JOURNAL OF COATING TECHNOLOGY AND INNOVATION
Apr-Jun 2024, VOL. 2, ISSUE 2, pp. 29-33
https://doi.org/10.61577/jcti.2024.100009

RESEAPRO JOURNALS

MINI REVIEW

OPEN ACCESS

Coated nanofibers for photocatalytic degradation of Antibiotics

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ABSTRACT

The nanofibers have garnered a lot of interest from researchers worldwide owing to their property of facile modulation properties, which in line could pave the way for a multiple number of beneficial applications. The surface functionalization of nanofibers through coating needs to be delved into, thus, to unlock a multitude of possibilities about their morphological and structural characteristics. Utilizing the above key concepts of coating and surface functionalization of various types of nanofibers, the as-fabricated nanofibers could be precast as composites for the sole purpose of photo-deactivation of various persistent compounds like discarded antibiotics that lead to bio-resistance. The review encompasses an outline of the recent works regarding the utilization of coated nanofibers for the photodegradation of antibiotics. It also enforces the challenges faced by real-world applications and the modifications and ramifications that need to be done in this regard.

KEYWORDS

Surface functionalization; Nanofiber; Coating; Photodegradation; Antibiotics.

ARTICLE HISTORY

Received 22 May 2024; Revised 11 June 2024; Accepted 17 June 2024

Introduction

Antibiotics have been overprescribed and used extensively in recent years, which has caused a buildup of the drugs in natural settings and raised serious concerns for both human health and ecosystems. Furthermore, even at low concentrations, the extended half-lives of antibiotic residues in aquatic settings might promote the growth of bacteria resistant to antibiotics and even several drugs, which can result in potentially fatal diseases [1].

Various kinds of chemical approaches like Fenton's oxidation, chlorination, and oxidation have been utilized for the photodegradation of harsh persistent chemicals. The insufficiency of conventional techniques in eliminating antibiotics from water sources has led to the creation of sophisticated technologies like photocatalysis [2]. Given that photocatalysis can break down organic contaminants when exposed to light, it is a viable strategy. Since photocatalysis makes it possible to remove antibiotic residues in an environmentally benign way, it has garnered a lot of attention. Over the past few years, a significant amount of progress has been made in the application of photocatalytic remediation of antibiotic residues [3].

Nanofibers have become popular photocatalytic materials because of their high surface area, adjustable characteristics, and ease of functionalization. Moreover, their fabrication methods are relatively easier and more cost-effective than other methods which have harnessed their popularity as the material of interest for most of the research. Different nanomaterials in the form of fibers are documented to exhibit relatively more efficiency owing to their enhancement in surface area, easy tunability, and adaptability to different suitable environments depending upon the presence of functional groups accordingly [4]. In addition to this, inorganic nanofibers outperform other traditional bulk materials due to their improved electrical and optical characteristics, unique mechanical and thermal stability, porosity, flexibility, and biocompatibility.

Photocatalytic Degradation of Antibiotics

Since Fleming discovered penicillin in 1928, antibiotics have been pivotal in saving numerous lives. There are approximately 250 different types of antibiotics used in both human and veterinary medicine. Unfortunately, their improper usage has led to a continuous discharge of antibiotics into aquatic ecosystems from sources like fisheries, households, livestock farms, and pharmaceutical industries. Consequently, antibiotics have emerged as significant contaminants in water, known as emerging contaminants (ECs), posing serious health risks. The structural characteristics of antibiotic molecules, such as the large lactone ring in macrolides, the β-lactam ring in β-lactams, and the fused tetracyclic nucleus in tetracyclines, make them resistant to breakdown by microorganisms in the environment. Additionally, the extended presence of antibiotic remnants in water bodies, even in small amounts, can promote the proliferation of bacteria that are resistant to antibiotics, including those resistant to multiple drugs [5]. This situation poses a significant risk of severe infections that could be life-threatening. Hence, it is imperative to devise an efficient method to degrade or eliminate antibiotic residues from aquatic environments.

Various techniques such as chlorination, ozonation, and Fenton's oxidation have been historically employed to address this issue. However, each method has its limitations, such as incomplete degradation of antibiotics, lack of specificity, high initial and operational expenses, prolonged treatment times, and technical intricacies. By using semiconductors to make electron-hole pairs when exposed to light, photocatalysis produces reactive oxygen species (ROS) that are then combined with oxygen and water. Because of their strong oxidative power, these ROS are capable of breaking down a variety of organic materials, including antibiotics [6]. The

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photocatalytic efficiency is highly dependent on the semiconductor material used; those that have been examined the most for this purpose are titanium dioxide (TiO_2), zinc oxide (ZnO), and the newly created metal-organic frameworks (MOFs). Significant advancements have been achieved recently; nevertheless, photocatalysis continues to face significant shortcomings such as inadequate harnessing of visible light, rapid recombination of photo-generated carriers, and incomplete degradation, all of which severely limit its practical use in industry [7].

