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Recent Sustainable Practices for Eco-Friendly Utilisation of Sericultural Waste Products

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Silk, a protein fiber renowned for its luxurious texture and sheen in textiles, generates significant waste during production, resulting in economic losses and environmental concerns. This review delves into innovative methods for utilizing silk waste through bio-degradation techniques. It highlights the resulting benefits of waste management and environmental conservation. The conversion of silk waste into bio-composites is highlighted as a promising approach that could potentially supplement or replace synthetic materials in various applications. Furthermore, the inherent biodegradability of silk makes it ideal for the development of environmentally friendly products, including bioplastics. In addition to these applications, silk waste is presented as a potential source for bioenergy production and as an eco-friendly replacement for traditional fossil fuels. Also, the water purification properties of silk waste are explored, showing that it could serve as a means of improving wastewater management techniques and providing clean water. By

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elucidating the numerous benefits of repurposing silk waste, this mini review elaborates on the remarkable advantages of recycling silk waste and therefore shows the necessity of inventive thinking that can guide the practices of industry toward environmental conservation. The use of silk waste not only offers an opportunity to correct environmental degradation but is also an indication of a fundamental change in resource management, thus paving the way for a sustainable future.

Keywords: Silk waste; bio-composites; bioplastics; environmental degradation; bioenergy; sustainable future.

1. INTRODUCTION

Silk is primarily categorized as mulberry silk, which is domestic, and non-mulberry silk such as eri, tasar, and muga [1,2]. Two primary proteins, sericin & fibroin, make up the majority of the raw silk fiber produced by silk worms, making up roughly 20–30% and 70–80% of the complete fiber composition, respectively. In addition, the silk fiber comprises of waxy matter (0.4-0.8%), pigment (0.2%), inorganic matter (0.7%), and carbohydrates (1.2-1.65%) [3]. The structure of raw silk fibers is made up of a fibroin core and a top layer of sericin protein, which provides the fiber with essential mechanical strength. Sericin has inherent hydrophilicity, which aids in the binding of fibroin fibers and the formation of cocoons [4]. Both sericin and fibroin proteins are composed of approximately 18 amino acids, including alanine, glycine, and serine, in varying proportions [5,6,7]. The cocoon is reeled to extract silk fiber threads, which are then used to make silk fabric.

Silk fabric, also known as the "queen of textiles," has long symbolized luxury, opulence, and refinement [8]. Throughout ancient times, people have utilized silk to create high-quality and beautiful fabrics [9]. Cultures all over the world have competed for it, wars have been fought over it, and trade routes have been established due to its allure. Despite its long history and popularity, the silk production process is complex, requiring meticulous attention and skill. Every step, from nurturing silkworms to unraveling their cocoons, requires precision. As with many intricate procedures, there is always an associated waste [10]. In the case of silk production, a large percentage of silk fibers do not meet the quality standards required for high-end garments or luxury goods. These discarded fibers, often considered inferior due to minor flaws, accumulate, resulting in a significant amount of silk waste. Fig. 1 represents various types of waste as well as the significant byproducts produced during the processing of silk cocoons. This waste generation raises more general environmental and economic issues, in addition to being a challenge for the silk industry.

Silk waste is a lost opportunity in terms of the economy. Any wasted gram of silk represents lost revenue opportunities, misutilized resources, and time and effort invested in vain. In contrast, this waste adds to landfills, requiring time and space for decomposition from an environmental perspective. Even though silk decomposes naturally, local ecosystems may still face challenges due to the enormous quantities of waste produced. Furthermore, any chemical treatments or dyes applied may leak into the ground and jeopardize the ecosystem.

However, like they say, "one person's trash is another person's treasure." For silk waste, this couldn't be more accurate. Using this waste is becoming more and more popular as a result of technological advancements and creative thinking. Researchers, environmentalists, and business executives are now beginning to view it as a potential goldmine with a wealth of untapped opportunities rather than as a waste product to be thrown away. This change in viewpoint is inextricably linked to more general global issues such as environmental conservation, sustainable resource management, and the reduction of industrial carbon footprints. It is not just about recovering economic value from waste.

A global evaluation and realignment of industrial practices is desperately needed, given the catastrophic effects of climate change, the quick depletion of resources, and environmental degradation. An important part of this transition is the textile industry, which is among the main causes of environmental pollution. Viewing silk waste through a different lens means that we are tackling a worldwide environmental issue as well as a problem unique to the industry.

