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 sericulture, 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. By balancing traditional practices with modern advancements, sericulture is poised for a sustainable and prosperous future.

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

1. INTRODUCTION

Formatted: Space After: 6 pt

Sericulture, the ancient practice of rearing silkworms for silk production, has evolved significantly over millennia, establishing itself as a crucial industry globally. Originating in China around 2700 BCE, the art of silk production has 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 as the second-largest producer of silk in world, contributing to a global industry that is predominantly concentrated in Asia. India's diverse silk production encompasses four primary types of silk: 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. Additionally, other plants like castor are also utilized, particularly for Eri silk production (Ganga & Chetty, 2017). The mulberry silkworm, *Bombyx mori* Linnaeus is predominantly used for silk production followed by~~, but sericulture practices extend to~~ other silkworm species as well. The sericulture industry is not only significant for its primary product-Silk fibre, but also for the valuable by-products ~~it~~ generateds~~s~~. 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. These include pest and disease management in host plants and silkworms, such as P~~p~~ebrine and M~~m~~uscardine, which can impact silk production quality and yield (Kovarova *et al*., 2021). 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 enhanced 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).

Formatted: Space After: 6 pt

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).

Comment [SK1]: Give this in the before paragraph while telling uses of sericulturw along with silk production.

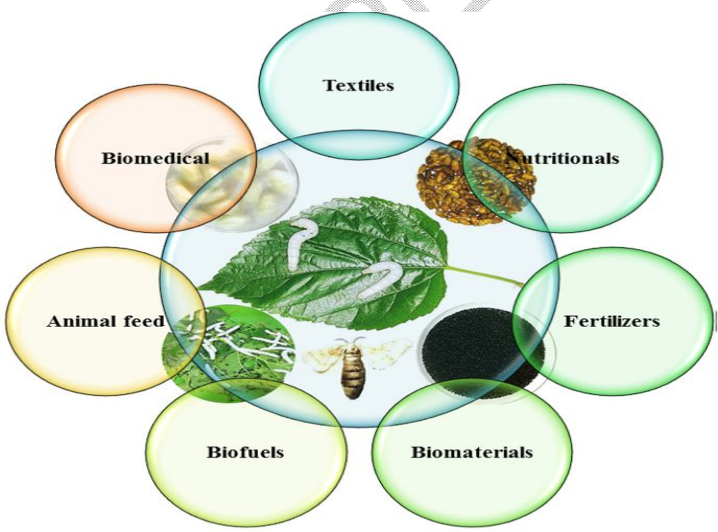

Fig.1 Schematic representation of sericulture in various field of applications.

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). SF forms the core of the silk structure, providing strength and load-bearing capabilities, while SS acts as a gumming agent. 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 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.

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).

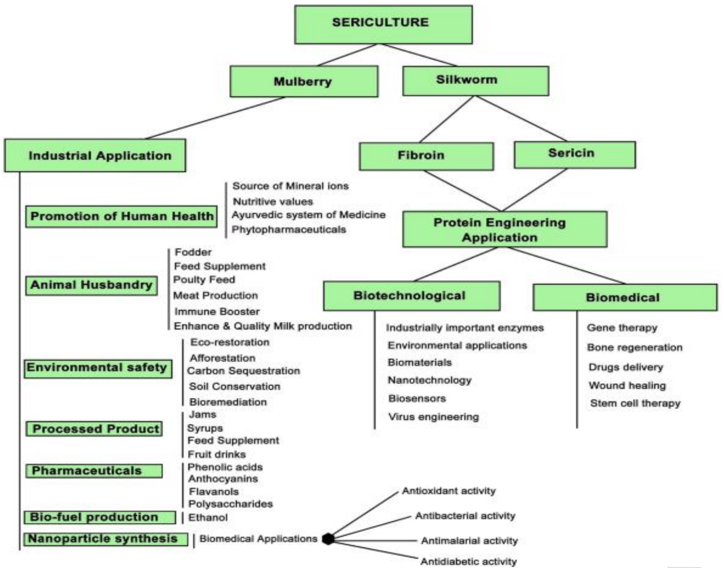

Fig.2 Schematic representation of Bioresources Applications of Sericulture.

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.

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

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 extends 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.

Mulberry fruits

Fruits 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 fruits have a rich history of use. They are known for their cooling, laxative and thirst-quenching properties. They are used to treat conditions such as 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 climate, with higher concentrations in dry regions, making it a valuable resource for industrial applications. Furthermore, mulberry fruits are utilized as a feed supplement for livestock. 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.

Mulberry tree

(*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). Mulberry;sies 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.

