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REVIEW

A review of the ecotoxicological effects of nanowires

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Abstract We briefly reviewed the existing research on the ecotoxicity of nanowires and suggested directions for further study. Nanowires are technological innovations that can benefit humans. However, it is important to consider the effects of nanowires on the environment. Only a few studies have reported acute and chronic ecological toxicity of nanowires on aquatic and terrestrial organisms, and limited research papers have reported antibacterial effects of nanowires. It is assumed that nanowires have a toxic mechanism similar to that of nanoparticles or ions, but the mechanism remains unknown because so little research has been conducted on the ecological toxicity of nanowires. More in-depth assessments of the chronic toxicity, bioavailability, cytotoxicity, and genotoxicity of nanowires on various species are needed.

Keywords Nanowires · Nanowire array · One-dimensional nanomaterials · Ecotoxicity · Toxicity

Introduction

Nanomaterials are widely used in the electronic, chemical, and medical industries and play a role in the global development of industry. The properties of nanomaterials differ from those of bulk materials and ions. Nanomaterials have various shapes, including nanospheres, nanorods, nanotubes, nanowires, nanodisk, nanofilms, nanofilaments, and nanoplates. They may be zero dimensional (0D), one dimensional (1D), two dimensional (2D), or three dimensional (3D). Nanospheres, nanoparticles, and quantum dots are defined as 0D nanomaterials. Nanowires, nanorods, nanotubes, nanobelts, and nanoribbons are 1D nanomaterials, whereas nanowire arrays, nanowire fabrics, nanodisks, nanofilms, nanoplates, nanosheets, nanowalls, nanofibers, and nanoprisms are 2D nanomaterials (An et al. 2009; Shingubara et al. 1997; Tiwari et al. 2012; Zhang et al. 2009).

By definition, a nanowire is a wire with a nanoscale diameter. Nanowires have potential applications in the biomedical and clinical industries (Brammer et al. 2009; Johansson et al. 2010; Nataraj et al. 2014; Singh et al. 2013), as antibacterial agents (Fellahi et al. 2013; Holtz et al. 2010, 2012; Wu et al. 2011), as sensors of metals (Luo et al. 2009; Mu et al. 2007), in solar cells (Garnett and Yang 2010; Hamilton et al. 2009), in the removal of metals (Jia et al. 2013; Youssef and Malhat 2014), and in energy storage (Chen et al. 2009; Tiwari et al. 2012).

The number of uses of nanowires continues to increase, and a number of toxicological studies on human or mammalian cells have confirmed the biocompatibility and biosafety of various nanowires. These studies examined silver nanowires (Kim and Shin 2014; Schinwald et al. 2012; Stoehr et al. 2011; Verma et al. 2012), zinc oxide nanowires (Müller et al. 2010; Li et al. 2008), titanium dioxide nanowires (Hamilton et al. 2009; Park et al. 2013), nickel nanowires (Poland et al. 2012), magnetic nanowires (Safi et al. 2011), silica nanowires (Adili et al. 2008; Alexander et al. 2012; Julien et al. 2010; Xie et al. 2014; Zhang et al. 2012), iron nanowires (Song et al. 2010), tellurium nanowires (Song et al. 2011), and cerium nanowire (Ji et al. 2012).

Because nanowires can be released into the environment, ecotoxicological studies of nanowires have also been conducted. In this brief review, reports of the

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ecotoxicological effects of nanowires and nanowire arrays were collected and intensively reviewed, and the need for future studies to assess the safety of nanowires was examined. To the best of our knowledge, this is the first review of the ecotoxicological effects of nanowires and is highly relevant to ecological risk assessments of nanomaterials by industries and governments.

Toxicity of nanowires to aquatic and sediment biota

There have been numerous reports of nanoparticles' ecotoxicity on aquatic and sediment biota, but few ecotoxicological studies of nanowires have been conducted (Table 1). The toxicity of nanowires has been evaluated in two fish species (*Danio rerio* and *Oncorhynchus mykiss*), three crustacean species (*Hyalella azteca*, *Daphnia similis*, and *Daphnia magna*), and three sediment-dwelling invertebrates (*Lumbriculus variegatus*, *Lampsilis siliquoidea*, and *Chironomus dilutus*).

