a gargle for throat infections and can help reduce blood sugar levels and arterial pressure. The leaves have diaphoretic and emollient properties, contributing to their popularity in traditional medicine (Goldsmith *et al*., 2005).

Leaf juice, whether fresh or dried, is used to maintain skin health and treat conditions such as throat infections and digestive issues. It has refrigerant, laxative and febrifuge properties, aiding in the treatment of ailments like diarrhoea, colds and malaria (Venkatesh Kumar & Chuhan, 2008).

Forage and Livestock Feed

Morus alba leaves are also valued as forage. They are highly nutritious, with a protein content of 22-23%, making them a suitable feed for livestock, including sheep, goats and poultry. Studies indicate that incorporating mulberry leaves into animal diets can enhance growth rates and milk production. For instance, mulberry leaves have been shown to improve wool production in Angora rabbits and increase egg production in poultry without adverse effects on egg quality (Singh *et al*., 1984; Narayana & Setty, 1977).

Pharmacological and Industrial Uses

Mulberry has potential in industrial applications. The fruit, which is often overlooked, is rich in nutrients and can be used to make a range of products such as jams, juices, wines and colorants. The ~~fruits use~~utilities extend~~s~~ to the pharmaceutical industry, where it can be exploited for its health benefits, including its role in controlling diabetes and managing hyperlipidaemia.

Recent studies highlight mulberry leaf extracts potential in treating neurodegenerative diseases like Alzheimer's by inhibiting amyloidal beta-peptide formation, thus reducing neurotoxicity (Iyengar, 2007). Additionally, the anti-oxidative properties of mulberry leaves are beneficial in preventing atherosclerosis and controlling cholesterol levels.

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Mulberry fruits

Mulberry f~~F~~ruits cherished for their sweet flavour and nutritional benefits.~~, are increasingly used in diverse applications from jams to medicinal remedies.~~ Recent advances have enabled the commercial production of mulberry juice, a popular health beverage in China, Japan and Korea. This juice remains fresh for up to three months under cold storage or twelve months at room temperature (Dharmananda, 2008). In sub-tropical India, an acre of mulberry cultivation can yield about 1,993 kg of fruit jam and 2,794 litres of pulp, generating significant revenue (Singhal *et al*., 2009). In the food industry, mulberry fruits are used fresh, dried or frozen to produce syrups, tonic wines and various sweet products, including marmalade, chocolate and fondant. Mulberry fruit juice also serves as a natural additive in both food and pharmaceutical industries. Mouro, a spirit distilled from fermented mulberry fruit, is popular in Greece and Azerbaijan (Ehow, 2009).

Medicinally, ~~mulberry~~ thefruits have a rich history of use. They are known for their cooling, laxative and thirst-quenching properties. They are rich in carotene, vitamins B1, B2 and C and various acids. They are used to treat conditions such as deficiencies in liver-kidney~~ deficiencies~~, tinnitus, dizziness, constipation and diabetes~~. Rich in carotene, vitamins B1, B2 and C and various acids.~~ Mulberries help in balancing internal secretions and enhancing immunity (Singhal *et al*., 2001; ~~Venkatesh~~ Kumar and Chauhan, 2008). The fruits juice is a common remedy for high fever and throat infections (Shivakumar *et al*., 1995). Additionally, mulberry fruit powder, rich in anthocyanins and resveratrol, offers antioxidative benefits, potentially preventing heart disease and cancer (Kim *et al*., 1996; Hou, 2003).Mulberry fruit also finds use as a natural food colorant due to its high anthocyanin content. These pigments, such as cyanidin-3-glucoside are used in natural food colorants and have potential health benefits (Wrolstad, 2001; Liu *et al*., 2004). The anthocyanin content varies ~~by~~ with climate~~, with~~ *viz.*, higher concentrations in dry regions, making it a valuable resource for industrial applications. Furthermore, mulberry fruits are utilized as a feed supplement for livestock *i.e.,* ~~-~~ Incorporating mulberry intofeed blocks has been shown to boost milk production by 30-50% and offers a profitable microenterprise opportunity (Habib, 2004). This multifaceted use of mulberry fruits highlights their economic and health benefits, making them a valuable agricultural product.

