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The effects of material loading and flow rate on the disinfection of pathogenic microorganisms using cation resin-silver nanoparticle filter system

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ABSTRACT

Waterborne diseases have a negative impact on public health in instances where the available drinking water is of a poor quality. Decentralised systems are needed to provide safe drinking water to rural communities. Therefore, the present study aimed to develop and investigate the point-of-use (POU) water treatment filter packed with resin-coated silver nanoparticles. The filter performance was evaluated by investigating the effects of various bed masses (10 g, 15 g, 20 g) and flow rates (2 mL/min, 5 mL/min, 10 mL/min) by means of breakthrough curves for the removal efficiency of presumptive *Escherichia coli*, *Shigella dysenteriae*, *Salmonella typhimurium* and *Vibrio cholerae* from spiked groundwater samples. The results revealed that, as the bed mass increases the breakthrough time also increases with regards to all targeted microorganisms. However, when the flow rate increases the breakthrough time decreased. These tests demonstrated that resin-coated silver nanoparticle can be an effective material in removing all targeted microorganisms at 100% removal efficiency before breakthrough points are achieved. Moreover the filter system demonstrated that it is capable of producing 15 L/day of treated water at an operating condition of 10 mL/min flow rate and 15 g bed mass, which is sufficient to provide for seven individuals in the household if they consume 2 L/person/day for drinking purpose. Therefore, the bed mass of the filter system should be increased in order for it to produce sufficient water that will conform to the daily needs of an individual.

1. Introduction

According to the WHO/UNICEF (2015), an estimated 663 million people around the world still lack access to safe drinking water. The problem is especially acute in Peoria-urban and rural regions of Africa, Asia and Latin America where the large bulk of the people are typically low-income earners. It appears unlikely that these communities, especially those in rural areas, will receive a potable, piped water supply in the near future. Due to the lack of access to a basic water supply, communities living in rural areas depend on groundwater sources as their main source of water. The WHO (2007) reported that groundwater is contaminated with faecal pathogenic organisms. These pathogens contribute to illness and death from waterborne diseases such as diarrhoea. Children, the elderly and immune-compromised individuals are those who are the most susceptible to diarrhoeal and other waterborne infectious diseases (Lee and Jones-Lee, 1993; Brown, 2007).

To prevent waterborne diseases in developing countries, new approaches to treat and deliver microbiologically safe drinking water to rural communities at household level have to be considered. Decentralised POU systems are possible options for improving water quality for rural communities and could be very beneficial to individuals or families who treat their own water. POU systems are particularly useful in geographically isolated areas where centralised water networks are not feasible. Studies have shown that simple and inexpensive POU systems are capable of reducing diarrhoeal disease and deaths caused by pathogenic organisms found in drinking water (Mintz et al., 2001; Sobsey, 2002; Clasen et al., 2004).

Filter units, which are appropriate POU treatment systems, are usually easy to operate and small enough to be used in individual

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households. Sand is the most commonly used filter media for the filtration system. The contaminant removal effectiveness of the filtration process depends on the type of medium, size, porosity, pore size and available surface area (Huisman and Wood, 1974; Sagara, 2000). Filters with small pores will perform more serious in reducing turbidity and microbiological contaminants to the requisite standards, but may experience very slow flow rates (Mwabi et al., 2011). On one hand, filters with a larger surface area will have a greater flow rate, as there is more space for water to flow through, while filters with low surface areas will have slower flow rates (Franz, 2005). POU filtration technologies that are efficient in reducing microbes are cloth or fibre filters, membrane filters, porous ceramic filters and granular media filters (Sobsey, 2002; Brown, 2007). A number of studies have pointed out that the porous ceramic filtration systems are the most promising technology that provides an effective barrier against microbial pathogens in water (Lantagne, 2001; Clasen et al., 2004). Yet, a recent study that compared a ceramic candle filter with a Silver Impregnated Porous Pot (SIPP) indicated that the latter was more efficacious than the former, as it produced drinking water that complied with the recommended limits set by the South African National Standard (SANS) 241 (2015) drinking water specifications in terms of turbidity and indicator coliform bacteria, regardless of the type of water source (Mwabi et al., 2012). Nano-filtration is therefore a distinctive instance of the fact that advanced physical barriers can, by chastity of their small pore size, prevent the passage of bacteria and allow only water to fall through.

Resin materials have been identified to be used in a wide range of POU and other water treatment options, usually in the form of ion exchange and reverse osmosis (Janda, 2009; Water Science and Marketing, 2007). They are really small plastic porous beads with a diameter of approximately 0.6 mm and contain invisible water, measured as “humidity” or “moisture content”. Gottlieb (2005) reported that cation resins are produced by attaching negatively charged functional groups to the copolymer structure. Furthermore, he described that the fixed ions of this cation exchange resin are solvents ($R\text{-}SO_3^-$) that are tied to the frame. Resins have been used in ion exchange and are reported to be a very powerful technology that removes impurities from water and other solutions. Many industries (nuclear and thermal power stations, semiconductors, information processing system chip and display panel production, purification plants that remove toxic contaminants from drinking water) use ion exchange resins (Lenntech, 2008).

