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Silver nanowire-carbon fiber cloth nanocomposites synthesized by UV curing adhesive for electrochemical point-of-use water disinfection

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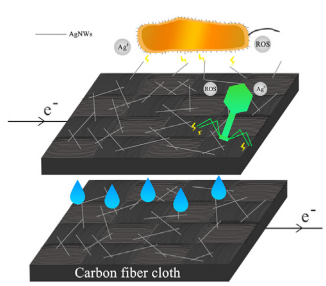
HIGHLIGHTS

- The AgNWs-CC were synthesized with UV curing adhesive by a convenient method.
- Complex 3D conductive networks of AgNWs with controllable release of silver.
- Excellent intrinsic antibacterial activity relied on the release of silver.
- Enhanced disinfection efficiency in the point-of-use electrochemical filter device.
- The influences of AgNWs and UV adhesive on the disinfection were studied.

GRAPHICAL ABSTRACT



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ABSTRACT

Novel silver nanowire (AgNW) – carbon fiber cloth (CC) nanocomposites were synthesized by a rapid and facile method. Acting as filter in an electrical gravity filtration device, the AgNW-CC nanocomposites were applied to electrochemical point-of-use water disinfection. AgNW-CC nanocomposites were characterized by FESEM, XRD, and FTIR. Their disinfection performance toward *Escherichia coli* and bacteriophage MS2 was evaluated by inhibition zone tests, optical density growth curve tests, and flow tests. The results showed that complex 3D AgNW networks with controllable silver release (<100 ppb) were fabricated on CC by using UV curing adhesive. AgNW-CC nanocomposites exhibited excellent intrinsic antibacterial activities against *E. coli*. The concentration of AgNWs and UV adhesive controlled the released silver and hence led to the change in antibacterial activity. The external electric field significantly enhanced the disinfection efficiency of AgNW-CC nanocomposites. Over 99.999% removal of *E. coli* and MS2 could be achieved. More complex AgNW networks contributed to higher disinfection efficiency under 10 V and 10^6 CFU (PFU) mL^{-1} of microorganism. UV adhesive could keep the disinfection performance from being affected by flow rate. The convenient synthesis and outstanding disinfection performance offer AgNW-CC nanocomposites opportunities in the application of electrochemical point-of-use drinking water disinfection.

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1. Introduction

Safe and reliable water is important for public health. Due to the construction of modern water utilities and distribution systems, clean and high-quality water can be easily delivered to developed regions. However, it remains a great challenge to supply safe water to people in the undeveloped regions, especially rural areas. According to the 2014 World Health Organization (WHO) report, more than 700 million people lack access to improved source of drinking water. Most of them live in Sub-Saharan Africa, Caucasus and Central Asia, and Southeast Asia (WHO, 2014). Due to insufficient funds, these areas cannot afford basic water infrastructure. Furthermore, centralized treatment facility for tap water is not suitable for dispersive water supply in rural areas. Additionally, contaminated water is associated with the spread of diseases. Diseases caused by water-borne pathogens are among the most serious threats to public health. As a result of drinking unsafe water, 2 million people die annually from diarrhea, mostly children under the age of 5 (WHO, 2009, 2014). The lack of disinfection for drinking water is largely responsible for these diseases.

Chemical or physical disinfection by such means as chlorination, ozonation, and ultraviolet light can effectively inactivate pathogens in water. However, the conventional technologies have several shortcomings against today's standards, including unfitness for dispersive water supply, generation of potentially toxic disinfection by-products (DBPs) (Krasner et al., 2006; Hua and Reckhow, 2007), ineffectiveness against resistant microorganisms (Kerwick et al., 2005), and professional management of the equipment. For these reasons, conventional disinfection methods are not suitable for rural areas without water utilities. To overcome the problems mentioned above, innovative, high-efficiency, low-cost, and point-of-use (POU) water disinfection methods should be investigated.