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Mulberry tree

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~~(~~*Morus* spp.~~)~~ is emerging as a valuable plant in ecological and industrial applications, including phytoremediation and biogas production. In phytoremediation, mulberry is used to detoxify soils contaminated with heavy metals. This suggests that the mulberry-silkworm system effectively cleans heavy metal-polluted soils while minimizing contamination in the final silk product (Dharmananda, 2008). ~~Mulberries role extends to environmental decontamination, where~~ it addresses soil polluted with traffic-related lead and phytopharmaceuticals, with therapeutic products derived from its roots, fruits and leaves (Singhal *et al*., 2009).

Additionally, mulberry plants offer potential in biogas production, mulberry leaves are evaluated for their efficiency as a feedstock. Studies employing the in vitro gas production technique have shown that young mulberry leaves produce a high potential biogas yield of 60.6 ml per 200 mg of leaf material, with a degradation rate of 0.0703 (Menke *et al*., 1979). Mature leaves, while still productive, yield less biogas-35.4 ml per 200 mg with a degradation rate of 0.0624. Compared to other forages, young mulberry leaves exhibit higher fermentability, making them a superior source for biogas production, although *Moringa oleifera* remains slightly more efficient. The high biogas production rate of mulberry underscores its significant potential as a high-nutrition forage for energy production (Tanase *et al*., 2008). Recent evaluations also highlight mulberry's economic potential as a renewable energy source in intensive cultivation systems.

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SILKWORM BASED RESOURCES(Fig.2).

Silkworm Eggs

Silkworm eggs are rich in nutrients, containing approximately 56% albumin, 19.2% fats, and 7.7% sugars. The~~se eggs~~ yare consumed directly and have been traditionally used in various health applications. In popular medicine, silkworm eggs are believed to act as a male sexual stimulator and are used in extracts known for their high protein content, vitamins B_1, B_2, and glycoproteins. Such extracts, including the Human Fort B product sold in Romania, are purported to offer energizing and hepatic protective benefits while reducing lipids and blood glucose levels (Chen *et al*., 2002). Additionally, processed silkworm egg extracts are employed in pharmaceuticals and the food industry, although claims about their effects on alcohol dependence remain anecdotal and lack scientific validation.

Silkworm Larvae

Silkworm larvae are used as a protein-rich feed for young animals and reptiles and are also processed into protein powder for dietary supplements. They contain significant levels of bombycisterol, a cholesterol isomer and are utilized in pharmaceutical preparations for their anti-diabetic properties. Traditional medicine in China, Korea and Japan has long used silkworm larvae to manage diabetes, supported by recent studies showing that silkworm powder effectively lowers blood glucose levels, particularly when derived from larvae on the third day of the fifth instar stage and processed *via* freeze-drying (Ryu *et al*., 1997). The major active component, 1-deoxynojirimycin (DNJ) is present in high concentrations in silkworms compared to mulberry leaves and fruits, indicating its significant role in glucose regulation.

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Silkworm Extract

Silkworm extract, derived from the larvae of *Bombyx mori*, has been a part of traditional Chinese medicine for centuries. It contains unsaturated fatty acids, proteins, amino acids and cephalic compounds, which are believed to support male reproductive health and enhance sexual desire. Additionally, this extract is claimed to alleviate migraines, carpal tunnel syndrome, osteoarthritis and skin lesions that is also used in treating prostate hyperplasia and erectile dysfunction (Qian, 1997). Despite these claims, the benefits of silkworm extract are not universally validated and products containing silkworm extract are not generally reviewed or approved by regulatory bodies like the FDA.

Silkworm Pupae

Silkworm pupae are a highly nutritious food source, containing 50-60 per cent protein, 25-35 per cent fat and essential vitamins and minerals. They are used in various culinary applications across Asia, including as human food in Korea, China, Japan and Thailand. The high fat content makes silkworm pupae suitable for producing chrysalis oil, which has applications in cosmetics, pharmaceuticals and as a natural organic fertilizer (Singh & Suryanarayana, 2003). Pupal proteins and oils are also utilized in medical treatments and dietary supplements due to their anti-inflammatory and cholesterol-lowering properties. The pupae chitin is used in wound healing and as a dietary supplement to improve intestinal health (Koundinya &Thangavaleu, 2005; Majumder, 1997). Moreover, silkworm pupae's high-quality protein makes them a viable food source for astronauts, as confirmed by studies conducted by the Japan Aerospace Exploration Agency (JAXA) (Velayudhan *et al*., 2008).