Mwangi et al. (2011) assessed the toxicity of silicon carbide nanowires (SiC NWs) to sediment-dwelling invertebrates exposed through water or sediment, using *H. azteca*, *L. variegatus*, *L. siliquoidea*, and *C. dilutus*. When *H. azteca* were exposed to sonicated or nonsonicated SiC NWs in hard water and sediment, no significant mortality was observed due to nonsonicated SiC NWs, but 0 % survival was observed after exposure to the sonicated SiC NWs. Mwangi et al. (2011) assumed that sonication broke the SiC NWs into particles and caused surface hydroxylation that had fatal effects on *H. azteca*. Otherwise, sediment-dwelling worms, mussels, and insects that were exposed only to sonicated SiC NWs were not affected, even by exposure for 96 h at a concentration of 1.0 g/L. This result indicated that sediment-dwelling worms, mussels, and insects showed less sensitivity than amphipod *H. azteca* to the sonicated SiC NWs. Mwangi et al. (2011) also found that layering of SiC NWs on the sediment surface induced more growth inhibition of *H. azteca* than did mixing SiC NWs in the sediment because layered SiC NWs were more available to the *H. azteca* than mixed SiC NWs in the sediment.

In tests of nanowires' effects on fish embryos, silica nanowires (Si NWs) (Nelson et al. 2010) and silver nanowires (Ag NWs) (George et al. 2012) were fatal to zebrafish embryos (*D. rerio*). According to Nelson et al. (2010), Si NWs caused mortality of developing *D. rerio* embryos at an LD50 of 110 pg/g and also induced birth defects (teratogenicity) by interfering with neurulation and disrupting the expression of *sonic hedgehog*. George et al. (2012) investigated the different shapes of Ag nanomaterials (nanospheres, nanowires, and nanoplates), using *D. rerio* embryos and *O. mykiss* gill cells in vitro. In the embryo test, Ag NWs did not affect hatching rate (48 hpf at 5 µg/mL), but mortality was induced at 120 hpf at 5 µg/mL. In the in vitro test, Ag NWs did not reduce cell viability but did cause potential oxidative stress.

Ag NWs were potentially acutely toxic to *Daphnia*. Artal et al. (2013) studied the role of silver and vanadium release in the toxicity of silver vanadate nanowires ($AgVO_3$ NWs) to *D. similis*, using $AgVO_3$ NWs decorated with Ag NPs, and estimated the EC50-48 h at 1 µg/L. Scanlan et al. (2013) investigated the acute toxicity of different-sized and coated Ag NWs on *D. magna* and concluded that short and SiO_2-coated AgNWs were more toxic to this species than were long or PVP-coated AgNWs. However, no correlation between gene expression and LC50 was apparent.

Toxicity of nanowires to terrestrial biota

To date, only one article has reported the impacts of nanowires on terrestrial organisms (Table 2). Adolfsson et al. (2013) investigated the effects of bare and hafnium oxide-coated gallium phosphide nanowires (GaP NWs) on the lifespan, fertility, rate of gene mutation, and immune response of the fruit fly, *Drosophila melanogaster*, using a food-exposure approach. There were no changes of gene expression or immune responses when *D. melanogaster* larvae were exposed, until the third instar (88–99 h). In addition, GaP NWs did not significantly affect lifespan or fecundity of adult flies, except for a slight decrease in fertility at day 29, although the test subjects were exposed chronically for 49–58 days. Adolfsson et al. (2013) detected a slight decrease in fecundity when adult flies were exposed to hafnium oxide-coated GaP NWs. In order to determine the acute and chronic ecotoxicity of nanowires to terrestrial organisms, many further studies using various terrestrial species and exposure through soil tests are needed.