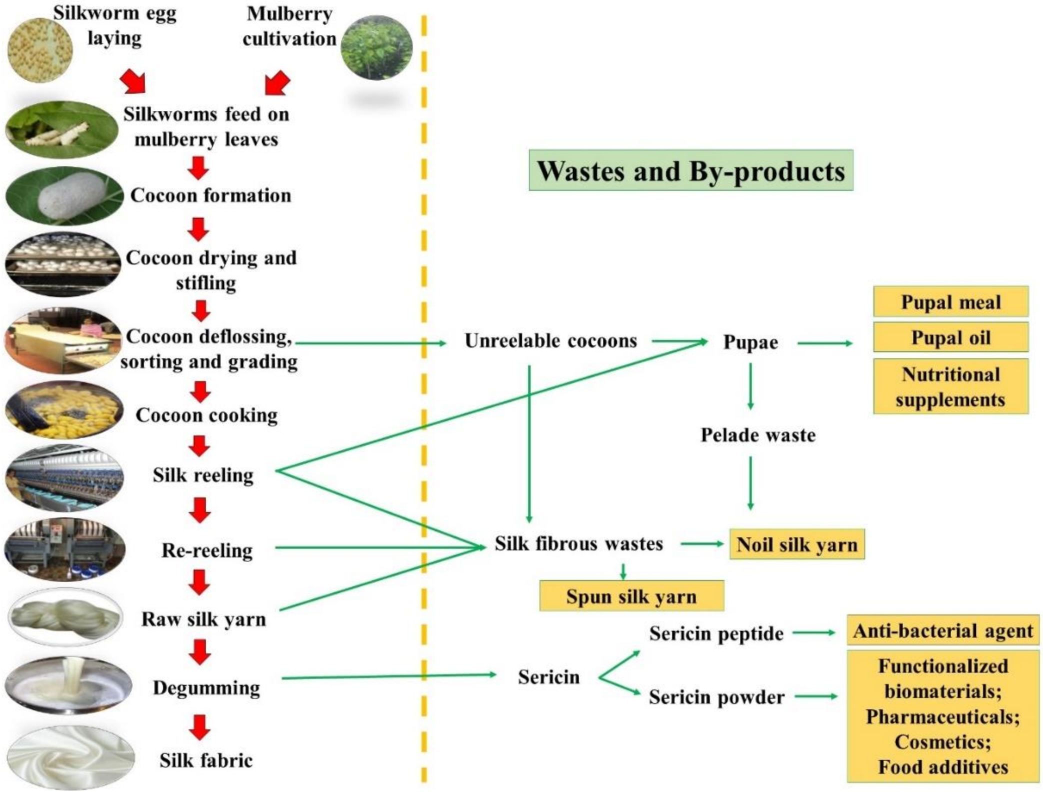

Fig. 1. Waste and by-products of the silk industry

2. SILK WASTE PRODUCTION

The production of silk is not an exception in the textile industry, where production waste can make up as much as 25% [11] of the input of raw materials, leading to financial losses for businesses and environmental concerns. Sericulture, or the silk production process, is a long-standing custom with complex procedures that guarantee the production of silk fibers of the finest quality. The most commonly domesticated insect is the mulberry silkworm (*Bombyx mori* L.), which has been used for commercial purposes. It accounts for 89% of total silk production [12]. Basically, sericulture consists of raising silkworms and harvesting raw silk from their cocoons. From egg hatching to silk extraction, this intricate cycle is tarnished by unavoidable inefficiencies that result in the generation of silk waste. Excreta and leaf waste are two examples that are directly related to the problem of insect breeding. Small-scale farmers have the ability to produce 250-300 kg of silkworm waste, which is the same as 2500 kg of farm manure and can be applied to 0.067 ha of land [13]. The ability to distinguish between various grades of silk is a significant component of sericulture, and it is done primarily using the fiber's length, uniformity, and luster. These determinants are influenced by a number of factors, including the silkworm's development, the surrounding environment, and the quality of the mulberry leaves that are fed to them. Twenty percent or so of the cocoons are chosen as first grade, meaning that there will be no waste when they are fully reeled. Since the remaining cocoons are of the second and third grade, silk factories do not fully process them. The fibers are categorized based on their grade during the silk extraction process [11]. The combined waste from silk weaving and spinning makes up 55% of the waste generated by the silk industry as a whole [11]. In addition to silk, many other waste materials and byproducts from various stages of silkworm rearing are obtained in sericulture [14]. In addition to the immediate environmental issues it brings up, there is certainly an economic component to take into consideration.