Silkworm Litter

Silkworm litter, comprising left over mulberry leaves, twigs and excreta, offers significant benefits for agriculture and waste management. This by product contains 7.35 per cent water, 13.88 per cent crude protein, 1.44 per cent raw fats, 15.41 per cent raw cellulose and 47.15 per cent non-nitrogenous substances (Sharma & Madan, 1992). The litter can be repurposed into high-quality organic manure or biogas, providing a sustainable option for recycling agricultural waste. In Japan, silkworm litter is utilized as compost for ornamental plants and as fodder for livestock during winter. The litters organic matter enriches soil, enhances plant growth, and contributes to biogas production, benefiting both farming communities and environmental sustainability (Sharma & Madan, 1992).

Silk Proteins: Sericin and Fibroin

Silk proteins, primarily sericin and fibroin,harvested from the silk glands of silkworms are increasingly recognized for their diverse applications in biomedical fieldsemployed in the production of medical devices such as bandages, artificial skin and surgical sutures. ~~These proteins are harvested from the silk glands of silkworms and have been utilized in innovative ways across various industries. Sericin and fibroin are employed in the production of medical devices such as bandages, artificial skin and surgical sutures.~~ They are also used in advanced applications like wound healing, tissue regeneration, and the treatment of conditions such as diabetes, impotence and arthritis (Dandin & Kumar, 2007). These are notable for their biocompatibility, biodegradability and potential for cross-linking with other polymers. This makes them suitable for creating controlled delivery systems and bio-active textiles. Their polar functional groups enhance antibiotic absorption and improve the efficacy of various biomedical applications. ~~Silk proteins~~They are used in manufacturing contact lenses, wound dressings and scaffolds for bone formation and burn treatment (Ramesh *et al*., 2005). These proteins are also applied in anti-aging and moisturizing products, showcasing their versatility in cosmetic and medical fields.

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Applications of Silk Sericin and Fibroin

Silk Sericin

Silk sericin, a protein ~~derived from silkworms,~~ demonstrates a wide range of potential applications in both medical and cosmetic fields. Traditional uses of silk fibers, particularly as sutures, have long highlighted their clinical benefits. Tasubouchi (1999) developed a silk fibroin-based wound dressing that enhances healing and can be easily removed without damaging new skin. Combining fibroin with sericin in wound dressings further leverages sericin properties, including UV absorption and moisture retention, making it effective as a skin moisturizer, anti-wrinkle agent and sun protector (Kumaresan *et al*., 2007). Sericin capabilities extend to being an anticoagulant through sulfonation treatments (Tamada, 1997) and exhibiting antioxidant properties that inhibit lipid peroxidation and tyrosinase activity (Kato *et al*., 1998). It is valuable in cosmetics for its moisturizing effects, similar to natural moisturizing factors and its ability to reduce water loss from the skin (Padamwar*et al*., 2005). Sericin is also used in various industrial applications, including soil conditioning, wastewater purification and as additives in health foods, medical composites and cosmetic products (Gulrajani, 2005).

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Silk Fibroin

Silk fibroin has been extensively explored for its biomedical applications. It is known for its ability to hold and release moisture based on environmental conditions, making it suitable for cosmetics like pressed powders and lipsticks. Fibroin has shown promise in drug delivery systems and wound healing. For instance, fibroin membranes have been used to promote bone regeneration (Matta *et al*., 2004) and controlled release tablets (Wu *et al*., 1996). ~~Fibroin~~ it has unique properties also include high biocompatibility and flexibility, making it useful for developing bio-sensors and in various environmental applications such as separating water-alcohol mixtures (Chisti, 1998). Both silk sericin and fibroin continue to offer diverse, innovative uses across multiple fields (Dandin & Kumar, 2007).

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Technological innovations in sericulture

Seri-bioscience, the intersection of biology and sericulture, has made substantial strides with technological and scientific advancements in recent years. This dynamic field focuses on enhancing silk production and quality through innovations in genetic engineering, biotechnology and nanotechnology. Key areas of progress include genetic modifications, RNA interference and the use of nanotechnology for disease management and production optimization. Sericulture, the ancient art of silk production, has undergone significant transformation due to technological advancements. These innovations have not only improved productivity and quality but also enhanced the sustainability of the industry.

