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Nanotechnology Enhancing Silk Production and Quality Through Nanoparticle Interventions: Sericultures Latest Development

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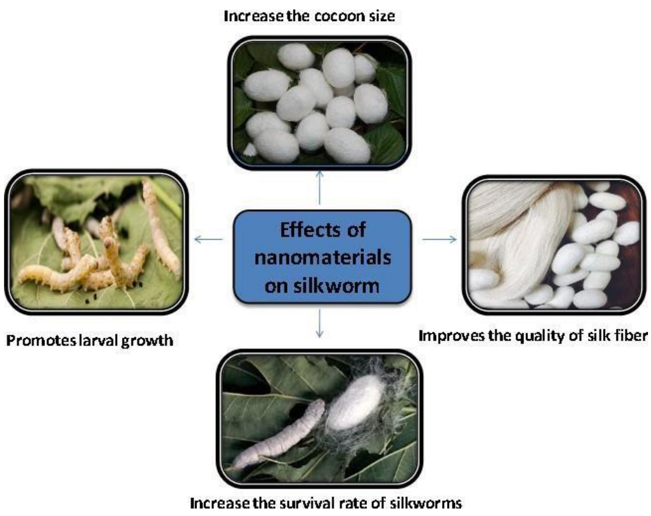
ABSTRACT

Sericulture, the art of making silk, is essential to many sectors because it produces high-quality silk, biomass, silk protein, and animal feed. The development and creation of cocoons by silkworms, which predominantly rely on mulberry leaves as a food also these are crucial to the success of silk manufacture. Over the past few decades, several studies have been initiated to explore the possible applications of nanotechnology as a viable means of improving sericulture. A significant improvement in the quality of silk fibers produced can be attributed to the incorporation of nanotechnology into sericulture practices, which has shown promising results in terms of improving silkworm survival, encouraging growth and development, and improving cocoon weight and length. Additionally, nanotechnology can dramatically alter the way silk is produced by boosting the synthesis of fibroin, which has far-reaching effects on industries like bioengineering and biomedicine. In addition to improving silk fiber quality, enhanced fibroin production also creates new opportunities for the creation of cutting-edge biomaterials and biological applications. This paper seeks to examine the effects of nanoparticles on several characteristics of sericulture, including the weights of mature silk glands, pupae, cocoons, cocoon shells, and the contents of fibroin and sericin. The use of nanotechnology in sericulture has greatly aided developments in several fields, and its application in this sector continues to draw interest and funding.

Graphical Abstract:



Highlights:

1. Nanoparticles enhanced the growth and development of silkworms.
2. Nanoparticles improved silk quality.
3. Nanoparticles exhibit potent antiviral activity.
4. Nanoparticles beneficial effects on silk production