Products from sericulture are extensively exploited in China [14]. The pharmaceutical, cosmetic, paper, and leather industries all use eggs, larvae, pupae, and excrement [15]. Fibrous silk wastes generated at various points during the reeling process are put through a degumming and spinning process to produce spun silk yarns.

Even the shorter fibers that remain after spinning are spun in an open-end manner to produce noil silk yarns. After the fibrous silk waste has been degummed, spun silk yarns are produced. Pupal oil, derived from silkworm pupae, is known for its high fat content (25-30%), with approximately 20-25% extractable as pupal oil. After Japan, Italy is the world's second-biggest supplier of pupal oil [16]. Pupae and pupal oil from silkworms are rich sources of alpha-linolenic acid (ALA), one of the essential omega-3 fatty acids that is vital to human health [17]. DNJ, a potent alpha-glucosidase inhibitor used to treat diabetes, is also present in pupal oil [18]. Pupal oil is used in many different industrial products, including biofuels, paints, varnishes, medicines, soaps, and candles [19]. Poultry and livestock feeds have traditionally been utilized as powdered silkworm pupae [20,21]. When used as poultry feed, silkworm pupae meal demonstrates superior nutritional value, outperforming casein by approximately 130% in terms of body weight gain and achieving a high digestibility of roughly 90% when compared to pepsin [22]. According to Virk et al. [23], untreated, acid-treated, and water-treated de-oiled silkworm pupal meals were evaluated for their nutritional value as fish meal alternatives. They took into account variables like feed conversion ratio, protein conversion ratio, and body weight gain. The study found that in starter diets, untreated silkworm pupae can substitute for 50% of the protein found in fish meal, while in finishing diets, they can replace 75% of the protein.

Silk-derived sericin is a well-known substance that is both biocompatible and biodegradable. It is widely used in the pharmaceutical and cosmetic industries due to its versatile properties, which include its ability to form gels, retain moisture, and adhere to the skin [24]. Due to its advantageous qualities, the pupal skin offers a promising raw material for a variety of sectors. It offers great potential for a range of commercial uses because it is rich in chitin, a polysaccharide with a structure essentially similar to cellulose. The exoskeleton cover that forms during the pupal stage of the silkworm, *Bombyx mori* L., may be used to produce the polymer chitin, which is made up of lengthy chains of N-acetylglucosamine [25]. The most well-known chitin derivative is chitosan, which is essentially chitin in its deacetylated state. A number of industries use chitin and its derivatives, especially chitosans, for a variety of purposes. They are used in breweries, cheese processing, oil refineries, as thickening agents for food, as anticoagulants, in the production of vascular grafts and sutures, for cell aggregation, artificial kidney membranes, feed supplements, digestive aids, and probiotics (bifido bacteria). They are also added to paper to improve its surface strength and to remove environmental contaminants, heavy metals, radioactive metals, and colors [20]. Furthermore, chitin and chitosans aid in the suppression of plant parasites and the inhibition of plant growth [20].

The immediate value of the silk as well as the resources (such as labor, feed, and water) used in its production result in a direct economic loss for each kilogram of wasted silk. The textile industry faces both an opportunity and a challenge as a result of recognizing the effects silk waste has on the environment and the economy. The opportunity is in using this waste for creative applications, which could lead to a paradigm shift in resource conservation and management. The challenge is controlling and reducing the waste produced. These creative methods are explored in more detail in the following sections.

3. BIO-DEGRADATION TECHNIQUES: TURNING WASTE INTO VALUE

The field of biodegradation presents interesting responses to the growing problem of silk waste. The process by which organic materials are reduced to smaller molecules by the action of enzymes produced by organisms is referred to as "bio-degradation." It is basically nature's recycling process, breaking down organic materials into their component parts. Since silk is a protein fiber, it degrades naturally. Fibroin, its main protein, serves as an excellent substrate for certain bacteria that can decompose it into simpler molecules. The reduction of waste volume and the possibility of this waste being converted into useful byproducts are two benefits of this biodegradation process. To effectively manage silk waste through bio-degradation, however, requires a thorough comprehension of the underlying factors (Table 1).