Toxicity of nanowires to bacteria

As shown in Table 3, 18 studies have examined the antibacterial properties of nanowires. The antibacterial effects of Ag-based NWs (Holtz et al. 2010, 2012; Jiang et al. 2012; Liu et al. 2013; Schoen et al. 2010; Singh et al. 2014; Tamboli et al. 2012; Tang et al. 2014; Visnapuu et al. 2013; Zhang et al. 2007), Si NWs (Lv et al. 2010), ZnO NWs (Kılıç and Omay 2014; Wu et al. 2011), MgO NWs (Al-Hazmi et al. 2012), Mn_2O_3 NWs (Hassan et al. 2012), Ti-based NWs (Nataraj et al. 2014; Shang et al. 2010), and CdO NWs (Kumar and Ojha 2013) were evaluated. Test subjects included the pathogenic bacteria species *Escherichia coli*, *Bacillus subtilis*, *Staphylococcus aureus*,

Table 1 An overview of nanotoxicological studies regarding the effects of nanowires on aquatic and sediment species

	Ref.	Nanowire (NW)	NW diameter (nm)	NW length (μm)	Test species	Exposure media	Test duration	Observation	Endpoint	Endpoint value
Fish	Nelson et al. (2010)	Si NW	55 (SEM)[a]	2.1	*D. rerio*	Sterile, nuclease-free water	132 hpf	Si NWs showed mortal and teratogenic effects on developing *D. rerio* embryos	Mortality, teratogenesis	LD50 = 110 pg/g
	George et al. (2012)	Ag NW	60 (TEM)[b]	50–20	*O. mykiss*	L-15 medium	24 h	Ag NW did not induce cell death, but induced superoxide production	Cell viability, oxidative stress	–
					D. rerio	Holtfreter's medium	120 hpf	Ag NW did not affect hatching rate (48 hpf at 5 μg/mL), but induced mortality (120 hpf at 5 μg/mL)	Survival, hatching, morphological defects	–
Crustacean	Mwangi et al. (2011)	SiC NW	40–800 (DLS)[c]	5–65	*H. azteca*	Hard water	24 h	No significant mortality was observed after nonsonicated SiC NW exposure, but 0 % survival was observed after sonicated SiC NW exposure	Survival	–
						Sediment	10 days	Sonicated SiC NW inhibited the amphipods' growth	Survival, growth	–
	Artal et al. (2013)	AgNPs-$AgVO_3$ NW[d]	–	–	*D. similis*	OECD M4	48 h	EC50-48 h of silver vanadate nanowires decorated with silver nanoparticles were observed at 1 μg/L	Immobilization	EC50 = 1 μg/L
	Scanlan et al. (2013)	Ag NW-PVP[e]	65	20	*D. magna*	COMBO	24 h	Short and SiO_2-coated Ag NWs were more toxic to daphnia than were long or PVP-coated Ag NWs. LC50 was not correlated with gene expression.	Survival, gene expression, accumulation	LC50 = 234 μg/L
		Ag NW-SiO_2[f]	65	20						LC50 = 522 μg/L
		Ag NW-PVP[e]	30	2						LC50 = 421 μg/L
		Ag NW-SiO_2[f]	30	2						LC50 = 155 μg/L
		Ag NW-PVP[e]	65	20		EPA				LC50 = 415 μg/L
		Ag NW-SiO_2[f]	65	20						LC50 = 227 μg/L
		Ag NW-PVP[e]	30	2						LC50 = 261 μg/L
		Ag NW-SiO_2[f]	30	2						LC50 = 3.6 μg/L
Mussel	Mwangi et al. (2011)	SiC NW	40–800 (DLS)[c]	5–65	*L. siliquoidea*	Hard water	96 h	Sonicated SiC NW was not toxic to mussels	Survival	–
Worm	Mwangi et al. (2011)	SiC NW	40–800 (DLS)[c]	5–65	*L. variegatus*	Hard water	96 h	Sonicated SiC NW was not toxic to oligochaetes	Survival	–
Insect	Mwangi et al. (2011)	SiC NW	40–800 (DLS)[c]	5–65	*C. dilutus*	Hard water	96 h	Sonicated SiC NW was not toxic to midges	Survival	–

[a] Transmission electron microscope, [b] scanning electron microscope, [c] dynamic light scattering, [d] silver nanoparticle-decorated $AgVO_3$ NWs, [e] PVP-coated Ag NWs, [f] SiO_2-coated Ag NWs

