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Review

Governing factors affecting the impacts of silver nanoparticles on wastewater treatment

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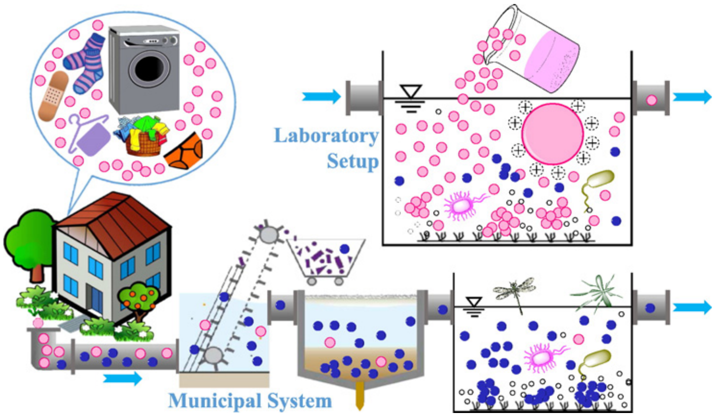
HIGHLIGHTS

- Reactor configuration controls the ecotoxicity of silver nanoparticles.
- Microbial functional redundancy reduces the adverse effects of silver nanoparticles.
- Susceptibility of microorganisms to silver nanoparticles is species-specific.
- Wastewater microbes can adapt to silver nanoparticles.
- Silver nanoparticles at realistic concentrations have minimal ecotoxicity in sewage.

GRAPHICAL ABSTRACT



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ABSTRACT

Silver nanoparticles (nanosilver or AgNPs) enter municipal wastewater from various sources, raising concerns about their potential adverse effects on wastewater treatment processes. We argue that the biological effects of silver nanoparticles at environmentally realistic concentrations (μg L^{-1} or lower) on the performance of a full-scale municipal water resource recovery facility (WRRF) are minimal. Reactor configuration is a critical factor that reduces or even mutes the toxicity of silver nanoparticles towards wastewater microbes in a full-scale WRRF. Municipal sewage collection networks transform silver nanoparticles into silver(I)-complexes/precipitates with low ecotoxicity, and preliminary/primary treatment processes in front of biological treatment utilities partially remove silver nanoparticles to sludge. Microbial functional redundancy and microbial adaptability to silver nanoparticles also greatly alleviate the adverse effects of silver nanoparticles on the performance of a full-scale WRRF. Silver nanoparticles in a lab-scale bioreactor without a sewage collection system and/or a preliminary/primary treatment process, in contrast to being in a full scale system, may deteriorate the reactor performance at relatively high concentrations (e.g., mg L^{-1} levels or higher). However, in many cases, silver nanoparticles have minimal impacts on lab-scale bioreactors, such as sequencing batch bioreactors (SBRs), especially when at relatively low concentrations (e.g., less than 1 mg L^{-1}). The susceptibility of wastewater microbes to silver nanoparticles is species-specific. In general, silver nanoparticles have higher toxicity towards nitrifying bacteria than heterotrophic bacteria.