Nanofibers as Photocatalytic Materials

In light of their special qualities, nanofibers are the best options for photocatalytic uses. They can absorb light efficiently and quickly transport reactants and products in large quantities due to their high surface area-to-volume ratio. In addition, a variety of materials, including metal oxides, polymers, and carbon-based materials, can be used to create nanofibers, each of which has unique benefits for photocatalysis. While metal oxide nanofibers have inherent semiconductor characteristics that lead to increased photocatalytic activity, polymer nanofibers are more pliable and readily functionalized. Researchers have focused on optimizing the structure and composition of nanofibers to improve their efficiency in degrading antibiotics. This includes controlling the morphology (such as nanotubes, nanowires, or hierarchical structures) and surface properties to enhance light absorption and catalytic activity. One significant development is the selective degradation of antibiotics using tailored nanofibers. Functionalized nanofibers can target specific antibiotic molecules while minimizing the degradation of other organic pollutants present in water, thereby improving treatment efficiency [8]. Stability over extended use is crucial for practical applications. Recent studies have investigated methods to enhance the stability and reusability of nanofibers in photocatalytic processes, such as surface modification or encapsulation techniques. These advancements are being applied in environmental remediation scenarios, where nanofiber-based photocatalysts are tested under realistic conditions such as varying pH, temperature, and water quality parameters [9]. This aims to bridge the gap between laboratory-scale studies and practical implementation in wastewater treatment plants or natural water bodies.

Overall, recent articles highlight the promising potential of nanofibers in photocatalytic degradation of antibiotics, emphasizing advancements in efficiency, selectivity, stability, and environmental applicability. Continued research in this area aims to overcome current limitations and accelerate the adoption of nanofiber-based technologies for sustainable water treatment solutions.

Coatings for Enhanced Photocatalytic Performance

The performance of nanofibers in photocatalysis can be further enhanced through surface modification and coating strategies. Coatings serve multiple purposes, including improving light absorption, enhancing charge separation and transport, and providing stability under harsh environmental conditions. Common coating materials include noble metals (e.g., gold and silver nanoparticles), metal oxides (e.g., iron oxide and zinc oxide), and organic polymers (e.g., polymeric carbon nitride and conducting polymers). Each type of coating imparts specific functionalities to the nanofibers, thereby tailoring their photocatalytic activity towards targeted pollutants like antibiotics [10].

Nanofibers inherently have high surface area-to-volume ratios, which provide more active sites for photocatalytic reactions. Coatings or functionalization can further increase this surface area by creating hierarchical or rough surface structures, thereby enhancing the exposure of photocatalytic sites to antibiotic molecules and light. Coatings and functionalization can modify the optical properties of nanofibers to improve light absorption efficiency [11]. For instance, coating with light-absorbing materials like carbon-based nanomaterials (carbon nanotubes, graphene) or noble metal nanoparticles (silver, gold) can extend the absorption spectrum into visible light, where more energy is available for photocatalytic reaction functionalized surfaces can selectively adsorb antibiotic molecules due to specific interactions such as hydrogen bonding, π-π stacking, or electrostatic interactions. This selective adsorption concentrates antibiotic molecules near photocatalytic sites, enhancing their degradation efficiency while minimizing interference from other organic compounds. Photocatalytic degradation involves the generation of electron-hole pairs upon light absorption, followed by their separation and utilization in redox reactions. Coatings or surface functionalization can facilitate efficient charge separation by acting as electron sinks or by providing pathways for charge transfer, thereby reducing electron-hole recombination rates and improving overall photocatalytic efficiency [12].

Coatings can protect the underlying nanofiber substrate from environmental degradation or photo corrosion, thereby improving the stability and durability of the photocatalyst during prolonged operation. This is crucial for maintaining long-term photocatalytic performance in practical applications. Surface functionalization with dopants or catalytic promoters (e.g., metal ions, and non-metal elements) can modify the electronic structure and chemical reactivity of nanofibers. This tailoring can optimize the photocatalytic activity towards specific antibiotics or enhance overall catalytic activity under certain environmental conditions [13]. Wang et. al. reported the photocatalytic degradation of antibiotics by synthesizing a three-layered membranous PAN@PDA/Tb-g-C_3N_4 nanofiber membrane which effectively reduces the percentage of antibiotics and exhibits a negligible leaching effect on plant germination [14].