Harnessing the biodegradation of silk waste is more than just a disposal method; it is a strategic approach to converting this waste into value-added products. When silk waste undergoes controlled biodegradation, the resulting compounds can be used as raw materials in a variety of industries, including agriculture, cosmetics, and food. For example, using silkworm larvae, pupae, and moths is an effective way to create biologically rich organic compost [26]. The valuable fertilizer that silkworm pupae provide to agriculture is derived from their high concentration of essential mineral components [27]. With an approximate nitrogen content of 8%, the three different forms of dried silkworm pupae—unprocessed, powdered, and de-oiled—can be applied as fertilizer to mulberry trees [20]. Considering that silkworm excrement contains vital nutrients for plants, it has been effectively utilized as a good source of farm manure [9]. Sangeetha et al. [28] investigated the impact of comparing the effects of pupal waste and composted silkworm litter with other organic manures on the development and leaf production of the mulberry tree. They found that composted silkworm litter and pupal waste outperformed farmyard manure and vermicompost in terms of performance and nutrient content. Furthermore, producing focused solutions is made possible by comprehending and refining the biodegradation process. Specific by-products can be obtained by adjusting the process parameters based on the desired outcome. In addition to opening up opportunities for waste repurposing, this highlights the relationship between waste management and economic gain.

4. SILK WASTE AS BIO-COMPOSITES

Polymeric materials are used extensively around the world. Their special qualities and performance make them superior to other, more traditional materials like metals and wood, with many advantages [29]. Since fossil fuels account for 99 percent of these polymeric materials, their primary raw material poses a threat to environmental conservation [29]. Using renewable resources like natural fibers, biocomposites, also known as natural fiber composites, have become a viable substitute for traditional glass fiber/polymer composites. Many advantages, such as low density, affordability, suitable specific mechanical strength, recyclable nature, and environmental friendliness, have contributed to the growing popularity of these biocomposites [30]. The silk waste problem is dynamically solved by the inventive field of bio-composites. Natural fibers, such as silk, are combined with a matrix to create materials known as bio-composites. These composites make use of the innate qualities of the component materials to create a product with improved mechanical, thermal, and acoustic qualities. The tensile and flexural properties of biocomposites made with raw silk fibers have been reported to be similar to those of biocomposites made with natural plant fibers. This suggests that using silk fibers as reinforcement could improve the qualities and performances of biodegradable bio-composites [31]. Our reliance on entirely synthetic materials, many of which present serious environmental challenges because they are non-biodegradable, may be lessened by incorporating silk waste into composite materials. Moreover, the inherent characteristics of silk, like its moisture-absorbing capacity, biocompatibility, and lightweight nature, offer special benefits when combined with other materials to create composites.

These improved bio-composites can be customized for a wide range of uses, including electronics, construction materials, automobile parts, and textiles. The integration technique and matrix selection play a critical role in the sustainability of bio-composites made from silk waste. Essential elements in the development process include the matrix's compatibility with silk, the final composite's desired properties, and its application (Table 2). Furthermore, a substantial change in material science is highlighted by the use of silk waste in these applications. The old, linear economic model of "take, make, dispose" is being replaced with a more circular strategy in which waste is continuously "repurposed, reused, and reintegrated" into the production cycle. As a result, industries leave less of an ecological footprint and are able to repurpose materials that were previously thought to be waste.

Table 1. The impact of different factors influencing silk bio-degradation

Factor	Impact on bio-degradation
Environmental conditions (i.e., temperature, humidity, and pH)	Optimal conditions can accelerate the process, whereas unfavorable conditions can impede degradation.
Microbial species	The effectiveness of silk waste degradation is dependent on the type of microbe selected.
Pre-treatment of silk (i.e., chemical or physical treatments applied before degradation)	The biodegradability of silk can be improved by some treatments, but it can also be inhibited by other microbial actions.

Table 2. Potential applications of silk waste bio-composites

Application sector	Attributes of silk-based bio-composites	Benefits derived
Textiles	Lightweight; enhanced tensile strength; biocompatibility	Durable clothing; eco-friendly accessories
Automotive	Sound absorption; lightweight; high strength-to-weight ratio	Fuel efficiency; reduced noise; sustainable interiors
Construction	Thermal insulation; moisture resistance; lightweight	Energy-efficient buildings; sustainable infrastructure
Electronics	Biodegradability; flexibility; non-toxicity	Eco-friendly gadgets; reduced e-waste

5. SILK-BASED BIOPLASTICS

The quest for environmentally friendly materials has prompted scientists and business executives to look into substitutes for traditional plastics, which are mostly made of petroleum and are frequently non-biodegradable and harmful to environmental conservation [32]. Due to landfill's restricted capacity, high costs, and strict regulations, a long-term study conducted in the North Atlantic Sea revealed that a seawater sample contained 580,000 plastic pieces per square kilometer [33]. Waste management has also created a crisis. This quest has brought attention to a class of plastics known as bioplastics, which are made from renewable resources and usually have biodegradable qualities [32]. Silk waste appears to be a viable option in this field for the creation of novel bioplastics.