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Contents

1. Introduction

Silver nanoparticles (nanosilver or AgNPs) are clusters of zero-valent silver (Ag^0) with a size between 1 nm and 100 nm (Ivask et al., 2014; Pachapur et al., 2016; Prabhu and Poulose, 2012; Zhang et al., 2009). Numerous technologies and fields take advantage of the promising and desirable merits of silver nanoparticles (Benn et al., 2010; Chen et al., 2007; Gorenšek and Recelj, 2007; Reidy et al., 2013), including but not limited to intensive catalytic activities (Ankamwar et al., 2016; Bindhu and Umadevi, 2015; Jiang et al., 2005; Mandi et al., 2016; Tsujino and Matsumura, 2005), unique optical properties (Bakr et al., 2009; Evanoff and Chumanov, 2005; Lee and El-Sayed, 2006), high electrical conductivity (Chen et al., 2009; Kamyshny et al., 2005; Li et al., 2016b; Peng et al., 2016), and excellent antimicrobial behavior under select circumstances (e.g., at high silver concentrations and/or with significant silver ion release) (Chen and Schluesener, 2008; Hu and Hsieh, 2015; Rai et al., 2009; Wong et al., 2015; Yu et al., 2013). Silver nanoparticles are the most used nanoparticles in consumer products (Bondarenko et al., 2013; Orta-García et al., 2015; Samberg et al., 2010). The antimicrobial behavior, in particular, finds its use in the medical industry in multitudinous therapeutic devices and/or health care products (e.g., wound dressing and burn dressing) to control the growth of pathogenic microorganisms (Chaloupka et al., 2010; Chen and Schluesener, 2008; Dos Santos et al., 2014; GhavamiNejad et al., 2016; Liang et al., 2016; Mukherjee et al., 2014; Salata, 2004). In daily life, a wide array of consumer products, such as underwear, footwear, and wet wipes, incorporate silver nanoparticles for their antibacterial properties (Benn et al., 2010; Benn and Westerhoff, 2008; Schluesener and Schluesener, 2013; Tulve et al., 2015). In addition, silver nanoparticles serve as a new generation of antimicrobial materials for drinking water disinfection (Biswas and Bandyopadhyaya, 2016; Dankovich and Gray, 2011; Gangadharan et al., 2010; Jain and Pradeep, 2005; Lalley et al., 2014; Li et al., 2008; Lin et al., 2013; Ren and Smith, 2013), bacterial inactivation in stormwater runoff (Schifman et al., 2015), and membrane fouling control in a membrane bioreactor (MBR) (Huang et al., 2016; Sawada et al., 2012; Yang et al., 2009, 2016; Zodrow et al., 2009).

The processes of fabrication, application, and consumption of silver nanoparticle-containing products all release a certain quantity of silver nanoparticles into both sewage treatment systems and natural aquatic environments (Benn and Westerhoff, 2008; Lazareva and Keller, 2014; Mueller and Nowack, 2008; Nowack and Bucheli, 2007; Telgmann et al., 2016; Voelker et al., 2015; Wigger et al., 2015). Silver nanoparticle-coated textiles can release particulate silver (mostly in a size range of 450 nm) into washing liquid or wastewater during laundering (Geranio et al., 2009). The silver particle-laden washing liquid may subsequently enter sewage treatment systems, which are now often referred to as municipal water resource recovery facilities (WRRFs). Conventional silver (e.g., ionic silver) incorporated textiles also release silver nanoparticles during household laundering into wastewater (Mitrano et al., 2014). In addition, it is estimated that 15% to 25% of silver nanoparticles released directly into the air and soil during the use of consumer products end up in WRRFs (Lazareva and Keller, 2014). Silver nanoparticles possess strong antimicrobial activities (Banasiuk et al., 2016; Fabrega et al., 2011; Franci et al., 2015; Meng et al., 2016; Shayani Rad et al., 2016; Tolaymat et al., 2010; Yang et al., 2013b), which cover a broad range of microorganisms even at mg L^{-1} levels or lower (Lara et al., 2011; Nirmala et al., 2013; Yah and Simate, 2015). As a result, the release of silver nanoparticles has raised great concerns regarding their potential to negatively impact ecosystems in both engineered and natural aquatic environments (Brittle et al., 2016; Huynh et al., 2016; Marambio-Jones and Hoek, 2010; Siripattanakul-Ratpukdi and Fürhacker, 2014; Yu et al., 2013). This concern persists even though production volume and release quantity of silver nanoparticles are insignificant compared with some other engineered nanoparticles such as titanium dioxide (TiO_2) and silicon dioxide (SiO_2) nanoparticles (Bondarenko et al., 2013; Hendren et al., 2011; Keller et al., 2013; Piccinno et al., 2012; Sun et al., 2014).

Researchers have conducted numerous studies to screen the ecotoxicity of silver nanoparticles in biological wastewater/sludge treatment processes (Hou et al., 2012; Liang et al., 2010; Ma et al., 2015; Zhang et al., 2013). In addition, available reviews have well summarized our current understanding of the potential biological effects of silver nanoparticles on microbial communities in municipal sewage treatment systems (Kunhikrishnan et al., 2015; Musee et al., 2011; Siripattanakul-Ratpukdi and Fürhacker, 2014; Wang and Chen, 2016; Yang et al., 2013b; Yu et al., 2013). Nonetheless, to the best of our knowledge, the critical role of reactor configurations in controlling or determining the environmental behavior of silver nanoparticles in WRRFs has not been well documented. This review summarizes state-of-the-art research regarding the responses of microbes in biological sewage treatment processes to silver nanoparticles. A special emphasis