Table 2 An overview of nanotoxicological studies examining the effects of nanowires on terrestrial species

	Ref.	Nanowire (NW)	NW diameter (nm)	NW length (μm)	Test species	Exposure media	Test duration	Observation	Endpoint	Endpoint value
Insect	Adolfsson et al. (2013)	GaP NW[a]	80 (particle analyzer)	4	Fruit fly (*Drosophila melanogaster*)	Food exposure (yeast)	49 days 88–96 h	No adverse effects of GaP NWs were observed	Life span, fertility, gene mutation, immune response	–

Enterococcus faecalis, *Salmonella enterica*, *Candida albicans*, and *Aspergillus niger*. All studies shown in Table 3 assessed growth inhibition, and some studies also calculated the maximal inhibitory concentration (MIC) and minimal bactericidal concentration (MBC) of tested nanowires by performing MIC and MBC tests. Although test methods, tested nanowires, exposure concentration, exposure duration, medium, and tested bacteria strains varied, the research studies demonstrated the potential antibacterial properties of each nanowire. However, it is not well confirmed that nanowires have adverse effects on environmentally important and beneficial microbial communities when nanowires are released into the environment.

Antibacterial properties of nanowire arrays and fabrics

A range of types of nanowires have applications as nanowire arrays and fabrics. Table 4 presents the literature evaluating the ecotoxicity of nanowire arrays or fabrics. These studies investigated the antibacterial properties of nanowire arrays or fabrics to eliminate pathogenic bacteria species in antibacterial applications. Unfortunately, the ecotoxicological effects of nanowire arrays and fabrics on aquatic and terrestrial organisms have not been studied.

Three studies tested the effects of Si NW arrays, and one study tested the effects of ZnO NW arrays on organisms. Wang et al. (2007) reported that well-defined, less-oriented or randomly oriented ZnO NW arrays reduce the survival of *E. coli* after a 90-min exposure. Wang et al. (2011) confirmed that Si NW arrays modified with quaternized poly (2-(dimethylamino ethyl) methacrylate) (pDMAEMA) led to high bacterial adhesion and cell death of *E. coli* after an 18-h exposure. Fellahi et al. (2013) reported that Si NW arrays decorated with AgNPs or CuNPs showed antibacterial activity after a 24-h exposure and induced leakage of sugars and proteins from the cell membranes of bacteria, reducing cell viability. Li et al. (2014) observed antibacterial effects of Si NW arrays on *E. coli*, *B. subtilis*, and *S. aureus*.

Davoudi et al. (2014) synthesized silver-7,7,8,8-tetracyanoquinodimethane nanowire fabrics and confirmed that they have potential antimicrobial applications by observing antibacterial effects on *E. coli* and *Staphylococcus albus*.

Toxic mechanism of nanowires

Demonstrations of the toxicity level and the relative contributions of dissolved ions and nanomaterials are important in order to understand the toxic mechanisms in nanotoxicology. However, studies have reported different results for the relative contribution to toxicity of dissolved ions from nanowires and from nanomaterials themselves. Davoudi et al. (2014) observed that Ag NW fabrics possessed antibacterial properties. Visnapuu et al. (2013) reported that dissolved Ag ions from Ag NWs caused toxic effects on microorganisms, after conducting an analysis with AAS. Jiang et al. (2012) reported that released Ag ions from Ag-doped trimolybdate nanowires caused toxic effects and produced reactive oxygen species (ROS) in bacteria.

In the studies reporting bactericidal properties of nanowires, the way in which nanowires reduced cell viability was confirmed. Nataraj et al. (2014) observed that TiO_2 NWs disrupted the membrane potential of *S. aureus*. Fellahi et al. (2013) confirmed that Si NWs induced the leakage of sugars and proteins from the cell membrane. Al-Hazmi et al. (2012) reported that MgO NWs broke bacterial cell membranes and damaged *E. coli* cells. Mn_2O_3 NWs were also observed to disrupt *E. coli* cell membranes and to cause leakage of intracellular contents in a study that used TEM analysis (Hassan et al. 2012). According to Zhang et al. (2007), the effects of Ag NWs on bacteria may be similar to those of Ag, which has strong antibacterial activity and inactivates bacterial proteins by interacting with the -SH group in the bacterial protein molecules. Likewise, Wang et al. (2007) speculated that the toxic mechanism of ZnO NW arrays affecting bacteria was similar to the toxic mechanism of ZnO NPs, which are broadly known to generate ROS.