The strength and flexibility of silk fibers combined with the environmentally beneficial qualities of biodegradable materials could be combined in bioplastics made from waste silk. These bioplastics would lessen the environmental problems brought on by plastic waste while also reducing reliance on plastics derived from petroleum. Fibroin, the main protein found in silk, can be processed into a variety of shapes, including films and gels, which can subsequently be applied to a wide range of sector (Table 3). Bioplastics made from silk have the advantages of being non-toxic, biocompatible, and having the ability to degrade under controlled conditions without leaving any hazardous residues behind.

Using silk waste to produce bioplastics has wider implications beyond these uses; it is a sign of a paradigm shift in materials science and industry standards. Industries can facilitate the adoption of a circular economy model, which maximizes resource utilization while minimizing environmental damage, by emphasizing sustainability and utilizing waste as a resource.

6. SILK WASTE AS A SOURCE OF BIOENERGY

Biological energy, or bioenergy, provides a sustainable substitute for conventional fossil fuels. As the world's energy needs and environmental concerns increase, there is a dire need to investigate renewable energy sources [9]. Biogas can be produced from any agricultural waste, including seri-wastes. Silk waste, due to its organic nature, has untapped potential in the field of bioenergy. Sources such as corn, sugarcane, or even algae may come to mind when we think of biofuels. However, because silk waste is high in proteins, it can disintegrate into simpler molecules, which can then be used for producing biofuels. The process generally entails the fermentation of silk proteins by microorganisms, resulting in the production of biofuels such as alcohols that can serve as sources of energy.

Table 3. Description of potential applications of silk-based bioplastics

Application	Attributes of silk Bioplastics	Potential impact
Packaging materials	Lightweight; biodegradable; non-toxic	Reduction in landfill waste; reduced carbon footprint
Medical implants and devices	Biocompatibility; controlled degradation	Safe medical interventions; reduced post-surgery complications
Agricultural films	Soil compatibility; moisture retention	Improved soil health; reduced water consumption
Consumer goods	Aesthetic appeal; eco-friendly	sustainable products; reduced environmental impact

Utilizing silk waste to produce bioenergy has many benefits. It's a way to turn something that would otherwise be thrown away into a useful resource. The by-products obtained from various conversion processes (Table 4) may offer additional benefits in addition to direct energy generation. For example, the pyrolysis residue can improve soil quality and support sustainable agricultural methods.

Even though using silk waste for bioenergy has a lot of potential advantages, there are some difficulties that must be overcome. The factors that require careful consideration and optimization are economic viability, production scalability, and conversion process efficiency.

7. REVOLUTIONIZING WATER PURIFICATION WITH SILK WASTE

Water scarcity and pollution remain two of the most highlighted environmental challenges of the 21st century. The need for clean, readily available water has grown due to factors such as growing industrialization, urbanization, and climate change effects. An estimated 15% of the world's population is thought to reside in areas with limited water supplies, and each year, 2-2.5 million people die from diarrheal illnesses brought on by contaminated water [34]. Innovative water purification techniques, in this context, have the potential to completely transform our approach to managing and conserving this vital resource.

Silk waste has shown promise in the field of water purification because of its special qualities and organic composition. Silk proteins, mainly fibroin, can form structures or membranes that can filter impurities out of water by undergoing certain treatments. Since these silk-based filters come from a biological source, they are biocompatible and frequently remove particular pollutants from water while leaving the healthy elements unchanged. Further, as researchers [35] have delved into the microstructure of silk fibers, there have been discoveries related to its potential in trapping heavy metals, organic compounds, and even some microbes, making it a versatile solution for diverse water contamination challenges and have claimed that the hydrophilic functional groups present in silk fibers are mainly responsible for the adsorption of toxic pollutants/ions from the waste water/liquid effluents (Fig. 2).