The rapid growth of nanotechnology has the potential to provide an alternative and revolutionary method for water disinfection. Among various antimicrobial nanomaterials, silver nanoparticles (AgNPs) have been taken for the most effective bactericidal material for POU water disinfection (Rai et al., 2009). As an effective bactericidal material, silver has been used in the medical field for centuries because of its broad-spectrum antimicrobial properties (Chernousova and Epple, 2013), and it is non-toxic to humans in minute concentrations (Rai et al., 2009). Currently, nanotechnology can further increase the surface-to-volume ratios and catalytic properties of silver; thus, it can improve the silver antimicrobial properties (Yu et al., 2013). In addition, AgNPs are not expected to produce harmful DBPs due to their relatively weak oxidability and inertia in water (Li et al., 2008). Meanwhile, the controllable and reproducible synthesis of different types of AgNPs (Wiley et al., 2005; Xia et al., 2009) makes them attractive to incorporate with other materials, such as porous ceramic (Ehdaie et al., 2014), carbon fiber (Kumar et al., 2013), paper (Dankovich and Gray, 2011), titanium dioxide (Liu et al., 2013b), cotton (Schoen et al., 2010), and polyurethane (Tijing et al., 2012). These nanocomposites reduce the leakage of AgNPs and improve their stability and dispersity, thereby controlling the toxicity (Rai et al., 2009; Suresh et al., 2013) and enhancing the antimicrobial efficiency (Sharma et al., 2009; Liu et al., 2012). Therefore, many efforts have been made in water disinfection using AgNPs nanocomposites. For example, poly(sodium acrylate)/silver cryogels achieved rapid water disinfection by absorbing and squeezing water (Loo et al., 2013), porous ceramic tablet embedded with AgNPs showed long-term water disinfection by dropping into a household water storage container (Ehdaie et al., 2014), and blotter paper impregnated with AgNPs provided a light, cheap, and easy water disinfection by filtration (Dankovich and Gray, 2011). However, in most previous studies, the synthesis of composites was complicated. For example, in the synthesis of polymer-AgNPs nanocomposites, volatile and toxic polymer solution was prepared in advance, then the modification of AgNPs was achieved by evaporation method or simultaneous polymerization-reduction method, which needed reductant and energy (Sharma et al., 2009). The preparation process was time-consuming and used a number of chemicals that were not environmentally friendly. Therefore, better synthesis methods for nanocomposites should be developed.

In addition, appropriate disinfection methods are also important to a POU water disinfection system. It has been reported that electrochemical disinfection can inactivate pathogens by electroporation and reactive oxygen species (ROS) within a short time at relatively low potential (Jeong et al., 2007; Vecitis et al., 2011; Liu et al., 2013a). Electrochemical treatment devices can be portable and compact design (Schoen et al., 2010; Vecitis et al., 2011; Kumar et al., 2013), which do not need professional operation and maintenance. Furthermore, the production of DBPs can be reduced (Radjenovic et al., 2012). Therefore, electrochemical disinfection can be regarded as an effective and promising alternative for POU water disinfection.

Using UV curing adhesive, this study developed novel AgNWs-CC nanocomposites synthesized by a facile and rapid method, and investigated their performance in the electrochemical POU water disinfection system. Serving as the substrate of the filter, a cheap, chemically inert, and porous material, CC provided a conducting bed for AgNWs. AgNWs decorated CC with sharp nanoscale tips to build a strong electric field for electroporation and production of ROS, which played the key role in disinfection. UV curing adhesive was used to stabilize AgNWs loaded on CC and control silver release. The photoinitiator in UV adhesive could produce active radicals under UV radiation, which induced a polymerization and crosslinking reaction. Next, the liquid adhesive was transformed into crosslinked polymers (Scherzer et al., 2002). And the compositions of UV curing adhesive contained bisphenol-α-diglycidylether methacrylate, triethylene glycol dimethacrylate and camphorquinone, which were not toxic and used in the medical study, including dental adhesive and bone defect treatment (Schroeder et al., 2008; Schneider et al., 2010). UV curing adhesive was chosen due to its rapid cure, strong adhesiveness and environmental friendliness (Sangermano et al., 2014). These materials helped to construct an antimicrobial and conductive nanocomposite filter. X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), field emission scanning electron microscopy (FESEM), and graphite furnace atomic absorption spectrometer (GFAAS) were used to analyze the physicochemical properties of AgNW-CC nanocomposites, and their intrinsic antimicrobial activities were evaluated by inhibition zone tests and optical density (OD) growth curve tests. Together with a compact electrochemical filter device, the performance of this POU water disinfection system was evaluated with both bacteria and viruses by flow tests, and the effect of voltage, flow rate, and microbial concentration on the disinfection performance were discussed in detail. Therefore, this work may offer insights for new strategy of silver nanocomposites synthesis and potential application of electrochemical POU drinking water disinfection.

2. Materials and methods

2.1. Materials and chemicals

Silver nanowires with a diameter of 100 ± 10 nm and a length range of 20–80 μm were purchased from NanoMeet Technolog y Company (Beijing, China). Carbon fiber cloth with a thickness of 0.5 mm was purchased from Tianxiang Textile Technology