INTRODUCTION

Nanotechnology has had a significant impact on agriculture by providing innovative solutions to improve crop productivity and sustainability [1]. Nanomaterials, with their unique physical, chemical, and biological characteristics, are increasingly being used in various agricultural sectors such as crop enhancement, crop protection, water purification, and food processing [2]. These materials, which range in size from 1 to 100 nm, play a vital role in the efficient delivery of fertilizers and pesticides, thus reducing environmental pollution and promoting sustainable agriculture [3]. Nanotechnology allows for precise distribution of nutrients and agrochemicals to plants, helps in quickly detecting plant viral diseases, and has the potential to revolutionize traditional agricultural practices [4]. The incorporation of nanotechnology into agriculture aims to optimize nutrient management, reduce chemical usage, and enhance crops' ability to adapt to changing climates [5]. Nanomaterials have revolutionized sericulture by enhancing silkworm survival, growth, and silk quality. Green synthesis methods, like using sericin protein waste for gold nanoparticle biosynthesis, have shown promise in wound healing, antioxidant, and antibacterial activity taking them valuable for food, cosmetics, and biomedical fields [6]. Nanomaterials, including nanoparticles and nanocomposites, have been utilized as carriers for targeted delivery of active ingredients in agriculture, improving nutrient efficiency, crop protection, and soil fertility. The application of nanotechnology in agriculture has demonstrated potential in developing bio-stimulants for plant growth, pest control, and weed management, benefiting agricultural practices [7]. Sustainable nanomaterial design from renewable resources is crucial to mitigate environmental and health impacts, ensuring optimized performance in various applications, including sericulture [8]. The integration of nanotechnology in sericulture has attracted considerable attention from scholars due to its capacity to improve various industries like healthcare, beauty products, and farming [9]. Silkworms, exemplified by *Bombyx mori*, present distinct advantages over alternative insects, encompassing economical breeding expenses, large offspring quantities, swift reproduction rates, and varied genetic foundations. These attributes establish silkworms as valuable assets in silk manufacturing and as reservoirs of genetic materials for research and progression in sericulture. Moreover, the application of bioinspired nanocomposites, such as materials based on silk proteins, demonstrates the potential for developing cutting-edge biomaterials with exceptional biocompatibility and biodegradability attributes for applications in biomedical and biotechnological domains. The incorporation of sensors and FPGA technology in sericulture systems also supports the supervision of critical environmental conditions essential for the well-being and vitality of silkworms, thereby contributing to enhanced silk yield [10]. As shown in Figure 1 Nanomaterials exert diverse impacts on silkworms. Research indicates that NPs have the capacity to amass silkworms, resulting in stunted growth and unfavorable physiological consequences. While Magnesium Oxide Nanoparticles (MgO NPs) exhibit no significant effects on silkworm growth, they do modify the expression of genes associated with transporter activity and pathways regulating longevity [11]. The introduction of glucose-coated silver nanoparticles (Ag NPs) to silkworm diets enhances silk characteristics, antibacterial properties, and mechanical resilience, with optimal concentrations stimulating the synthesis of silk proteins [12]. Moreover, pretreatment with Titanium Dioxide Nanoparticles (TiO_2 NPs) enhances silkworm immunity against Bombyx mori cytoplasmic polyhedrosis virus (BmCPV) by impeding virus proliferation and activating immune response pathways. Titanium Dioxide (TiO_2) NPs were shown to be effective, higher cocoon growth, increased cocoon shell mass, and improved feed efficiency and development [13]. Small concentration mulberry (*Morus Alba)* leaf extract-derived bio-Ag NPs also helped larvae growth. According to Gudikandula Krishna et al (2019) larger Ag NPs concentrations initially aided *B. mori* growth, lower Ag NPs concentrations enhanced growth rates and cocoon weights. Instead of affecting silkworm weight, the synthesis of silk proteins can be encouraged, and their mechanical qualities can be improved, with the right concentration of Ag NPs in the diet of silkworms [14]. The most effective antiviral activity has been shown by Ag NPs against *Bombyx mori* Cytoplasmic polyhedrosis Virus (BmNPV). As a result, the virus pathogenicity decreased and afflicted silkworms lived longer [15] and Gold (Au) NPs remarkably show that they have an important impact on the improvement of silk proteins, and consequently, increase the cocoon weight in silkworms [16]. In summary, nanomaterials possess the capacity to impact silkworm physiology, gene expression, silk attributes, and immunity, underscoring both potential advantages and hazards in sericulture. The effects of silkworms and their silk fibers containing NPs are highlighted in this review.

Figure1: Effects of nanomaterials on silkworm

Effects of nanomaterials on silkworm growth and development

The utilization of nanomaterials in sericulture, particularly in relation to the silkworm Bombyx mori, has garnered significant attention due to its potential to enhance various aspects of silk production and the health of silkworms [17]. Over the past decade, numerous studies have explored the effects of nanomaterials, including TiO_2, Ag, Au, and Zinc Oxide (ZnO) NPs, on silkworm growth, development, silk quality, and immune responses. Table 1 shows the effects of various NPs on silkworm have been studied.