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Genetic Engineering of Silkworms

Genetic engineering has been a game-changer in sericulture. The advent of techniques such as CRISPR-Cas9 allows for precise genetic modifications in silkworms, enhancing traits related to silk production. ~~For example, T~~Targeted gene editing has led to the development of silkworm strains with increased fibre strength, higher silk yield and improved resistance to environmental stressors. This precision in genetic manipulation enables the creation of silkworms that produce silk with superior qualities and are better adapted to varying climatic conditions.

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Disease-Resistant Silkworm Breeds

~~Disease management is crucial in sericulture, as diseases can severely impact silkworm populations and silk production.~~ Through selective breeding and genetic modification, researchers have developed disease-resistant silkworm breeds. These breeds exhibit enhanced immunity to common pathogens such as the *Bombyx mori*nucleo polyhedrosis virus (BmNPV) and various bacteria, thereby stabilizing production systems and reducing the economic losses associated with disease outbreaks in silk production~~.~~

Genetically Modified Organisms (GMOs) and Transgenic Silkworms

One of the most notable advancements in Seri-bioscience is the development of genetically modified (GM) and transgenic silkworms. Transgenic silkworms have been engineered to produce silk with novel properties by incorporating foreign genes. For instance, Japanese scientist Tetsuya Iizuka created silkworms capable of spinning fluorescent silk by inserting DNA sequences that produce fluorescent proteins derived from corals and jellyfish. This fluorescent silk, although slightly weaker in tensile strength compared to conventional silk, has found applications in high-fashion garments such as wedding dresses and ties due to its unique aesthetic appeal.

Another significant development is the creation of "monster silk moths" through advanced genetic techniques. Researchers replaced the silkworm fibroin heavy chain gene with the major ampullate spidroin-1 gene from spiders. This modification aimed to replicate spider silks exceptional mechanical properties in silkworm silk. The transgenic silkworms exhibited enhanced silk extensibility, offering a new approach to large-scale spider silk production. This technique, employing transcription activator-like effector nucleases (TALENs) for gene editing, provides a scalable method for producing spider silk proteins and highlights the potential for developing new biomaterials (Xu *et al.*, 2018).

RNA Interference (RNAi) Technology

RNA interference (RNAi) technology ~~has emerged as a powerful tool for manipulating gene expression in sericulture. RNAi~~ enables the silencing of specific genes, which can be leveraged to enhance silk production. One application is the suppression of the Juvenile Hormone Epoxide Hydrolase (JHEH) gene in *Bombyx mori*, responsible for degrading juvenile hormones that signal pupation. By silencing JHEH, ~~researchers can extend the~~ larval stage can be extended, potentially leading to the formation of larger cocoons and increased silk yield. This approach holds promise for enhancing productivity and optimizing the sericulture process (Smith, 2021).

Seri-Biotechnology: Seri-biotech Research Laboratory

The Seri-biotech Research Laboratory (SBRL), established in 1993 under the World Bank-aided National Sericulture Project, has been pivotal in advancing Seri-biotechnology. The laboratory focuses on several research areas:~~**Biotechnology Applications in Sericulture**~~

Biotechnology has introduced new methods to enhance silk production. The use of probiotics and microbial enzymes improves silkworm digestion and silk protein synthesis, leading to higher yields and better silk quality. Additionally, bioremediation techniques involving silk-producing bacteria have been explored to address environmental pollution from sericulture waste (Gupta *et al.*, 2021). These biotechnological interventions promote sustainability by reducing the ecological footprint of silk production.

1. Silkworm Genomics:

The SBRL is working on identifying and characterizing genes related to resistance against viral pathogens, regulation of diapause and silk protein synthesis. This includes studying RNA-dependent RNA polymerase (RdRp) genes and other critical components influencing silkworm biology (Mahesha, 2017).

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2. Proteomics:

This area focuses on identifying immune response proteins in silkworms and analysing the transcriptome under stress conditions. Research includes studying interactions between silkworms and pests such as the U~~u~~zi fly (Mahesha, 2017).

3. Molecular Pathology:

The laboratory aims to identify and characterize pathogens infecting silkworms, including viruses, bacteria and microsporidia. Developing diagnostic tools for detecting various pathogen strains is a crucial aspect of their work (Mahesha, 2017).