SILKWORM BASED RESOURCES(Fig.2).

Silkworm Eggs

Silkworm eggs are rich in nutrients, containing approximately 56% albumin, 19.2% fats and 7.7% sugars. These eggs are 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.

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, are increasingly recognized for their diverse applications in biomedical fields. 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 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.

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).

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 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).

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.

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, 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.

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.

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, 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:

1. Silkworm Genomics:

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).

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 uzi 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).

Comment [SK2]: SBRL?

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

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.

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 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."

Comment [SK3]: ???

ETHICAL APPROVAL

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

Formatted: Font: 10 pt, No underline, English (United States)

Formatted: No underline

REFERENCES

Alakbarov F, I. Aliyev.Silk Road – The origin of the mulberry trees. Azerbaijan International. 2003;8: 3.

Altman GH, Diaz F, Jakuba C, Calabro T, Horan RL, Chen J, Lu H, Richmond J, Kaplan D.Silk-based biomaterials. Biomaterials. 2003; 24: 401–416.

Aramwit P, Sangcakul A. The effects of sericin cream on wound healing in rats. Bioscience, Biotechnology, and Biochemistry. 2007; 71: 2473–2477.

Attri K, Sujatha G S, Jekinakatti B, Thrilekha D, Devi D L, Garai I, Tripathy A. Advancements in Sericulture: Innovations and Sustainability in Silk. Uttar Pradesh Journal of Zoology. 2024: 45(16): 305-317.

Bandyopadhyay A, Chowdhury SK, Dey S.Silk: a promising biomaterial opening new vistas towards affordable healthcare solutions. Journal of the Indian Institute of Science. 2019. 99: 445-487.

Bartow B.The further application of the intra-articular silk ligament in the flail joints of poliomyelitis paralysis. The Journal of Bone & Joint Surgery.1916; 2: 217–220.

BuhrooZ I, Bhat M A, Malik M A, Kamili A S, Ganai N A, Khan I L.Trends in development and utilization of sericulture resources for diversification and value addition. International Journal of Entomological Research. 2018; 6(1): 27-47.

BuhrooZ I, Nagoo S A, Rafiq I, Bhat M A.Biotechnological advances in silkworm improvement: current trends and future prospectus. Journal of Entomology and Zoology Studies.2019; 7: 100-106.

BuhrooZI, Bhat MA, Kamili AS, Ganai NA, Bali GK, KhanIL, Aziz A. Trends in development and utilization of sericulture resources for diversification and value addition. Journal of Entomology and Zoology Studies. 2018; 6: 601–615.

Chen YG M, Zi LN, HaiY, Zhang. Analysis of amino acids from silkworm chrysalis. Yunnan Chemical Technology. 2002; 6:22-23.

Chen ZS, Liao Q, Li L, Chen Y, Wu X, Yao.Study on multivoltine yellow blood silkworm for edible and medicine utilization. Silkworm Science. 2002; 28: 73–76.

Chisti Y. 1998. Strategies in downstream processing; in Bio separation and bioprocessing: a handbook. G. Subramanian (ed). New York: Wiley-VCH. 3–30.

Dandin SB, Kumar SN.Bio-medical uses of silk and its derivatives. Indian Silk. 2007; 45(9): 5-8.

Dharmananda S. Fruit as medicine – Morus fruit (Mulberry). Institute for traditional medicine, Portland, Oregon, USA. 2008; pp. 1-7.

Ehow.How to make mulberry wine. Food and Drink. 2009; www.eHow.com.

Ganga G, Chetty J. An Introduction to Sericulture (2nd ed.,). Oxford & IBH Publishing Co. Pvt. Ltd. 2017; 1-2.

Gogoi M, Gogoi A, Baruah B. Exotic Muga Silk: Pride of Assam. International Journal of Applied Home Science. 2017;4(1, 2):72-78.

Goldsmith MR,Shimada T,Abe H.The Genetics and Genomics of the Silkworm, *Bombyx mori*. Annual Reviews Entomology. 2005;50: 71-100.

GrenierAM, Da Rocha M, Jalabert A, Royer C, Mauchamp B, Chavancy, G.Artificial parthenogenesis and control of voltinism to manage transgenic populations in Bombyx mori. Journal of Insect Physiology. 2004. 50; 751–760.

Gulrajani ML.Sericin: A Bio-molecule of value. Souveni 20th congress of the international sericultural commission, Bangalore, India 15-18th December. 2005; pp. 21-29.