Using silk waste to purify water represents a more comprehensive approach to resource management than just recycling waste. Additionally, there are significant economic consequences. Energy-intensive procedures or costly chemicals are frequently used in traditional

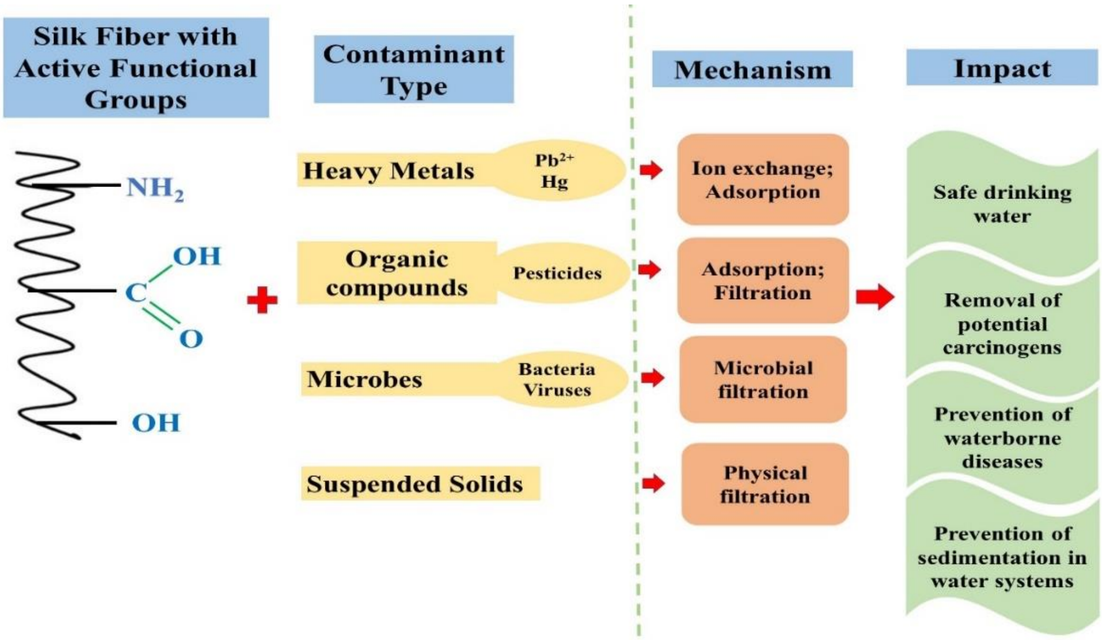

Fig. 2. Mechanism of interaction between toxic contaminants and functional groups present on silk fibers

Table 4. Conversion processes and the applications of potential biofuels obtained from silk waste

Conversion process	Description	Potential biofuel	Applications
Fermentation	Microbial breakdown of silk proteins	Ethanol	Blendable with gasoline; lower emissions of greenhouse gases.
Pyrolysis	Thermal decomposition in absence of oxygen	Bio-oil	Reduces air pollution; can be processed into fuel for transportation or used to generate heat.
Gasification	Conversion of silk waste into syngas	Syngas ($CO + H_2$)	Versatility in applications; can be transformed into liquid fuels or used straight for heat or electricity.
Anaerobic digestion	Decomposition in the absence of oxygen	Biogas (Methane + CO_2)	Utilized as fuel for vehicles, to generate electricity, or for heating; may reduce waste.

water purification techniques. There is potential for affordable water treatment solutions by utilizing silk waste, which would otherwise be discarded; these solutions are particularly advantageous for areas with limited resources. Though silk waste offers a promising avenue, it is important to realize that extensive research and optimization are required to ensure its effectiveness, flexibility, and long-term effects.

8. CONCLUSION

Reassessing the function of silk waste is a journey that skillfully combines innovative thinking with a persistent dedication to sustainability. Harnessing the latent potential of silk waste, whether in the form of bio-composites or as a bioenergy source, signifies not just an industrial evolution but captures a profound societal shift towards a deeper, more resonant understanding of our environment. By repurposing waste materials into necessary activities, such as producing electricity or purifying water, one can learn the fundamentals of a circular economy, which holds that every component, no matter how insignificant appears at first glance, has inherent value. Peering into the future, the real test will be in effectively scaling, refining, and mainstreaming these innovative approaches. These strategies must not only be supported by solid scientific evidence, but also be feasible financially and aligned with desired social norms. In order to bring these innovative concepts from the experimental stage to the real world, it will be essential to invest in technology, conduct more research, and create supportive policy frameworks.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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