Coated nanofibers are designed to be scalable for practical applications in water treatment facilities and natural water bodies. They can be incorporated into filtration systems or used as suspensions for batch treatment processes, demonstrating versatility in various treatment scenarios. Coatings or functionalization can also impart environmental compatibility by reducing the leaching of toxic components or by facilitating the recovery and recyclability of nanofiber-based photocatalysts after use, making them more sustainable for large-scale applications [15]. These strategies are pivotal for advancing nanofiber-based photocatalysts toward efficient and sustainable water treatment solutions. Figure 1 illustrates the schematic illustration of electro spun-coated nanofibers for the photocatalytic degradation of antibiotics.

https://doi.org/10.61577/jcti.2024.100009

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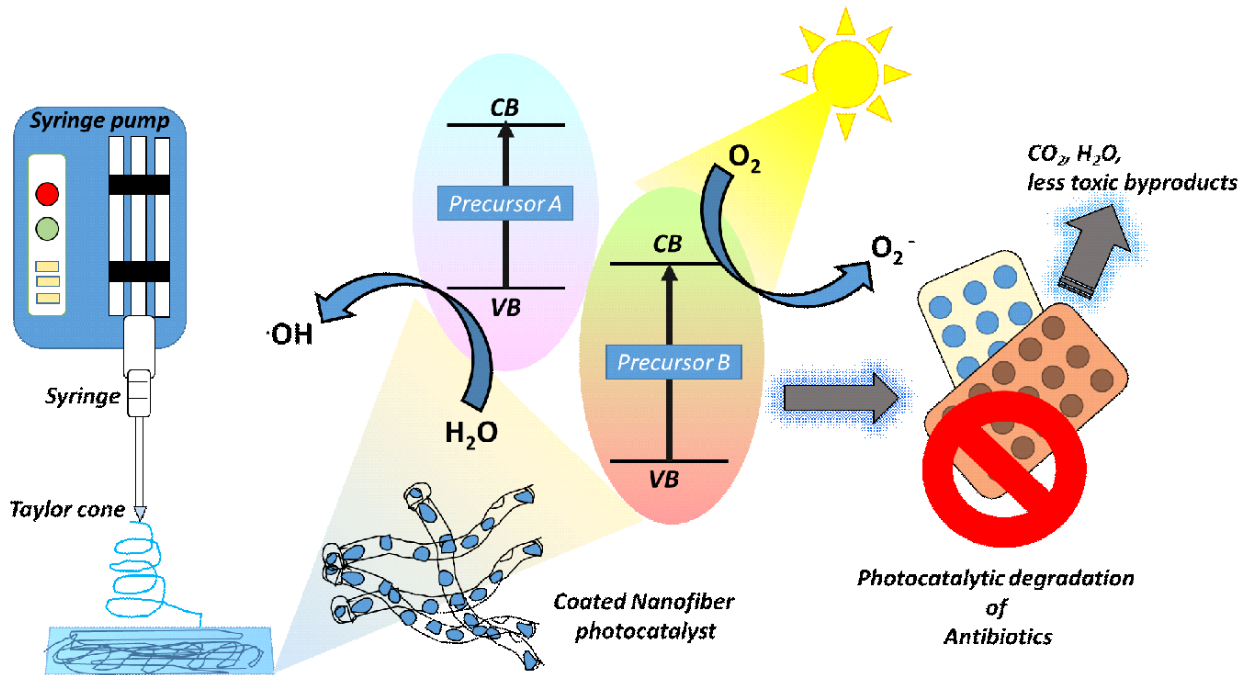

Figure 1. Diagrammatic representation of the synthesis of electro spun nanofibers for the photocatalytic degradation of antibiotics.

Applications in Antibiotic Degradation

The potential for water purification and environmental remediation has drawn a lot of attention to the photocatalytic breakdown of antibiotics employing coated nanofibers. Many research investigations have verified how well nanofiber-based photocatalysts work in replicating natural sunshine or artificial light sources to break down antibiotics including ciprofloxacin, sulfamethoxazole, and tetracycline [16]. While they minimize electron-hole recombination, enhance effective charge separation, and lengthen the life of nanofiber photocatalysts, coatings are essential for enhancing photocatalytic performance. As reported in the works of Zhao et.al., using the triaxial electrospinning method, TiO_2/β-FeOOH nanoparticles are coated on the polymeric nanofibers and the resulting hetero-catalyst exhibits promising results towards the degradation of the antibiotic doxycycline [1]. Sunlight exposure was utilized to investigate how pH, irradiation duration, initial concentration, and H_2O_2 levels influence the photodegradation of DC. The ideal pH was determined to be 6, with equilibrium achieved within 5 hours. The most effective initial DC concentration was found to be 30 µg/ml, and the optimal H_2O_2 concentration was 9 mmol/l.