Gupta S, Chaubey KK, Khandelwal V, Sharma T, Singh SV. Genetic engineering approaches for high-end application of biopolymers: Advances and future prospects. microbial polymers: Applications and Ecological Perspectives. 2021;619-630.

Habib G.Mulberry fruitbased feed blocks – a key supplement for livestock in mountainous regions.Mountain Research Development. 2004; 24: 106-109.

Hou DX.Potential mechanisms of cancer chemoprevention by anthocyanins. Current. Molecular Medicine.2003; 3:149-159.

IyengarM N S. Research Beliefs. Indian silk. 2007; July, 29.

Jaiswal K K, Banerjee I, Mayookha V P. Recent trends in the development and diversification of sericulture natural products for innovative and sustainable applications. Bioresource Technology Reports. 2021; 13: 100614.

Jauzein V, Colomban P. Types, structure and mechanical properties of silk. Handbook of Tensile Properties of Textile and Technical Fibres. 2009; 144–178. https:// doi.org/10.1533/9781845696801.1.144.

Kato NS, Sato A, Yamanaka H, Yamadam N, Fuwam M, Nomura. Silk protein, sericin, inhibits lipid peroxidation and tyrosinase activity. Biosciences Biotechnology and Biochemistry. 1998; 62: 145–147.

Kim KY, KangPD, LeeKG,HyungK,Kim MJ, Kim KH,Park SW,Lee SJ, Jin BR,and Kim.Microsatellite analysis of the silkworm strains (Bombyx mori): high variability and potential markers for strain identification. Genes & Genomics. 2010;32: 532-543.

Kim TW, Kwon TB, Lee JH, Yang IS. A study on the antidiabetic effect of mulberry fruits. Korean Journal of Sericulture Science. 1996; 38: 100-107.

KirkerHead C, Karageoriou V, Hofmann S, Fajardo R, Betz O, Merkle HP, Hilbe M, von Rechenberg B, Abrahamsen L, Nazarian A, Cory E, Curtis M, Kaplan D, Meinel L. BMP–silk composite matrices heal critically sized femoral defects. Bone. 2007; 41, 247–255.

Koundinya PR, Thangavaleu K. Silk proteins in biomedical research. Indian Silk. 2005; 43 (11): 5-8.

Kovarova M, Pyszko P, Plasek V. How does the pH of tree bark change with the presence of the epiphytic bryophytes from the family Orthotrichaceae in the interaction with trunk inclination? Plants2021; 11(1):63. https://doi.org/10.3390/plants11010063.

KumaresanP,Sinha RK, Urs SR. Sericin – A versatile by-product. Indian Silk. 2007; 45(12):11-13.

Kundu SC, Kundu B, Talukdar S, Bano S, Nayak S, Kundu J, Acharya C. Non mulberry silk biopolymers. Biopolymers. 2012; 97, 455–467.

Kunz RI, Brancalhao RM, Ribeiro LF, Natali MR. Silkworm sericin: properties and biomedical applications. BioMed Research International.2016. 8175701.

Liu X, Xiao G,Chen W, Xu Y, Wu J. Quantification and purification of mulberry anthocyanins with macroporous resins. Journal of Biomedicine and Biotechnology 2004; 5: 326-331.

Liu H, Ge Z, Wang Y, Toh AL, Sutthikhum V, Goh JCH.Modification of sericin free silk fibers for ligament tissue engineering application. The Journal of Biomedical Materials Research. 2007; 82: 129–138.

Lovett M, Cannizzaro C, Daheron L, Messmer B, Vunjak-Novakovic G, Kaplan DL. Silk fibroin microtubes for blood vessel engineering. Biomaterials. 2007; 28, 5271-5279.

Luan XY, Wang Y, Duan X, Duan QY, Li MZ, Lu SZ, Zhang HX, Zhang XG. Attachment and growth of human bone marrow derived mesenchymal stem cells on regenerated *Antheraea pernyi*silk fibroin films. Biomedical Materials. 2006;1:181–187.

Mahesha HB. Seri biotechnology. University of Mysore, Mysuru. 2017. Retrieved on 2 December. 2021; from http://hbmahesh.weebly.com/uploads/3/4/2/2/3422804/1.

Majumder SK.Scope for new commercial products from sericulture. Indian Silk. 1997;35(12):13-18.

Matta AC, Migliaresi F, Faccioni P, Torricelli M, Fini R, Giardino. Fibroin hydrogels for biomedical applications, preparation, characterization and in vitro cell culture studies. Journal of Biomaterial Science Polymer Edition. 2004; 15:851-864.

