Environmental Pollution 238 (2018) 52–62

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Performance of ceramic disk filter coated with nano ZnO for removing *Escherichia coli* from water in small rural and remote communities of developing regions☆

Jing Huang [a, b], Guohe Huang [a, b, *], Chunjiang An [c], Yuan He [a], Yao Yao [b], Peng Zhang [b], Jian Shen [b]

[a] Institute for Energy, Environment and Sustainability Research, UR-NCEPU, North China Electric Power University, Beijing, 102206, China
[b] Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, S4S 0A2, Canada
[c] Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, H3G 1M8, Canada

A R T I C L E I N F O

Article history:
Received 22 December 2017
Received in revised form
5 February 2018
Accepted 4 March 2018

Keywords:
Water safety
Ceramic disk filter
E. coli removal
Nano ZnO
Factorial analysis

A B S T R A C T

Global water safety is facing great challenges due to increased population and demand. There is an urgent need to develop suitable water treatment strategy for small rural and remote communities in low-income developing countries. In order to find a low-cost solution, the reduction of *E. coli* using ceramic water disk coated with nano ZnO was investigated in this study. The performance of modified ceramic disk filters was influenced by several factors in the filter production process. Based on the factorial analysis, the pore size of the disk filters was the most significant factor for influencing *E. coli* removal efficiency and the clay content was the most significant one for influencing flow rate of modified disk filters. The coating of nano ZnO led to the change of disk filter surface and porosity. The reduction of *E. coli* could be attributed to both filter retention and photocatalytic antibacterial activity of nano ZnO. The effects of filter operation factors including initial *E. coli* concentration, illumination time and lamp power on *E. coli* removal effectiveness were also revealed. The results can help find a safe and cost-effective approach to solve drinking water problems in small rural and remote communities of developing regions.

1. Introduction

Global water safety is facing great challenges due to increased population and demand (Bao et al., 2012; Harmon and Wyatt, 2008; Huang and Loucks, 2000; Li et al., 2009; Power et al., 2016; Qin et al., 2007). According to the report of the World Health Organization (WHO), 663 million people around the world have no access to improved water sources (WHO, 2016). Reducing by half the number of people without access to safe drinking water is one of the key Millennium Development Goals of the United Nations (Firth et al., 2010). Water quality issue is often associated with the water-related diseases which are one of the major health problems globally. In 2000, it was estimated that 4 billion cases of diarrhoea annually accounted 5.7% of the global disease burden (Fawell, 2003). One of the major strategies for tackling this problem is to ensure the good performance of water treatment facilities (An et al., 2016, 2017; Wang et al., 2016). However, the limited capital and investment become an obstacle for applying a comprehensive water treatment plan in low-income developing countries. This is especially true for the small rural and remote communities, where opportunities for building centralized water treatment infrastructures are rare and connection to the water supply system is not cost effective (An et al., 2016a). Therefore, there is an urgent need to develop suitable water treatment strategy in such regions.

For the implementation of water treatment technologies in small rural and remote communities of developing countries, considerations are usually given to the relevant cost. Massive investment in water technology is difficult to achieve in less wealthy regions. Easy operation and maintenance are also preferred after the installation of treatment facilities. Some water treatment technologies such as adsorption, biosand filtration and household-

☆ This paper has been recommended for acceptance by Dr. Harmon Sarah Michele.

* Corresponding author. Institute for Energy, Environment and Sustainability Research, UR-NCEPU, North China Electric Power University, Beijing, 102206, China.
E-mail address: huang@iseis.org (G. Huang).

https://doi.org/10.1016/j.envpol.2018.03.008
0269-7491/

based flocculant-disinfectant drinking water treatment have been used in household applications (Ali and Gupta, 2006; Baig et al., 2011; Crump et al., 2005; Hu et al., 2016; Joseph et al., 2012; Noubactep et al., 2012; Reller et al., 2003; Silva et al., 2012; Sobsey et al., 2008; Van Halem et al., 2007). There is also an increasing interest in using ceramic filters as a viable option for inexpensive and rapid water treatment (Van Halem et al., 2009). The ceramic filters are produced from the raw materials such as clay, biomass and water, which are inexpensive and locally available (Rayner et al., 2013; Ren et al., 2013). The cost is less than several US dollars for each filter and it is affordable for household applications (Van Halem et al., 2007). The porous structure and inner microchannels can help retain microorganisms and particles, while permit clean water to pass through (Kretzschmar et al., 1997; Oyanedel-Craver and Smith, 2008; Van Halem et al., 2007). Although some previous studies are encouraging, the knowledge about filtration through ceramic filters under complicated conditions is still limited. The interactions among treatment performance, filter characteristics and operation modes are not clear.