SL No	NPs	Concentration size and shape	Purpose	Activity	Reference
1	Ag	25, 50, 75 and 100	Effect of Ag NPs On silkworm using white rot fungi	Improving feed efficiency	[14]
2	Au	86-150 nm	Effects of Au on silkworm	Improving silk proteins and cocoon weight in silkworms.	[16]
3	TiO_2	1000 mg / L _	To investigate the gene expression in silkworm fat and nutrition metabolism	Boost the production of fibroin	[18]
4	CNTs	6-8 nm	The mass manufacture of silk fiber with great strength	Improved silk can be harvested directly	[19]
5	Zn	98.8% 50 ± 10 nm,	Susceptibility to ZnO Nps toxicity and buildup (silk gland and midgut)	Catalytic activity report proved that midgut cells expressed antioxidant enzymes	[20]
6	CS	5 Mg/ml	To Study the antibacterial properties of Chitosan solution and effects in protecting silkworms from bacteria	Chitosan solution was significantly reduced bacterial infection in silkworms	[21]

Table 1: Effect of Nanoparticles on *Bombyx mori*

Yun-Hu Zhang et al. (2019) stated that glucose coating was employed to improve the biocompatibility of AgNPs, and that the AgNPs were successfully integrated into silk by feeding. They stated that when larvae were fed AgNPs, they created silk with altered secondary structures and significantly improved antibacterial capabilities, and that at high concentrations, the secondary structural trend of the silk proteins was totally reversed. Low to medium concentrations of AgNPs in silkworm feed can improve the mechanical and antibacterial properties of silk proteins while also boosting their synthesis [12].

Yang Yang Li et al. (2015) revealed that low amounts of TiO_2 NPs can be used as feed additives with high biological activity, but high concentrations of TiO_2 NPs are reproductively harmful. Recent research has shown that TiO_2 NPs can improve cocoon quality and increase silkworm growth at low concentrations. TiO_2 NPs were delivered to B. mori at several concentrations. They watched and tracked the silkworms' development, feed effectiveness, and cocoon formation, and discovered that low doses of TiO_2 NPs resulted in significantly greater weight gains. They claimed that TiO_2 NPs at low concentrations improved feed efficiency and boosted B. mori growth. This is the first complete research on B's growth and development, feed effectiveness, and cocoon quality [13].

Gudikandula Krishna et al. (2019) reported that they used white rot fungi Trametes ljubarskyi and Ganoderma enigmaticum to synthesize Ag NPs, which may improve some biological features in silkworms. The concentrations of Ag NPs solution were increased to 25%, 50%, 75%, and 100% respectively. They stated that AgNps serve as vitamins, increasing silkworm eating activity. That were employed to promote silkworm feeding had a higher nutritional intake than the control. This development may also help to promote sericulture objectives economically. Therefore, farmers may be encouraged to utilize this supplement to generate more silk [14].

K. Govindaraju et al. (2011) stated that AgNPs were produced using Spirulina platensis, and their antiviral activity was investigated at different dosages. The most effective antiviral activity against BmNPV was demonstrated because AgNPs produced by spirulina may function as an immunostimulant, improving natural defenses against BmNPV, such as prophenolxidase, superoxide anion, and silkworm nitric oxide. As a result, the virus's virulence decreased, and the affected silkworms lived longer [15].

Patil R R et al. (2016) investigated the effect of green AuNPs on Bombyx mori L. larvae at various doses (50, 100, 200, and 300 ppm). The highest effective dose among those tested was 300 ppm. The amount of fibroin was 78.07 at a dosage of 300 ppm green nano gold, while sericin dropped. It was observed that green AuNPs could change the fibroin protein and improve the properties of the cocoon and silk. They asserted that AuNPs reveal that they have a major impact on the enhancement of silk proteins, and hence the improvement of cocoon weight in silkworms [16].