Meechaisue C, Wutticharoenmongkol P, Waraput R, Huangjing T, Ketbumrung N, Pavasant P, Supaphol P. Preparation of electro spun silk fibroin fiber mats as bone scaffolds: a preliminary study. Biomedical Materials. 2007; 2, 181–188.

Meinel L, Fajardo R, Hofmann S, Langer R, Chen J, Snyder B, Vunjak Novakovic G, Kaplan D. Silk implants for the healing of critical size bone defects. Bone. 2005; 37, 688–698.

MeinelL, Hofmann S, Karageorgiou V, Zichner L, Langer R, Kaplan D, Vunjak- Novakovic G.Engineering cartilage-like tissue using human mesenchymal stem cells as silk protein scaffolds. Biotechnology and Bioengineering. 2004; 88: 379–391.

Meng X, Zhu F, Chen K. Silkworm: A Promising Model Organism in Life Science. Journal of Insect Science. 2017;17(5):97: 1-6.

MenkeKH, Raab L, Salewski A, Steingass H, Fritz D, Schneider W.The estimation of the digestibility and metabolizable energy content of ruminant feedstuffs from the gas production when they are incubated with rumen liquor in vitro. Journal of Agriculture Sciences. 1979; 92: 217-222.

Min BM, Lee G, Kim SH, Nam YS, Lee TS, Park W.H. Electrospinning of silk fibroin nanofibers and its effect on the adhesion and spreading of normal human keratinocytes and fibroblasts in vitro. Biomaterials. 2004; 25:1289–1297.

Murugesh Babu K. Silk Production and future trends. Handbook of Natural Fibres. 2021.

Narayana H, Setty SVS.Studies on the incorporation of mulberry (Morus indica) leaves in layers mash on health, production and egg quality. Indian Journal of Animal Science. 1977;47: 212-215.

Narzary P R, Das A, Saikia M, Verma R, Sharma S, Kaman P K, Baruah J P. Recent trends in Seri-bioscience: its prospects in modern sericulture. Pharma Innovation. 2022; 11(1): 604-611.

Padamwar MN, Pawar AP, Daithankar AV, Mahadik KR. Silk sericin as a moisturizer an in vivo study. Journal of Cosmetics and Dermatology. 2005; 4: 250-257.

Panwar S, Ikram M, Sharma A K.Emerging Trends and Future Opportunities in Sericulture. Journal of Survey in Fisheries Sciences. 2022; 625-629.

Ponnuvel M, Rao C. Recent Trends in Seribiotechnology. In: UGC National Symposium on Modern Biotechnology: Prospects & Challenges, Kodathi, Bangalore: Seri biotech Research Laboratory, Central Silk Board. 2013; 23-26.

PriestleyJV. Silky feeling. Materials World. 2007; 15, 19-21.

Punyavathi H B M. Seri-bioinformatics: emerging trends and challenges in silkworm research. Advances in Biochemistry. 2013 ;1(2): 33-42.

Qian J. The chemical constitution and utilization of silkworm pupae. Science Technology and Food Industry. 1997; 5: 42-43.

RahmathullaV. Management of climatic factors for successful silkworm (Bombyx mori L.) crop and higher silk production: a review.Psyche: A Journal of Entomology. 2012;

Ramesh S,Kumar CS, Seshagiri SV,Basha KI, Lakshmi H, Rao CGP, Chandrashekaraiah.Silk filament its pharmaceutical applications. Indian Silk. 2005; 44(2): 15-19.

Rockwood DN, Preda RC, Yucel T, Wang X, Lovett ML, Kaplan DL.Materials fabrication from *Bombyx mori* silk fibroin. Nature protocols. 2011; 6: 1612.

Royer C, Jalabert A, Da Rocha M, Grenier AM, Mauchamp B, Couble P, Chavancy G. Biosynthesis and cocoon-export of a recombinant globular protein in transgenic silkworms. Transgenic Research. 2005; 14: 463-472.

Ryu KS, Lee HS, Choue RW.An activity of lowering blood-glucose levels according to preparative condition of silkworm power. Korean Journal of Sericulture Sciences. 1997; 39:79–85.

Sasaki M, Kato N, Watanabe H, Yamada H.Silk protein, sericin, suppresses colon carcinogenesis induced by 1,2-dimethylhydrazine in mice. Oncology Reports. 2000; 7:1049-1101.

Savithri G, Sujathamma, P, Neeraja, P. Indian sericulture industry for sustainable rural economy. International Journal of Economics, Commerce and Research. 2013; 3: 73–78.

Sharma SM, Madan, Optimal utilization of sericulture waste. Resource Conservation. And Recycling. 1992; 7: 295–304.