Table 3 An overview of studies with nanowires on antibacterial properties

Ref.	Nanowire (NW)	NW diameter (nm)	NW length	Test species	Exposure media	Test duration (h)	Observation	Endpoint	Endpoint value
Zhang et al. (2007)	Ag NW composite	–	–	*Escherichia coli*	–	–	Ag NW/mesoporous silica composites showed highly inhibitory effects on bacteria	Growth inhibition	MIC = 90–300 ppm
Holtz et al. (2010)	AgNPs–$AgVO_3$ NW	60 (TEM)[a]	Micron	*Staphylococcus aureus* (3 strains)	Mueller–Hinton broth	18	MIC[a] of $AgVO_3$NW decorated with AgNPs was 6.75–12.5 μg/mL or 3.4–6.75 μg/mL	Growth inhibition	MIC = 6.75–12.5 or 3.4–6.75 μg/mL
Schoen et al. (2010)	Ag	40–100 (SEM)[b]	10 μm	*Escherichia coli*	Agar plate	Overnight	Bacteria were not observed in the Ag NW-treated filters	Growth inhibition	–
Shang et al. (2010)	AgNPs-titanate NW	80–100 (SEM)[b]	>100 μm	*Escherichia coli*	MacConkey sorbitol agar	18–24	Bactericidal activities of AgNPs on titanate nanowire and titanate nanowire were reduced	Growth inhibition	–
	Titanate NW								
Lv et al. (2010)	AgNPs–Si NW	–	–	*Escherichia coli* *Bacillus subtilis*	LB agar plate (Modified Kirby-Bauer technique)	24	SiNW decorated with AgNPs demonstrated long-term antibacterial activity	Growth inhibition	–
				Escherichia coli *Bacillus subtilis*	LB media (Bacterial kinetic test)	48		Bacterial kinetic	–
				Escherichia coli *Bacillus subtilis*	LB broth (MIC test)	36		Growth inhibition	–
				Escherichia coli	Sterile saline solution (airborne bacteria test)	Overnight		Growth inhibition	–
Wu et al. (2011)	Pure ZnO NW	~40 (TEM)[a]	–	*Escherichia coli*	Lactose broth agar	24	Pure or Na-doped ZnO NWs exhibited the antibacterial activity	Growth inhibition	MIC = 30 μg/mL
	0.6 mol% Na–ZnO NW								MIC = 10 μg/mL
	1.2 mol% Na–ZnO NW								MIC = 1 μg/mL
Al-Hazmi et al. (2012)	MgO NW	6 (SEM)[b]	10 μm	*Escherichia coli* *Bacillus subtilis*	Nutrient agar media	24	Increasing antibacterial activity was observed with increasing MgO NW concentration	Growth inhibition	–
				Escherichia coli *Bacillus subtilis*	Nutrient broth media	24		Growth inhibition	–
Hassan et al. (2012)	Mn_2O_3 NW	70–80 (SEM)[b]	–	*Escherichia coli*	TSV broth	24	Mn_2O_3 NW induced cytotoxicity and showed bactericidal potential	Growth inhibition	–
					Nutrient agar plate	72		Cell viability, morphological alterations, cell damage	