Antimicrobial resins can be fabricated by incorporating silver nanoparticles into the resins by employing chemical reduction methods. Lately, some investigations were held out on the use of resins containing silver or silver nanoparticles for oral and dental applications (Bürgers et al., 2009; Fan et al., 2011). Other researchers have also looked into the use of polymer composites (Jain and Pradeep, 2005) and polymer microspheres, employing plate and test tube batch methods (Gangadharan et al., 2010) for water disinfection. The synthesis of resins containing silver nanoparticles has been well researched (Nath et al., 2005; Jana et al., 2006).

Although a number of studies have been conducted on the removal of bacteria by using resin-silver nanoparticle substrates, there is a paucity of information in the literature on the use of resin-silver nanoparticles in filter systems for removing pathogenic bacteria from drinking water sources. Therefore, this study focused on the evolution of cation resins modified with silver nanoparticles and compared the efficiency of different filter bed masses and flow rates in removing pathogenic bacteria (*Escherichia coli*, *Vibrio cholerae*, *Shigella dysenterae and Salmonella typhimurium*) from a polluted groundwater source. Furthermore, investigate if the filter system was capable of producing adequate and safe drinking water at the POU for rural communities.

2. Experimental

2.1. Preparation of resin-silver nanoparticles substrate

The methods described by Nath et al. (2005) were used for the coating of cation resin. The silver amine complex $[Ag(NH_3)_2]^+$ was prepared by adding 10 mL of 25% ammonia solution drop by drop to a 200 mL aqueous solution of 0.1 M $AgNO_3$. A known amount (20 g) of cation exchange resin (RH^+) was added to this mixture, followed by a mixing process with a magnetic stirrer for 3 h. The resin-silver amine moiety $[R{-}Ag(NH_3)_2]$ was washed three times with deionised water and heated in an oven at 150 °C for 1 h. The yellow colour of the resin beads was transformed to black due to the formation of resin-silver oxide composite $[R(Ag_2O)]H^+$. This complex was subsequently reduced with an aqueous solution of freshly prepared 0.01 M sodium borohydride to form silver nanoparticle-coated resin beads $[R(Ag^0)]H^+$, with a white colour. These beads were washed three times with deionised water and finally dried in a water bath at 65 °C for 2 h to obtain dry silver-coated resin beads.

2.2. Characterisation of the synthesised resin-silver nanoparticle substrate

The synthesis and characterisation of silver nanoparticles cation resins by using scanning electron microscope (SEM), coupled with energy-dispersive spectroscopy (EDS), Transmission electron microscope (TEM), particle-size distribution (PSD) and X-ray diffraction (XRD) were described in the previous study conducted by Mpenyana-Monyatsi et al. (2012). However, in this study the silver nanoparticles cation resins were further characterised by using Fourier transformed infra-red (FT-IR) and Brunauer-Emmett-Teller (BET). The ALPHA FT-IR spectrometer (Bruker Optics GmbH, Ettlingen, Germany) was also used to identify the surface functional groups on the substrate. The mid-infrared spectra of the samples were dispersed on the attenuated total reflection (ATR) diamond crystal and recorded with a detector at a 4 cm^{-1} resolution of 4000 cm^{-1} -500 cm^{-1} with 32 scans per sample for the identification of bands. Conversely, the BET (Micromeritics ASAP, 2020 V3.00H, Norcross, USA) technique was applied to analyse the surface area and porosity of uncoated resin and resin coated with silver nanoparticles. The samples were automatically degassed with nitrogen gas at 150 °C for 10 h at a flow rate of 60 mL/min, prior to analysis.

2.3. Laboratory-scale substrate-silver nanoparticle filter system

The filter system consisted of a polyvinyl chloride (PVC) column with a diameter of 2 cm and a length of 20 cm (Fig. 1). Each filter was packed with a known quantity of silver-loaded substrate during the study period. A 2 cm layer of glass beads and a 2 cm layer of glass wool were placed in the upper and bottom ends of each filter, respectively. The glass beads were used to lower the pressure, thus preventing the accumulation of substrates at one end of the filter. Ten litre buckets served as storage containers for contaminated influent water, which was fed to the filter system using a 1 m length of 8 mm diameter latex tubing connected to a Rainin Dynamax peristaltic pump (Rainin Instrument Co., United State of America). The effluent sample (treated water) was collected at the top of the filter.

2.4. Preparation of bacterial suspensions

The microbial strains used for the inactivation (disinfection) experiments were *Salmonella typhimurium* (ATCC 14028) obtained

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