Application of Novel Natural Silk Filtration Material in Water Pollution Treatment

Zongsheng Qian

Bishop Montgomery High School, 5430 Torrance Blvd, Torrance, CA 90503, USA

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Abstract: Among the different environmental problems facing the modern world, water pollution is becoming one of the severe factors that may lead to harming human health and disrupting ecological balance. Most conventional technologies in water treatments, including filtration by activated carbon, chemical precipitation, and membrane separation, are effective in such a way as to be fraught with high costs, low efficiency, or secondary pollution problems. This review summarized and discussed the applications of natural silk in water pollution issues and their advantages. Through references in the literature review method, natural silk with excellent physical properties and biocompatibility could be chosen for research as a new filtration material. The theoretical implications of the results are discussed.

1. Introduction

The world today faces many environmental challenges, among which water pollution is particularly prominent. With the expansion of industry, population growth, and the evolution of agricultural production methods, the number and complexity of pollutants entering water bodies are increasing. Water pollution affects the quantity and species of aquatic organisms living in urban rivers and streams. Further, scarce and thin vegetation occurs along a few rivers and streams since the vegetation alongside urban water bodies is severely destroyed by the pollution within them. This is because the water quality contaminants and heavy metals within the sediment affect plant development and growth. This, in turn, exerts certain influences on the landscape and ecological service functions of the rivers and streams[1]. However, traditional water treatment methods are no longer adequate.

For decades, traditional water treatment technologies such as activated carbon filtration, chemical precipitation, and membrane separation have been the cornerstone of water purification. Undeniably effective at removing certain contaminants, these methods often have limited efficiency and carry the risk of secondary contamination. Such shortcomings demonstrate an urgent need for a breakthrough in providing innovative solutions for efficient and eco-friendly alternatives to water treatments.

In this context, natural silk has emerged as a promising candidate in the investigations on novel filtration materials. Well-known for its superior physical properties and excellent biocompatibility, natural silk has been widely investigated in various fields ranging from biomedical science to textile engineering, though until now, only limited applications have been found in the treatment of water pollution. Consequently, the main objective of the paper is to review and summarize existing research on the application of natural silk for the treatment of water contaminants, showing its unique advantages and theoretical importance.

2. Literature Review

With the acceleration of industrialization and urbanization, water and air pollution have become more serious than ever before, and filtration materials started to be in great demand. Traditional filtration materials, such as activated carbon and polymer membranes, have been seriously troubled in both filtration efficiency and environmental sustainability. Thus, a lot of researchers and engineers are interested in developing a new range of filtration materials. This chapter reviews the

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application and development of new filtration materials in water treatment.

Nanomaterials have extremely small-sized particles; hence, under these unique physicochemical properties, they perform excellently in water treatment. This allows for precise control of the filtration process and thus is very effective in the removal of organic pollutants, heavy metals, and pathogenic microorganisms from water. Xu Wufeng et al. summarized the research progress in the modification of nanofiltration membranes by GO, and they pointed out that GO can improve greatly not only the permeate flux but also the antifouling property of nanofiltration membranes, extending their service life[2]. Nanomaterials also show immense opportunities in renewable energy-driven water treatment systems, as was shown in a case study in Tanzania presented by Ma Hao, where NF and UF membranes combined with renewable energy are effective in solving the drinking water problem in rural and remote areas[3].

The sol-gel chemical formulation can also further condense upon application to the fabric into a polymeric structure. According to state-of-the-art techniques, thermal crosslinking between the adhesive system and the added organic polymer is required in case a certain durability effect is to be achieved. In the process, the textile fiber finished in a sol with nanoscale dispersion is immersed, followed by cross-linking and curing using heat treatment or UV irradiation, etc., to create a nanoscale film on the surface of the fiber. The present invention retains hand in this fabric, along with the color, and greatly enhances resistance to soiling. Besides, according to DSC measurement results and mechanical property tests, the treated silk fabrics confirm higher stability under thermal and UV exposure. These results confirm that the sol-gel chemical finishing technology can be an extremely effective means of enhancing antifouling properties and washability for natural silk fabrics[4].