Shivakumar GR, Anantha Raman KV, Magadum SB, Datta RK. Medicinal values of mulberry. Indian Silk. 1995;34: 15-16.

Singh, B, Goel GC, Negi SS. Effect of supplementing mulberry (Morus alba) leaves ad libitum to concentrate diets of Angora rabbits on wool production. Journal of Applied Rabbit Research. 1984; 7: 156-160.

Singh KC, Suryanarayana N. Eri pupae A popular cuisine too. Indian Silk. 2003;41(12): 57-58.

Singh KP, Ghosh PL. Mulberry cultivation under agro forestry and land management, Indian silk. 1992; 31:16.

Singh T, Nigam A, Kapila R. Innovations in silkworm rearing and importance: recent advances. TEXTILE Association. 2021; 82(2), 87-90.

Singhal BK, Dhar A, Sharma A, Qadri SMH, Ahsan MM. Sericulture by-products for various valuable commercial products as emerging bio science industry. Sericologia. 2001;41: 369-391.

Singhal BK, Dhar A, Khan MA, Bindroo BB. Utilization of sericultural byproducts as urgent need for sustainable sericulture. In: Govindan R.,Ramakrishna Naika, Sannappa B. and Chandrappa D. (eds), Progress of Research in Organic Sericulture and Seri byproduct Utilization, Seri Scientific Publishers, Bangalore, pp. 2005; 211-226.

Singhal BK, Dhar A, Khan MA, Bindroo BB, Fotedar RK.Potential economic additions by mulberry fruits in sericulture industry. Plant Horticulture Technology. 2009; 9: 47-51.

Smith A. What is RNA silencing what is the use of this strategy. Retrieved on 20 August 2021, from https://rehabilitationrobotics.net/what-is-rna-silencing-what-is-the-use-of-this-strategy/ 2021.

Tamada Y. Anticoagulant and its production. Japan Patent. 1997; 9: 227402A.

Tanase DC, Glavan M, Constantinescu E, Pau, Ungureanu C. The SWOT method for energetic potential of Morus biomass plants. International conference, Bucharest, July, 2008.

Thakur J, Bali RK. Innovations for reviving sericulture in Jammu and Kashmir. The Pharma Innovation Journal. 2002; 11(7): 1126-31.

Tsubouchi K. Occlusive dressing consisting essentially of silk fibroin and silk sericin and its production. Japan Patent. 1999;11-070160A.

Vanisree K, Upendhar S, Rajsekhar M, Prashanth Reddy R, Mahesh M. Sericulture as a Sustainable Tool for Economic Development of Small and Marginal Farmers. Biological Forum. 2023; 15(7): 248-252.

Velayudhan K, Balachandran N, Sinha RK, Kamble CK. Utility of silkworm pupae: A new dimension as food and medicine. Indian Silk. 2008; 47(1): 11-18.

Venkatesh Kumar R, Chauhan S. Mulberry: Life enhancer. Journal of Medicinal Plant Research. 2008; 2: 271-278.

Wang X, Wenk E, Matsumoto A, Meinel L, Li C, Kaplan DL. Silk microspheres for encapsulation and controlled release. J. Control. Release. 2007; 117, 360–370.

Wrolstad RE. The possible health benefits of anthocyanin pigments and polyphenolics, Linus Pauling Institute, Oregon State University. 2001.

Wu CY, Tian BZ, Zhu D, Yan XM, Chen W, Xu GY. Properties and application of wound protective membrane made from fibroin. In International silk congress, Suzou Institute of silk technology, Suzou, China, 25-28th October. Pp. 1996; 79-87.

Xu J, Dong Q, Yu Y, Niu B, Ji D, Li M. Mass spider silk production through targeted gene replacement in *Bombyx mori*. Proceedings of the national academy of sciences.2018; 115(35):8757-8762.

Yang Y, Ding F, Wu J, Hu W, Liu W, Liu J, Gu X.Development and evaluation of silk fibroin-based nerve grafts used for peripheral nerve regeneration. Biomaterials. 2007; 28: 5526-5535.

Zhang YJ, Gan RY, Li S, Zhou Y, Li AN, Xu DP, Li HB. Antioxidant phytochemicals for the prevention and treatment of chronic diseases. molecules (Basel, Switzerland). 2015; 20, 21138–21156.

Zhao G, Zhang X, Cheng J, Huang X, Qian H, Li G. Effect of titanium dioxide nanoparticles on the resistance of silkworm to cytoplasmic polyhedrosis virus in Bombyx mori. Biological Trace Element Research. 2020;196(1):290-296.