Nanotechnology in Sericulture

Nanotechnology offers innovative solutions for improving sericulture practices. One notable application is the use of nanoparticles to enhance silkworm health and silk production. Titanium dioxide nanoparticles (TiO2 NPs) have been employed to treat silkworm larvae, showing promising results in improving immunity and resistance to diseases like *Bombyx mori* cytoplasmic polyhedrosis virus (BmCPV). The TiO2 NPs treatment activates key immune signaling pathways and upregulates immune gene expression, thereby enhancing the silkworm resistance to viral infections (Zhao *et al*., 2020).

~~Biotechnology Applications in Sericulture~~

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Achievements and Ongoing Research

Significant achievements in silk biotechnology include the development of transgenic silkworms resistant to baculovirus (BmNPV) through RNA_i technology. These lines are undergoing controlled trials and represent a significant advancement in creating virus-resistant silkworm strains (Ponnuvel*et al*., 2013). Additionally, research on mulberry genomics has led to the development of over 10,000 expressed sequence tags (ESTs) and the identification of drought tolerance genes, contributing to improved crop resilience and productivity.

Other advancements include the application of silk proteins in novel biomaterials. For example, sericin-based hydrogels from silk industry waste have been developed for use in sanitary products and composite silk-based biomaterials are being explored for tissue engineering applications. These innovations highlight the expanding utility of silk and its by-products in various fields (Meng *et al*., 2017).

Advanced Sericulture Techniques with respect to Moriculture

Automated Rearing and Harvesting Systems

Automation has revolutionized sericulture, particularly in silkworm rearing and cocoon harvesting. Modern systems equipped with sensors, actuators and artificial intelligence (AI) algorithms regulate environmental parameters such as temperature, humidity and light, optimizing conditions for silkworm growth and silk production. Robotic harvesters have also streamlined the cocoon collection process, reduced labour costs and increasing efficiency. These advancements ensure consistent production quality and scalability in sericulture operations.

Use of Artificial Diets and Controlled Environments

Traditional sericulture is limited by the availability of mulberry leaves, but the development of artificial diets composed of alternative nutrients has expanded production possibilities. These diets allow sericulture to extend beyond mulberry-growing regions. Controlled environment rearing facilities, equipped with advanced climate control systems, enable year-round silk production independent of seasonal constraints, further enhancing productivity and flexibility in sericulture.

FUTURE TRENDS AND RESEARCH

Technological innovation, sustainability and socio-economic equity helps in realizing the potential of sericulture industry. Key areas of future work include, genetic modification for enhancing silk properties, improving mechanical strength and resilience drawing inspiration from vibrant uses of spider silk. The application of nanotechnology and biotechnology lead to novel silk-based products with advanced functionalities. Bio-pesticides and improved silk regeneration techniques are

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Comment [st26]: Write atleast one refernce under this subheading the prioritizing areas where the sericulture industry can achieve greater efficiency, profitability, and sustainability, contributing positively to economic development and environmental conservation.

CONCLUSION

Sericulture extends far beyond traditional silk production, offering significant benefits across various sectors. Recent advancements have demonstrated its critical role in biopharmaceuticals, bioactive materials and sustainable practices. Silk proteins are increasingly utilized in drug delivery systems, tissue engineering and enzyme immobilization, showcasing their versatility. Furthermore, sericulture by-products, including sericin, silkworm pupae and mulberry leaves, present valuable opportunities for generating bio-fertilizers, biofuels and animal feed, thereby contributing to environmental sustainability and economic enhancement. Despite its global evolution from a cottage industry to a luxury and biotechnological sector, India has yet to fully capitalize on these innovations. Effective utilization of sericulture by-products and incorporation of advanced technologies can transform the sector, improving efficiency and sustainability. Research should focus on optimizing the use of mulberry for livestock feed and exploring its therapeutic potentials. By embracing these strategies, sericulture can address protein deficiencies, enhance farmer incomes, and reduce environmental impact.

CONSENT (WHERE EVER APPLICABLE)

Authors may use the following wordings for this section: "All authors declare that 'written informed consent was obtained from the patient (or other approved parties) for publication of this case report and accompanying images. A copy of the written consent is available for review by the Editorial office/Chief Editor/Editorial Board members of this journal."

ETHICAL APPROVAL

This article does not contain any studies with human participants or animals performed by any of the authors

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