Meng Xue Li et al. (2020) evaluated the effect of TiO_2 NPs on lepidopteran insect's gut microbiome. Their findings revealed that TiO_2 NPs could modify the intestinal microbiota of B. mori, resulting in enhanced growth and development, regulated immune responses, and higher pesticide resistance. After 96 hours of exposure to TiO_2 NPs, larvae in the treatment group grew larger and had a significantly greater body weight than the control group. Furthermore, cocoon shell weight and ratio increased dramatically, indicating greater growth and development, most likely due to higher food digestion, nutrient absorption, feeding effectiveness, and amino acid transport ability [18]. In a study by J. H. Tian et al. (2016), the effect of TiO_2 NPs on gene expression in the silkworm fat body was studied using RNA sequencing. The results revealed significant changes in gene expression linked to nutrition, protein, fat, and carbohydrate metabolism. TiO_2 NP treatment enhanced food metabolism in silkworms, which improved growth and development [19].

Qi Wang et al. (2016) reported that graphene (GR) and carbon nanotubes (CNTs) are commonly used as reinforcement. Mechanically enhanced silk is recovered directly from Bombyx mori larval silkworms by feeding them single-walled carbon nanotubes (SWNTs) and graphene. In this study, inherently reinforced silkworm silk fibers were produced directly by feeding Bombyx mori silkworms meals containing SWNTs or GR. A highly developed graphitic structure with significantly improved electrical conductivity was formed, and the silk exhibits superior mechanical properties, such as higher fracture strength and elongation-at-break. By studying the silkworm and the silk fibers, they determined that some of the fed carbon nanomaterials were absorbed into the as-spun silk fibers, while others went into the feces. The coil conformation has more movable chains than the β-sheet, potentially increasing breaking elongation and toughness modules. Furthermore, the SWNTs and GR may function as "slipknots," enhancing breaking elongation [20].

Yuan yuan Xu et al. (2020) observed that while ZnO NPs are widely employed in sectors, there are rising worries about their ecotoxicity. In this study, the silkworm was used as a model organism; the larvae were grown at a temperature of 25°C, a light:dark ratio of 12:92, and a relative humidity range of 60% to 70%. At the beginning of the third day of the fifth instar, which was the ZnO NPs 96 treatment group, ZnO NPs 93 (10 L, 700 g per silkworm) After 12 hours of exposure to ZnO NPs, Zn element accumulation was visible in all tissues, with the midgut having the highest concentrations and the silk gland having the lowest. While slightly higher than in the control group, the level of Zn in the silk gland was significantly lower than in the midgut. They stated that catalytic activity measurements demonstrated that midgut cells expressed antioxidant enzymes in response to ZnO NPs [21].

Bin Li et al (2010) evaluated the effects of Chitosan solution on bacterial septicemia in silkworms through invitro studies. The antibacterial activity of chitosan solution increased with the incubation time. They claimed that the mortality of larvae inoculated with *S. marcescens* was significantly reduced when silkworm larvae were fed on mulberry leaves treated with chitosan solution. Chitosan solution had the potential to protect silkworm larvae from bacterial septicemia disease [22].

Ponraj Ganesh Prabu et al. (2011) reported that Ag Np was created via the chemical reduction procedure, and that when a certain dose of Ag Nps was administered to silkworms, the silkworm was encouraged to consume more nutrients than the control group. Ag NPs act as vitamins, increasing the silkworms' appetite. Ag Nps can thus increase the length, width, and weight of larvae and cocoons while simultaneously enhancing food digestion; however, different treatments produced varying cocoon characteristics. Ag Nps may increase feed efficacy and improve the length, width, and weight of silkworm larvae and pupae [23].

Guodong Zhao et al. (2019) found that TiO_2 NPs can boost silkworm immunity and tolerance to BmCPV infection. Silkworms given TiO_2 NPs showed no evidence of BmCPV infection, in contrast to the control group. TiO_2 NP treatment increased the survival and cocooning rates of diseased silkworms while decreasing the number of dead worm cocoons [24]. Min Ni et al. (2015) found that TiO_2 NPs induced unique gene and protein expression patterns in the B. mori silk gland. According to the physiological relevance of gene expression profiles, the biological functions most significantly enriched by differentially expressed genes were those related to protein synthesis, protein processing, protein transport, transcription, translation, and carbohydrate and lipid metabolism. Gene expression increased after feeding with TiO_2 NPs, indicating that TiO_2 NPs promote fibroin synthesis. In B. mori fed with TiO_2 NPs, mean protease activity increased, as did the transfer of four necessary amino acids for fibroin synthesis in the hemolymph. These findings indicated a new technique for enhancing fibroin synthesis in B. mori. [25].