Table 3 continued

Ref.	Nanowire (NW)	NW diameter (nm)	NW length	Test species	Exposure media	Test duration (h)	Observation	Endpoint	Endpoint value
Holtz et al. (2012)	AgNPs–$AgVO_3$ NW	20–60 (TEM)[a]	Micron	*Enterococcus faecalis* (two strains)	Mueller–Hinton medium	48	MIC of $AgVO_3$ NWs decorated with AgNPs was lower than that of oxacillin (a commonly used antibiotic). MBC[b] of $AgVO_3$NW demonstrated antibacterial activity	Growth inhibition	MIC = 5.00 µg/mL, MBC > 69 µg/mL
				Escherichia coli					MIC = 1.00 µg/mL, MBC = 1.00 µg/mL
				Staphylococcus aureus (three strains)					MIC = 3.15 µg/mL, MBC = 3.15 or 6.25 µg/mL
				Salmonella enterica					MIC = 3.15 µg/mL, MBC = 3.15 µg/mL
Jiang et al. (2012)	Ag-trimolybdate nanowire	10–100 (SEM)[b]	~100 µm	*Escherichia coli*	Martin medium	10	Ag-doped trimolybdate nanowire affected bacterial activity	Growth inhibition	–
				Staphylococcus aureus					
				Candida albicans					
				Aspergillus niger					
Tamboli et al. (2012)	Ag–PANI	50–70 (SEM)[b]	–	*Bacillus subtilis*	Mueller–Hinton medium	24	MIC and MBC values of Ag-polyaniline nanocomposites were same as 25 µg/mL	Growth inhibition	MIC = 25 µg/mL, MBC = 25 µg/mL
Kumar and Ojha (2013)	CdO NW	~15 (TEM)[a]	~1 µm	*Escherichia coli*	Mueller–Hinton agar medium	Overnight	CdO NWs showed antimicrobial activity. *B. subtilis* were more affected than *E. coli*	Growth inhibition	–
				Bacillus subtilis					–
Liu et al. (2013)	Ag NW	47 (SEM)[b]	–	*Escherichia coli*	Nutrient agar medium	24	AgNWs showed antimicrobial activity. *B. subtilis* were more affected than *S. aureus* or *E. coli*	Growth inhibition	–
				Bacillus subtilis					–
				Staphylococcus aureus					–
Visnapuu et al. (2013)	Ag NW	100	6.1 µm	*Escherichia coli*	LB broth	4	Dissoluted Ag from Ag NWs was toxic to bacteria	Bioluminescent	EC50 = 0.42 mg/L
Kiliç and Omay (2014)	ZnO NW	60 (TEM)[a]	10 µm	*Staphylococcus aureus*	LB agar media	18	ZnO NW-coated film showed antibacterial activity	Growth inhibition	–
Nataraj et al. (2014)	TiO_2 NW	50–150 (SEM)[b]	–	*Staphylococcus aureus*	LB broth	96	TiO_2 NWs affected bacterial growth and membrane potential more than did TiO_2 nanoparticles	Growth inhibition, change in membrane potential	–

Table 3 continued

Ref.	Nanowire (NW)	NW diameter (nm)	NW length	Test species	Exposure media	Test duration (h)	Observation	Endpoint	Endpoint value
Singh et al. (2014)	Ag/AgVO$_3$ NW	~80 (TEM)[a]	~3 μm (SEM)	*Escherichia coli*	Mueller-Hilton broth	18	The MIC values of Ag/AgVO3 NWs were lower than ciprofloxacin (reference antibiotic agent)	Growth inhibition	MIC = 1 μg/mL
				Bacillus subtilis					MIC = 5 μg/mL
				Escherichia coli		48			MBC = 0.5 μg/mL
				Bacillus subtilis					MBC = 5 μg/mL
Tang et al. (2014)	Ag NW	60–140 (SEM)[b]	–	*Escherichia coli*	Nutrient agar	24	Ag NWs had bactericidal efficiency	Growth inhibition	–
				Staphylococcus aureus					–

MIC minimum inhibitory concentration, *MBC* minimal bactericidal concentration

[a] Transmission electron microscope, [b] scanning electron microscope

However, there is limited information regarding the toxic mechanism of nanowires in aquatic and terrestrial organisms. Ag NWs generated superoxide in *O. mykiss* gill cells and affected the survival rates of *D. rerio* embryos (George et al. 2012). Si NWs also killed developing *D. rerio* and induced teratogenicity by interfering with neurulation and disrupting the expression of *sonic hedgehog* (Nelson et al. 2010). Because limited ecological toxicity tests have been conducted, the toxic mechanisms of nanowires are still under investigation and require further research.

