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# Toxicity and transfer of polyvinylpyrrolidone-coated silver nanowires in an aquatic food chain consisting of algae, water fleas, and zebrafish

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ABSTRACT

Nanomaterials of various shapes and dimensions are widely used in the medical, chemical, and electronic industries. Multiple studies have reported the ecotoxicological effects of nanaoparticles when released in aquatic and terrestrial ecosystems; however, information on the toxicity of silver nanowires (AgNWs) to freshwater organisms and their transfer through the food webs is limited. In the present study, we aimed to evaluate the toxicity of 10- and 20-μm-long AgNWs to the alga *Chlamydomonas reinhardtii*, the water flea *Daphnia magna*, and the zebrafish and study their movement through this three-species food chain using a variety of qualitative and quantitative methods as well as optical techniques. We found that AgNWs directly inhibited the growth of algae and destroyed the digestive organs of water fleas. The results showed that longer AgNWs (20 μm) were more toxic than shorter ones (10 μm) to both algae and water fleas, but shorter AgNWs were accumulated more than longer ones in the body of the fish. Overall, this study suggests that AgNWs are transferred through food chains, and that they affect organisms at higher trophic levels, potentially including humans. Therefore, further studies that take into account environmental factors, food web complexity, and differences between nanomaterials are required to gain better understanding of the impact of nanomaterials on natural communities and human health.

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## 1. Introduction

The increasing importance of nanomaterials in various fields, including medicine, industry, energy, engineering, and aerospace (Guo et al., 2006; Meng and Jin, 2011; Sund et al., 2011), has resulted in a rapid increase in demand. Consequently, large quantities of nanomaterials are being released into aquatic and terrestrial ecosystems (Klaine et al., 2008), having minor and major effects on natural communities. In addition to their direct effects on the environment, nanomaterials are transferred between individuals of different species via the food web (Holbrook et al., 2008) and have indirect effects on organisms in higher trophic levels. As a result, bioaccumulation and biomagnification are major threats to the environment and human health (Favari et al., 2002).

Nanomaterials are structures with at least one dimension that measures 100 nm or less (Nel et al., 2006) and exist in various shapes, including nanoparticles, nanowires, nanotubes, nanorods, and nanoplates. Nanowires are one-dimensional (1D) nanostructures with lateral length of 1–100 nm, such as nanorods, nanobelts, and nanotubes (Xia et al., 2003), that have been widely studied in dielectrophoretic manipulation and the investigation of mechanically enhancing composites, mainly due to their unique characteristics, including the high aspect ratio and high Young's moduli (Wissner-Gross, 2006; Grange et al., 2009). Additionally, they have gained popularity due to their versatility in optic, electronic, and sensor applications (Im et al., 2006). For instance, nanowires are utilized as elements in single and multicolor nanoscale light-emitting diodes (Greytak et al., 2005), biosensors for biological and chemical species (Cui et al., 2001), gas-detection sensors (Favier et al., 2001), and nanoconnectors in nanoelectronic devices (Hong et al., 2001) and nanolasers (Huang et al., 2001; Duan et al., 2003; Agarwal et al., 2005).

Silver nanowires (AgNWs) are especially significant as the base material of flexible, transparent, and conductive products such as electrodes and films (Langley et al., 2013). However, AgNWs are known for their direct toxic effects on several aquatic organisms. For example, George et al. (2012) reported that various shapes of silver nanomaterials, including AgNWs, cause oxidative stress and mortality in zebrafish (*Danio rerio*) embryos; Artal et al. (2013) demonstrated the toxicity of silver vanadate nanowires ($AgVO_3$NWs) to the water flea *Daphnia similis*; Scanlan et al. (2013) found that AgNWs, coated with silica dioxide ($SiO_2$) and polyvinylpyrrolidone (PVP), are toxic to the water flea *Daphnia magna*; and Sohn et al. (2015) reported the toxicity of AgNPs and AgNWs to the alga *Pseudokirchneriella subcapitata*, the water flea *D. magna*, and the juvenile fish *Oryzias latipes*.