According to Corrie Pelc, textiles as filtration materials offer several advantages, such as filtration efficiency, resistance to chemicals and temperature, and strength. Nonwoven fabrics, with their special fiber structure and porosity, are commonly utilized in air purifiers and personal respiratory masks[5]. With the improvement in living standards, indoor air quality has drawn increasing attention. In this way, it has facilitated the rapid development of textile filtration materials in the air purifier market. Besides, researchers have been exploring other fields of smart fabrics in air purification, embedding high-voltage electrodes to eliminate bacteria and viruses, thus increasing filtration efficiency and adsorption capacity.

3. Advantages of Natural Silk as a Filtration Material

The nature of natural silk, especially surface area, porosity, and the nature of fiber structure, principally determines its behavior in filtration, where major performance indicators like filtration efficiency, permeability, and durability are highly affected.

Meanwhile, natural silk is also a typical microfiber with a very high specific surface area. A large specific surface area means that more surface area is available per unit mass of fiber, which may provide greater possibilities for contact with contaminants and raise filtration efficiency. Besides, the microporous structure between natural silk fibers would allow for the effective retention of particulate pollutants while air or water was passing through. High surface area, combined with appropriate porosity, makes natural silk an ideal filtration material as it supports good permeability while ensuring proper filtration efficiency.

The characteristics of the fiber structure of natural silk further enhance the advantages that natural silk can offer as a filtration material. Firstly, natural silk fibers are slender and soft with good flexibility and plasticity and have a higher mechanical strength, which can be fabricated into different shapes and sizes according to different filtration requirements[6]. The smooth surface of the fibers facilitates lesser adhesion of impurities, adding to the durability of efficiency of the filtration material.

Natural silk is one type of renewable resource; it is biodegradable and non-polluting, degrading much quicker than synthetic fibers. The process involves low-impact production and is in the category of green production. In water treatment for drinking purposes, natural silk and modified materials make for a guarantee against pollution and reduce ecological burden so that development

will be sustainable. By integrating the nanofiltration technology with natural silk, we can develop systems in an effective and eco-friendly way to improve safe drinking water for rural and remote areas. At the same time, the protection of the environment can be addressed.

Natural silk falls into the category of food-grade materials because of their natural properties and generally recognized safety for various purposes. In that regard, they would need to fulfill the most stringent standards of food safety in production and processing stages, as well as at points of application, to guarantee that they are innocuous to humans and will not lead to contamination. Especially when referring to natural silk being used as a filtration material in water treatment, its food-grade characteristic is even more crucial. As a filtration medium, natural silk has been in direct contact with the source of water; minimal contamination could affect the safety of the water quality. However, because natural silk is pure by nature and has very strict specifications in processing, it should not be contaminated; hence, water filtered through it must be safe and free from impurities. This characteristic makes natural silk an ideal filtration material in water treatment, in that it efficiently removes impurities from water and ensures filtered water quality to be at least food-grade, thus providing people with safe and reliable drinking water.

Compared to activated carbon, natural silk fabrics have higher efficiency in removing the dissolved organic matter and tiny particles. The mechanism of activated carbon is mainly based on adsorption, which has a very limited effect on removing dissolved organic matter and tiny particles. Highly efficient filtration by polymeric membrane materials, such as nanofiltration membranes and reverse osmosis membranes, may face some issues like membrane fouling and performance degradation in treating complex water qualities. Besides, there are some limitations to the permeability of polymeric membrane materials owing to the size and structure of the membrane pores, which make it hard to reach high throughput at high filtration efficiency. Moreover, while most current materials focus on single classes of contaminants, this new filtration material can handle multiple types of contaminants simultaneously, making it more versatile.

4. Application of Natural Silk in Water Pollution Treatment

The filter mechanism of natural silk fibers mainly depends on their higher specific surface area and good adsorption characteristics. During water filtration through a layer of natural silk fibers, the suspended solid, impurities, and some dissolved organic matter are effectively adsorbed or retained on the fiber surface. This filtration mechanism not only removes contaminants from the water but also retains beneficial minerals and trace elements, thus comprehensively improving the quality of water. Besides, natural silk fibers have a certain antibacterial property to inhibit the growth of microorganisms in the water and further ensure the safety of water quality. Furthermore, natural silk fibers are renewable and biodegradable, hence showing very considerable environmental advantages in the treatment of water pollution.