Ongoing research continues to explore novel coatings and nanofiber materials to improve efficiency, selectivity, and stability in antibiotic degradation. This includes advancements in coating techniques, nanocomposite materials, and surface functionalization to optimize photocatalytic performance. The coatings used on nanofibers are often environmentally benign and compatible with water treatment regulations. They minimize the leaching of toxic substances and can be designed for easy recovery and recyclability, enhancing their sustainability profile. In the works reported by Moradi et.al., TiO_2 nanofibers integrating CuO nanoparticles were fabricated for the degradation of the antibiotic tetracycline [10]. The electro spun nanofibers with photocatalytic properties were not only easily recoverable and reusable with sustained effectiveness but also demonstrated significant reactivity under simulated solar illumination.

Coatings can be tailored to selectively adsorb and degrade antibiotics while minimizing the degradation of other organic contaminants in water. This selectivity enhances the efficiency of the degradation process and reduces the potential for by-product formation that could be harmful to the environment. Shang et.al. reported the Ag_2S-coated $BaTiO_3$ nanofibers which displayed high photocatalytic performance towards the degradation of tetracycline and hydrogen evolution [17]. Density functional theory (DFT) and experimental studies have shown that the S-scheme electron transfer mechanism facilitates the movement and separation of photoexcited charge carriers within the $BaTiO_3$/Ag_2S photocatalyst. This research presents a fresh approach to designing and preparing highly efficient bi-functional photocatalysts with S-scheme heterojunctions, suitable for both hydrogen evolution and wastewater purification applications.

Challenges and Future Perspectives

Although the use of coated nanofibers for photocatalytic antibiotic degradation has advanced significantly, there are still several issues that need to be resolved. These include scaling up the technology for real-world applications, enhancing the stability and recyclability of coated photocatalysts, and optimizing the production of nanofibers with specific features. Subsequent investigations ought to concentrate on creating multipurpose coatings that augment photocatalytic efficacy while tackling particular environmental and financial limitations. Despite advancements, the efficiency of photocatalytic degradation on nanofibers can still be limited by factors such as light absorption, charge carrier recombination, and reaction kinetics. Improving efficiency and speeding up

https://doi.org/10.61577/jcti.2024.100009

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degradation rates are ongoing challenges. While selectivity is a strength of coated nanofibers, achieving high selectivity for antibiotics over other organic compounds present in water remains challenging. Improving the specificity of antibiotics can reduce the generation of potentially harmful by-products. Moreover, photo corrosion, fouling, and loss of catalytic activity over time due to environmental factors (e.g., pH, temperature) need to be addressed to ensure long-term performance. Scaling up coated nanofiber photocatalysts from laboratory-scale experiments to industrial or municipal water treatment applications presents challenges in terms of cost-effectiveness, engineering design, and integration into existing infrastructure [18]. Assessing and mitigating any potential environmental and health impacts associated with the use of coated nanofibers, including the fate of nanomaterials in water systems and their potential interaction with organisms, is essential for safe deployment.

While coated nanofibers show great potential for antibiotic photocatalytic degradation, overcoming challenges related to efficiency, selectivity, durability, scalability, and environmental impacts is crucial for their successful implementation in water treatment systems. Addressing these challenges through ongoing research and innovation will pave the way for broader adoption and effective use of this technology to mitigate antibiotic contamination in aquatic environments. Combining coated nanofibers with other advanced technologies such as membrane filtration, adsorption processes, or electrochemical methods can create synergistic effects and improve overall efficiency in antibiotic degradation [19]. Emphasizing the sustainability of coated nanofibers by using eco-friendly materials, designing for recyclability, and minimizing energy consumption during production and operation. This calls for addressing regulatory frameworks and standards for the use of nanomaterials in water treatment to ensure compliance with safety and environmental regulations. In addition to this, conducting extensive field testing and validation studies to demonstrate the efficacy, reliability, environmental sustainability, and cost-effectiveness of coated nanofiber photocatalysts under real-world conditions is highly recommended.

Conclusions

In conclusion, coated nanofibers represent a versatile platform for photocatalytic degradation of antibiotics, offering enhanced performance through efficient light absorption, charge separation, and targeted functionalization. The integration of advanced coating materials holds promise for overcoming current limitations and advancing the field toward sustainable solutions for water treatment and environmental protection. Continued interdisciplinary research efforts are essential to realize the full potential of coated nanofibers in addressing the global challenge of antibiotic pollution in aquatic environments. The utilization of coated nanofibers for antibiotic photocatalytic degradation holds significant promise but also faces several challenges that need to be addressed for broader adoption and effectiveness.

Disclosure statement

No potential conflict of interest was reported by the authors.

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