Lingyue Cai et al. (2015) discovered that silkworms can create inherently altered silk after consuming TiO_2 NPs in vivo. By using this technology, the NPs can be easily absorbed into the silk gland of the silkworm due to interactions between the molecules of silk fibroin and TiO_2, which influences the mechanical and UV resistance qualities of silks. They asserted that future commercial manufacturing of silkworm silk will follow the green, sustainable, and promising in-vivo modification technique [26].

Surendra et al. (2023) reported that the synthesis of Ag NPs with the flower *Tridax trilobata* (*T. trilobata)* controls bacterial growth. They soaked the mulberry leaves in nanoparticles of various concentrations and fed them to larvae. The study found that Ag NPs inhibited biofilm growth in Bombyx mori L. larvae, pupae, and cocoons at concentrations ranging from 0 to 50 μg/mL. The surface coating of Ag NPs also improved feeding efficiency, body weight, and shell weight. Overall, this integrated investigation discovered that Ag NPs were helpful at lowering bacterial illness in silkworms. [27].

Jeyaraj Pandiarajan et al. (2016) found that AgNps had a deadly effect on the silkworm Bombyx mori, and a leaf extract from the mulberry plant was used to synthesize bio-nanoparticles. The fifth instar larvae were given varying concentrations of Ag Nps, including 1, 10, and 100 ppm. They reported that the maximum pupal weight was 100ppm, and the maximum larval weight was 10ppm. In addition, all treatment dosages had somewhat higher cocoon and shell weights than the control. However, there was an imbalance during both the larval pupal to adult transition and the pupal to adult transition, resulting in a substantial mortality rate at 100 ppm and a moderate mortality rate at 10 ppm. Treatment bias of AgNPs to Bombyx mori larvae explains the physiological traits [28].

Nuno ramos et al. (2020) found that producing functionalized silk fibers with modified diets containing nanomaterials is more environmentally friendly. The primary advantages of utilizing this greener process include the preservation of intrinsic silk qualities, the stability of the new capabilities introduced, and the possibility of large-scale production. These advantages stem from the use of less resources, such as water, energy, and additional chemicals, in the manufacturing of functional silk fibers. They stated that feeding silkworms various nanomaterials, such as carbon-based nanomaterials, metal and metal oxide nanoparticles, and quantum dots, resulted in silk fibers with improved properties and/or new functionalities. However, the uptake of nanomaterials by silkworms and the properties of silk fiber were found to be impacted by their concentration, size, and solubility [29].

Xiaoli Zhang et al. (2019) revealed that the study focuses on the surfactant (Lignosulfonate-LGS) and reveals that, when compared to untreated silkworm silk. It alone causes a substantial improvement in mechanical properties. They claimed that when silkworms drink LGS (anionic surfactant), the mechanical properties of the silk fibers are significantly improved, with increases in tensile strength, strain, toughness, and elastic modulus [30]. According to Hao Xu et al. (2019), the mechanical properties of silk fibers can be enhanced based on the amount of carbon nanofillers, specifically CNTs, present. Lignosulfonate (LGS) was used as a surfactant to improve CNT solubility, dispersibility, and biocompatibility, hence increasing CNT content. They claimed that, in addition to helping silk fibers self-assemble into buffering knots, the higher CNT concentration also improved the conductivity of graphitized silk [31].