These nanofibrils of silk were being treated into high-performance filtration membranes through highly precise extraction and reassembly techniques. This new technology of silk-woven filtration is introduced in Nano Letters entitled "Ultrathin Free-Standing Bombyx mori Silk Nanofibril Membranes". Silk nanofibrils bear great flexibility, high strength, and good toughness, hence are ideal filtration materials. It was confirmed by the observation of scanning electron microscopy that the diameters and elongated lengths of the silk nanofibrils are comparable with single linear nanofibrils, which made the ultrathin membranes with fine structures[7].

Figure 1 shows the use of Silk-CNC nanofiber technology to clean up contaminated water[8]. More precisely, this process first uses guided assembly of CNCs through silk and integrates them to create a new formation of nanofibers called Silk-CNC nanofibers. In the next step, these nanofibers are intelligently integrated into a vacuum filtration system. When the contaminated water flows through such a system, impurities get successfully intercepted and filtered out by the nanofibers of Silk-CNC, especially harmful chemicals like PFAS compounds. Eventually, this filtration would make the water crystal clear, pure, and blue, which signifies a great increase in water quality. The entire process not only demonstrates the innovative combination of silk and nanotechnology but also highlights the effective application of this technology in the field of water purification.

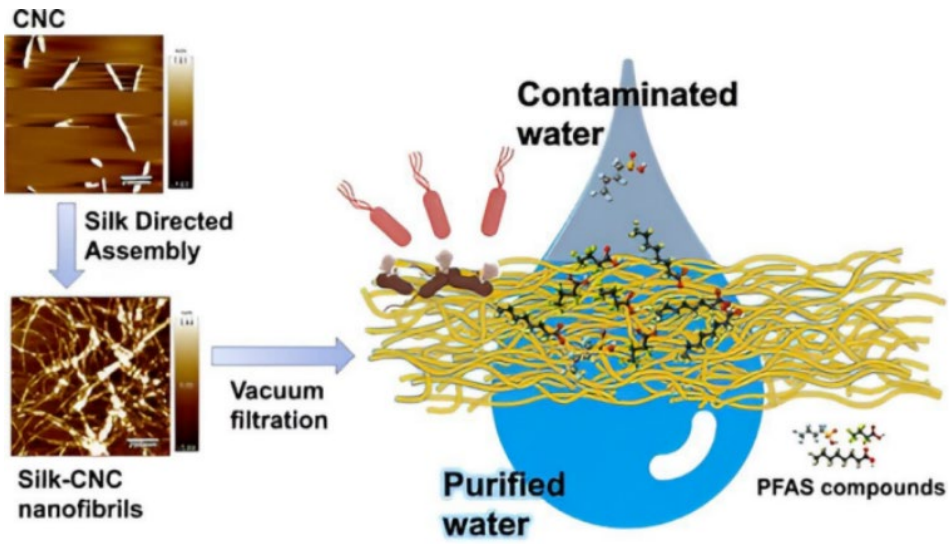

Figure 1 Process Diagram of Purifying Contaminated Water Using Silk-CNC Nanofiber Technology.

5. Theoretical Significance of Applying Natural Silk as a Filtration Material

Natural silk as a filtering material will be of great theoretical importance both in the innovation of water treatment technology and in ecological environmental protection.

5.1. Innovative Contributions to Water Treatment

In the area of water treatment, natural silk has opened up a new avenue as a filtration material for water treatment technology. Natural silk possesses some special physical and chemical properties compared to conventionally used filtration materials: activated carbon, ceramics, and polymer membranes.

The main difference between the various activated carbon materials is the abundance of different pore diameters in their complex internal structure, this characteristic allows them to adsorb many kinds of pollutants effectively[9]. However, natural silk's good performance in treating water with suspended solids, impurities, and other harmful substances is offered by natural silk due to its high specific surface area, excellent moisture absorbency, and breathability. Besides, antifouling performance has been improved with techniques such as sol-gel chemical finishing, among others, which expands its scope of applications in water treatment.

5.2. Positive Significance for Ecological and Environmental Protection

However, natural silk filtration materials can reduce dependency on such chemicals through good adsorption properties and effectively conduct water purification with minimal or no chemical agents. The reduction of chemicals minimizes chemical pollution and cuts down the costs related to chemical procurement, transportation, and storage, benefiting ecological and environmental protection.