Since many water-related diseases are caused by bacteria such as *Escherichia coli* (*E. coli*) (Saxena et al., 2015), some efforts have been made to modify the surface of ceramic filters and improve their ability to inactivate bacteria. The impregnation of silver-based agent on ceramic filters was a common approach in previous studies. Oyanedel-Craver et al. (2008) reported more than 97.8% of *E. coli* was removed through ceramic filters coated with colloidal silver. Kallman et al. (2011) studied the performance of ceramic filters impregnated with silver nanoparticles and found the average *E. coli* removal efficiency was 92%. Silver ions have been used as antimicrobial agents for decades due to their growth-inhibitory capacity against microorganisms. The presence of silver ions results in the inactive and the nonculturable state of bacteria, followed by cell death (Jung et al., 2008). It is also noted there are concerns about the potential toxicity caused by silver leaching and relatively high material cost (Prabhu and Poulose, 2012). Compared with silver-based agent, ZnO can act as the bactericide alternative with less risk and cost. Nano ZnO has been used in textile, rubber, food processing industries (Castro-Mayorga et al., 2017; Mirzaei and Darroudi, 2017; Rathnayake et al., 2014). The antibacterial activity of nano ZnO is attributed to the interaction between cells and radical oxygen species generated from nano ZnO (Zhang et al., 2009). To the best of our knowledge, there has been no report regarding the integration of ceramic filters and nano ZnO for the reduction of bacteria from water.

In order to find a sound solution for low-cost water treatment in small rural and remote communities, the reduction of *E. coli* using ceramic water disk coated with nano ZnO will be investigated. In detail, (1) the preparation of nano ZnO impregnated ceramic filters will be comprehensively studied through 2^4 factorial design of experiments; (2) the morphological and functional characteristics of ceramic filters coated with nano ZnO will be characterized; (3) the effects of filter operation factors including initial *E. coli* concentration, illumination time and lamp power on *E. coli* removal effectiveness will be revealed. This study represents the first attempt to investigate the features and patterns for removing bacteria using nano ZnO impregnated ceramic filters. The theoretical results obtained can be used in establishing new household water treatment strategy for small rural and remote communities in developing countries.

2. Materials and methods

2.1. Chemicals

In this study, *E. coli* was cultivated from strain ATCC 25922. Nano ZnO particles were obtained from the Aladding Industrial Corporation (Shanghai, China). Clay was purchased from Beijing Zhida Tenghui Trading Co., Ltd (Beijing, China) and rice husk was collected from Jiangsu Yancheng Grain Processing Plant (Yancheng, China). All other chemicals were of reagent grade or higher.

2.2. Cultivation and enumeration of E. coli

The Luria–Bertani (LB) culture medium including 1 g NaCl, 1 g tryptone, 0.5 g yeast extract per 100 mL deionized water was used in this study (Baev et al., 2006). The LB medium was sterilized in an autoclave before spiked with *E. coli* strain. The cultivation of *E. coli* was carried out at 37 °C in an incubator. LB agar nutrient medium included 2.5 g agar per 100 mL LB culture medium. The sterilized LB agar nutrient medium was maintained in a thermostatic water bath at 65 °C before testing. After dropping 1 mL water sample with *E. coli* onto a petri dish, the sterilized LB agar nutrient medium was cooled to 45 °C for several minutes and then poured into the petri dish. Meanwhile, the petri dish was shaken slightly for several seconds to enhance the mixing of water sample and nutrient medium. After drying at sterile platform, the petri dish was turned upside down and incubated at 37 °C for 12–18 h. The number of bacterial colonies was enumerated (Prosser et al., 1987).

2.3. Production of ceramic filter disks coated with nano ZnO

The ceramic disk filters were produced through mixing clay, rice husk and water. The mixture was shaped into disk with the diameter of 10 cm and thickness of 1.5 cm using press machine. The disk prepared was air-dried at cool ventilated place for 3–8 days. Then the clay disk was sintered in muffle furnace at 1000 °C with a heating rate of 2 °C/min. Nano ZnO particles (20–40 nm) were dispersed in deionized water. Sodium hexametaphosphate was used as dispersant (Ojha et al., 2010; Suganthi and Rajan, 2012). The solution with nano ZnO particles was stirred for 2 h followed by further ultrasonic-assisted dispersion for 20–30 min. 10 mL of obtained suspension was brushed on the surface of ceramic disk filters and dried for filtration.

In the production of ceramic filter disks coated with Nano ZnO, a 2^4 factorial design was used. It requires all combinations of two levels for each variable (Xin et al., 2016). Four factors including the rice husk size, clay content, sintering time at 1000 °C and concentration of nano ZnO suspension were investigated. Each factor had two levels as shown in Table S1. The experiments were conducted in triple replicates. The detailed factorial design for experiments was shown in Table 1. *E. coli* removal efficiency and flow rate were used as the responses.

2.4. Filtration system

A filtration system shown in Fig. 1 (a) and Fig. 1 (b) was designed and built to conduct experiments in this study. The system included a synthetic glass column, two flanges and an outlet valve. The synthetic glass column and a flange were joint-attached as well as other flange and the outlet valve. The ceramic disk was put between two flanges. The rubber seal ring was used at the flange edge to prevent leaking. The customized full spectrum lamp was obtained from Shenzhen Rapp-light Agricultural Lighting Co. Ltd (Shenzhen, China) and its emission spectrum is shown in Fig. 1 (c). The filtration column was covered with black cloth in filtration tests. The influent sample was taken before filtering while the outlet valve was close. The effluent was collected with sterile beaker in filtration process.