Lin Ma et al. (2018) used silkworms as a model animal to test the toxicity and biological impacts of BSA-Au NCs. Silkworms were grown in a bamboo tray at 260 degrees Celsius and fed with fresh mulberry leaves using a syringe from behind the foot 24 hours after receiving BSA-Au NC injections. The average length (AL) and average weight (AW) of silkworms are similar, and there is no evidence that BSA-Au NCs are harmful to silkworms at the concentrations used. The interaction between BSA-Au NCs and silk fibroin may disrupt the spinning process and affect the AD of silks, because BSA-Au NCs injected into silkworms could be transferred into the silk gland [32].

Kiruthiga V et al. (2017) reported that silkworm silk could be a useful biopolymer for producing gold nanoparticles and nanogold bioconjugates. The filament used in this experiment was manufactured from silkworm cocoons with the sericin removed. AuNPs and nanogold-silkworm silk bioconjugates were produced in 75 minutes at 850 degrees Celsius. Before adding the silk thread, the Erlenmeyer flask containing the aqueous auric chloride (10-3M) was reddish. After adding the silk filament, the flask turned ruby red, suggesting the formation of nanogold-silkworm silk bio-conjugate. After a few minutes, the solution's hue changed, indicating the creation of AuNPs. They stated that, using B. mori silk as a template for the spontaneous reduction of gold ions [33].

Rania Belal et al. (2023) studied the genotoxic effects of ZnO NPs at 50 and 100 µg/ml on Bombyx mori larvae in their fifth instar while eating treated mulberry leaves. They assess the effects on the hemolymph of treated larvae for catalase activity, antioxidant potential, Total and Different Hemocyte Count (THC and DHC). ZnO NPs at concentrations of 50 and 100µg/ml considerably lowered THC and DHC levels, causing morphological changes in the cell membrane, cytoplasm, and nucleus. However, the number of oenocytes increased greatly [34].

CONCLUSION

The use of NPs in sericulture has the potential to increase silk production and quality while also possibly enhancing silkworm development and general health. However, given that large concentrations of NPs may have unanticipated negative consequences, it is crucial to carefully assess the concentrations and particular circumstances under which they are used. To completely comprehend the long-term effects and safety implications of adding NPs to the sericulture process, more study and trial are required. Such techniques also require a detailed assessment of their economic and practical sustainability, considering elements like cost-effectiveness and scalability. While the potential advantages of NPs in sericulture are exciting, it is important to note that their adoption should be done with caution to guarantee both the health of the silkworms and the silk's production quality. Although the use of NPs in sericulture presents exciting potential, prudence and knowledge are required to ensure the well-being of silkworms, the excellence of the silk, and the sustainability of the sector. Future silk production techniques could be more economically and environmentally sound, with NPs playing a crucial role.

Future perspective

For the silk business, the use of NPs in sericulture holds out a lot of promise and potential. As we proceed, numerous important areas of concentration and viewpoint become apparent. Research should focus on determining the best NP concentrations for many elements of sericulture, including silk quality, silkworm growth, and disease resistance. It will be vital to strike the correct balance between advantageous impacts and potential hazards.

Sustainability and Environmental Impact: Using NP-enhanced techniques, it is possible to produce silk in an environmentally friendly and sustainable manner. Future studies should examine the sustainability, resource efficiency, and environmental impact of NP incorporation in sericulture.

Considerations for Safety and Regulation: When using NPs in sericulture, it is important to evaluate the long-term safety implications and any regulatory obligations. It is necessary to conduct thorough research on how NPs affect the environment and silkworms.

Economic viability: It is important to consider economic issues including the market demand for enhanced silk goods, scalability, and the cost-effectiveness of NP integration. Cost-benefit studies are essential for establishing whether NP adoption is practicable.

Advanced Nanomaterials: A potential field is the development of advanced nanomaterials with improved characteristics for silk manufacturing. These materials ought to be created to provide advantages while reducing potential dangers.

Applications in Biomedicine and Technical Textiles: NPs may be used in biomedicine and technical textiles in addition to silk manufacturing. The many potential applications of silk augmented with NPs in these sectors should be investigated through research. Collaboration across disciplines is essential, especially between experts in biology, materials science, and the silk business. This will aid in bridging the gap between innovative scientific research and useful application.

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