Conclusion

It is important to understand whether nanomaterials, including nanowires, pose a risk to the environment, but so far, there are limited studies of this area. Only 24 ecotoxicological studies of nanowires have been reported since 2007, and most of them were conducted since 2010. Many more studies of ecotoxicology have been conducted on nanoparticles than on nanowires. The most studied nanowire was Ag NW (15 citations), followed by Si NW (2 citations), ZnO NW (2 citations), TiO_2 NW (1 citation), MgO NW (1 citation), Mn_2O_3 NW (1 citation), CdO NW (1 citation), and GaP NW (1 citation). A number of studies have focused on the antibacterial capabilities of nanowires to evaluate their potential applicability in medicine; however, the impacts of nanowires on environmentally important microbial communities and ecosystems are poorly understood. Additionally, few studies confirmed modes of toxicity of nanowires or contribution of ion toxicity dissolved from nanowires.

The following types of studies are needed in order to assess the ecological effects of nanowires:

- Ecological toxicity data regarding aquatic and terrestrial organisms. The existing literature is insufficient and consists mainly of studies of microbial organisms. Reliable endpoint values (LCx, ECx, LOEC, NOEC) are also needed.
- Genotoxicity and cytotoxicity of nanowires. The mechanism of toxicity to organisms, particularly terrestrial ones, is not clear. Understanding genotoxic effects and cellular effects can provide clues to the mechanism.
- Bioavailability of nanowires to organisms (e.g., bioaccumulation studies, depuration studies). It is important to assess the fate of nanowires in the environment.
- Chronic effects of nanowires. Very limited results were reported for this topic.

Although we are challenging to confirm the risk of nanomaterials including nanowires, there are limited

Table 4 Studies of the antibacterial properties of nanowire arrays and fabrics

Ref.	Nanowire arrays	NW diameter (nm)	NW length (µm)	Test species	Exposure media	Test duration	Observation	Endpoint	Endpoint value
Wang et al. (2007)	ZnO NW array	150 (SEM)[a]	–	*Escherichia coli*	LB media	90 min	Antibacterial properties of ZnO nanoarrays were observed	Survival	–
				Staphylococcus aureus	–	90 min			–
Wang et al. (2011)	Si NW array	~100 (SEM)[a]	~25	*Escherichia coli*	PBS (Bacterial adhesion)	10 min	Si NW array modified with quarternized pDMAEMA[b] inhibited bacterial activity	Bacteria adhesion	–
					LB agar plate (Antibacterial activity)	18 h		Growth inhibition	–
					LB media (viability)	18 h		Viability	–
Fellahi et al. (2013)	Si NW array	20–100 (SEM)[a]	5	*Escherichia coli*	Nutrient agar medium	24 h	Si NW arrays decorated with AgNPs or CuNPs showed antibacterial activity and induced leakage of sugars and proteins from the cell membranes of bacteria	Growth inhibition, growth kinetics, membrane leakage	–
	AgNP-Si NW array[c]	–							–
	CuNP-Si NW array[d]	–							–
Davoudi et al. (2014)	Ag/AgTCNQ NW fabrics[e]	50–300 (SEM)[a]	100	*Escherichia coli*	Nutrient broth	10–60 min	AgTCNQ NWs fabrics showed antibacterial activity against bacteria	Cell viability	–
				Staphylococcus albus					–
Li et al. (2014)	Si NW array	100–250 (SEM)[a]	8	*Escherichia coli*	PBS	60 min	Functionalized three-dimensional NW substrate eliminated bacterial activity	Cell viability, growth, morphology	–
				Bacillus subtilis					–
				Staphylococcus aureus					–

[a] Scanning electron microscope, [b] poly (2-(dimethylamino ethyl) methacrylate), [c] silver nanoparticle-coated silica nanowire array, [d] copper nanoparticle-coated silica nanowire array, [e] silver-7,7,8,8-tetracyanoquinodimethane nanowire fabrics

ecotoxicological results to protect the ecosystem. We suggest further ecotoxicological testing of nanowires be conducted in order to protect the environment before nanowires are widely commercialized.

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