Meanwhile, traditional materials for water treatment usually pose a threat of secondary pollution when used, such as material aging and shedding or the re-release of pollutants. Being one of the renewable biodegradable materials, natural silk contributes much to mitigating this type of secondary pollution risk when applied in water treatment. Its good biocompatibility and biodegradability can make sure that it is stable and safe during the treatment process, reducing the probability of material aging and shedding[10]. Even at the end of service life, natural silk degrades into residues that do not contribute to pollution.

6. Limitation

Considering such diverse applications of natural silk filtration materials, there are several

limitations and challenges associated with their practical uses: sensitivity to ambient conditions, high production cost, the utilizing limitation of fiber, and so on.

The first limiting factor that concerns the practical application of natural silk filtration materials relates to their chemical stability, which needs improvement. Natural silk degrades or denatures easily under so many varied environmental conditions, especially concerning pH and temperature in the specific filtration environment. This makes it prone to chemical changes that could seriously weaken any potential use as a filtration material, possibly even preventing it from standing the conditions required for effective filtration. Such an improvement is achieved only with active research into methods of natural silk stabilization as chemical treatment or the making of composite materials to enhance its resiliency against degradation.

The second is that the natural silk material is expensive. The production cost and processing costs of natural silk are high, and its resources are comparatively scarce. This factor seriously restricts its large-scale filtration system use in water pollution treatments. The main cause of such high costs of natural silk is its limited availability and the complexity of the processes involved in its production and processing. The rarity of natural silk and the tedious steps involved in its processing into a filtration material make it less commercially feasible for application in water filtration systems.

Thirdly, while natural silks possess a certain level of filtration capability, it is important to note that their precision and efficiency may not adequately meet the stringent demands of specific fields, such as medical and electronic applications. The requirements for filtration in these domains are often extremely high, necessitating materials that can achieve a high degree of purity and precision in removing contaminants. Natural silk, despite its many advantages, may not always be able to meet these high standards, limiting its use in these particular areas.

Therefore, future studies should be used to develop new silk composite materials or improve existing material processing technologies of silk. In this way, the chemical stability and filtration properties of silk could be enhanced to extend its application in the filtration industry. This would enhance the potential of natural silk through the development in these areas for extended use in filtration applications.

7. Insights and Prospects for Future Research

Indeed, research in natural silk filtration materials in the future will be concentrated on quite a few key areas. First and foremost, there is an urgent need for the development of more effective finishing techniques that could substantially improve the durability and antipollution properties of the filtration materials based on silk. These techniques also need to reduce the cost of processing to make natural silk filtration economically viable. Further development of other composite techniques that combine natural silk with other materials needs to be considered. For example, the production of composite filtration material may resolve high-performance and low-cost challenges by harnessing the unique properties of natural silk in addition to the strengths of other materials. Finally, studies on regeneration and recycling technologies in the case of natural silk filtration material are required for environmental sustainability improvement. We contribute to minimizing waste and improving their economic benefits for the betterment of the environment and economy through the development of technologies that can firmly perform the recycling and regeneration of silk filtration materials.

8. Conclusion

As one of the filtration materials, natural silk has advantages in many aspects and has a wide application prospect. The micro-fine fiber structure and excellent chemical composition of natural silk enable it to have a high affinity with impurities carried in water, hence its ability to efficiently trap the impurities. High surface area and porosity further develop the filtration capacities of natural silk fibers, making them very effective in purifying water. This, combined with excellent biocompatibility and biodegradability, enables natural silk to serve as an environmentally friendly sustainable alternative in water treatment.

However, natural silk filtration materials also have certain limitations. Their thermal sensitivity and sensitivity to UV radiation restrict their application under certain extreme conditions. Additionally, the relatively high cost of silk materials may increase the overall cost of filtration materials. Moreover, the fragile nature of silk fiber structure may lead to fiber breakage during long-term use or when handling high loads of contaminants, thereby affecting filtration efficacy.

In a word, the continuous upsurge of current technologies in water pollution prevention gave robust support to water resource protection. Simultaneously, there is still the need for ongoing, in-depth research to figure out more effective measures for water resource conservation to make more massive contributions to human health and environmental protection.

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