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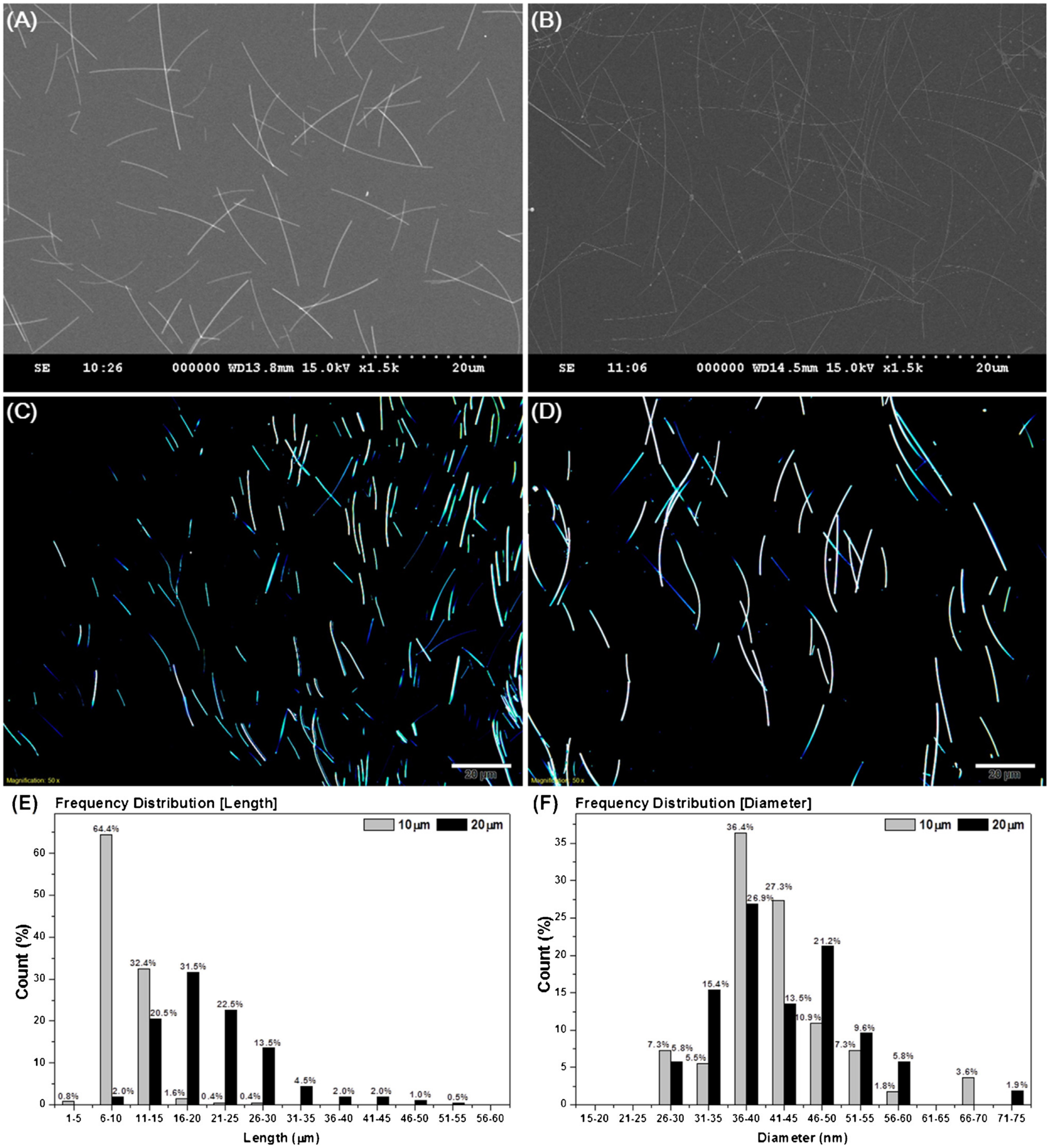


**Fig. 1.** Characterization of 10- and 20-μm silver nanowires (AgNWs). Scanning-electron micrographs of 10-μm AgNWs (A) and 20-μm AgNWs (B) High-resolution microscope images of 10-μm AgNWs (C) and 20-μm AgNWs (D) Scale bar, 20 μm. Frequency distribution of length and diameter of 10-μm (E) and 20-μm (F) AgNWs.

Nanomaterials are also known to have indirect effects on organisms via their transfer to high trophic levels through the food web and consequent accumulation. Several studies have explored the trophic transfer of various nanomaterials, including quantum dots (QD), gold nanoparticles (AuNPs), titanium dioxide nanoparticles ($TiO_2$NPs), and polystyrene nanoparticles, in freshwater food chains (Bouldin et al., 2008; Renault et al., 2008; Zhu et al., 2010; Cedervall et al., 2012). Additionally, other studies have investigated their transfer via more complex systems of 2–3 food chains (Holbrook et al., 2008; Lewinski et al., 2011; Cedervall et al., 2012; Lee and An, 2014) and calculated their bioconcentration and biomagnification factors (Holbrook et al., 2008; Zhu et al., 2010; Mielke et al., 2013; Yeo and Nam, 2013; Dalai et al., 2014; Pakrashi et al., 2014; Lee and An, 2014) in a variety of trophic interactions such as alga-water flea, water flea-fish (Bouldin et al., 2008; Zhu et al., 2010; Lewinski et al., 2011; Cedervall et al., 2012; Gilroy et al., 2014; McTeer et al., 2014; Pakrashi et al., 2014; Skjolding et al., 2014; Lee and An, 2014), ciliate-rotifer (Holbrook et al., 2008), alga-bivalve (Renault et al., 2008), diatom-snail (Croteau et al., 2011), and alga-amphipod (Jackson et al., 2012).

Despite the abundance of available information regarding the transfer of nanomaterials through aquatic food webs, this process

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