Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22908

122 (2018) 284–292
August

Ecotoxicological effects of typical pollutants on algae in aquatic environment: a review

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Received 12 April 2018; Accepted 3 August 2018

ABSTRACT

The ecotoxicological effects of heavy metals, organic compounds, and artificial nanomaterials on algae growth were reviewed in the this paper, from which we conclude that the pollutants had stimulating effects on the growth of algae within the low concentration range, and the number of algal cells increased in the short term. This phenomenon occurred during early exposure to the low concentration group and in the middle and late stages of exposure to the medium concentration group. However, algae growth was highly inhibited, and the algal cells were stressed in the high concentration group. Toxic mechanisms of pollutants on algae were explained through the influencing perspectives of enzyme activity, photosynthesis, cell structure, and metabolism of algae. The present review will be certain to provide guidance for the biological evaluation of water pollution.

Keywords: Algae; Heavy metals; Organic compounds; Artificial nanomaterials; Ecological toxicology

1. Introduction

With the rapid development of industry and technology, various pollutants continue to enter into the water bodies, thereby participating in the biochemical cycle of water and affecting the eco-environmental security of water. Research regarding the harmful effect of pollutants on aquatic ecosystems, the physiological and ecological responses of aquatic organisms to pollutants was usually used to indicate the degree of water pollution [1].

Algae are the primary producers in aquatic ecosystems and play a key role in material cycles and energy flow [2]. There has been a rapid growth of pollution of aquatic environment, mostly from anthropogenic sources, and chief sources of the aquatic pollution are either direct dumping of industrial effluents or spills or indirect, via leaching or runoff [3]. The pollutants that enter into water via various channels are first to have an impact on the primary producers. Therefore, algae are often used as a crucial indicator for monitoring changes of water environments. In addition, due to the characteristics of small individuals for the algae, that is rapid reproduction and sensitivity to poison, the impacts of the tested substances on the generation and populations of such individuals can be determined in a short period, and

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Presented at the 3rd International Conference on Recent Advancements in Chemical, Environmental and Energy Engineering, 15–16 February, Chennai, India, 2018.

the poisoning situation at the cellular level can be directly observed [4]. Therefore, ecotoxicology research of algae has received increasing attention [5].

To date, the main pollutants used in the research of algal ecotoxicology are heavy metals or organic compounds. Related studies mainly focused on the damage of toxicants to algae in water bodies and its effect on different levels of life, such as cells, organs, individuals, populations, and communities [4,6]. However, as the progress in science and technology, increasingly more nanomaterials are entering into water environments. Because of their special physical and chemical properties, these materials pose a threat to the ecological environment and human health. Therefore, the harmful effect of heavy metals, organic compounds, and nanomaterials on algae from the perspective of algae growth, enzyme activity, photosynthesis, cell structure, and metabolism was summarized to provide guidance for the biological evaluation of water pollution.

2. Ecotoxicological effects of heavy metals

2.1. Single heavy metals

Algae growth requires not only macroelements such as C, H, O, N, P, S, K, Ca, and Mg, but also microelements such as Cu, Fe, and Mn. However, excessive heavy metals have harmful effect on the growth of algae. Low concentrations of heavy metals promoted the growth of algae, whereas high concentrations inhibited algae growth [7].

2.1.1. Effective concentration of heavy metals on algae

The half maximal effective concentration (EC_{50}) was determined by the algal growth inhibition test to confirm the harmful effect of heavy metals on algae. Among the previous ecotoxicology experiment regarding Cyanophyta, Chlorophyta, Bacillariophyta, Chrysophyta, and Pyrrophyta, Chlorophyta was the frequently used test species in large part. The heavy metals used are mainly Cu, Cr, Cd, Zn, Pb, and Mn. For Cu, *Phaeodactylum tricornutum* in Bacillariophyta is the most sensitive type of algae, and *Phormidium* sp. in Cyanophyta has the strongest tolerance. For Cd, *Anabaena flos-aquae* in Cyanophyta is the most sensitive alga, and *Karenia mikimotoi* in Pyrrophyta was the most tolerant. The EC_{50} of various types of algae subject to single heavy metal stress is summarized in Table 1.

2.1.2. Influence of heavy metals on algae photosynthesis

Different algae under heavy metal stress yield different accumulation patterns of heavy metals, which affect the biosynthesis of photosynthetic pigments to different degrees [30]. Accumulated heavy metals in plants interact with the photosynthetic mechanisms and produce a series of toxic effects such as photo-oxidation injuries. In particular, heavy metals alter the function of chloroplast membrane and affect the formation of the components of optoelectronic transport chains, which in turn affect the photoreaction stage in photosynthesis [31]. Experiments have shown that treating *Scenedesmus obliquus* with a high concentration of copper ions (Cu^{2+}, 20–100 μmol/L) restrains its photosynthesis, hinders the electron transport of photosystem II (PSII), and inhibits the photosynthetic rate and light use efficiency. However, the results were no significant with a low concentration of Cu^{2+} [31]. Nevertheless, the effects of some heavy metals on photosynthesis were determined by affecting the membrane permeability, interfering with the distribution of ions, and inhibiting the enzyme activity [32]. Excessive Cu^{2+} hindered the formation and stability of chlorophyll by forming coordination compounds, thereby reducing the content of chlorophyll [32,33]. Nevertheless, the effects of some heavy metals on photosynthesis were reflected in disturbing the membrane permeability, interfering with the distribution of ions, and inhibiting the enzyme activity [34].

2.1.3. Influence of heavy metals on algae enzyme activity

Generally, heavy metals have two mechanisms that affect enzyme activity: one is the hampering of the absorption and utilization of metal ions as cofactors of enzymes by heavy metals, and the other is the forming of chelates by the combination of heavy metals and enzyme proteins, resulting in changes in the structure and configuration of the enzyme, which influence enzyme activity [35]. Experiments have shown that a low concentration of cadmium ions (Cd^{2+}) promotes the activity of peroxidase (POD) in *Microcystis aeruginosa*, whereas a high concentration of Cd^{2+} has a strong toxic effect on the same substance. In one experiment, algae cells were severely damaged and protein synthesis decreased, which reduced the activity of the antioxidant enzyme system. With an increase in the concentration of Cd^{2+}, the activity of catalase (CAT) in *M. aeruginosa* and *S. obliquus* cells presented a trend of initially rising then falling, both peaking when the concentration of Cd^{2+} was 0.15 mg/L, which was significantly different from that of the control group [36,37]. Studies on the toxic effects of Cd^{2+} on *Selenastrum capricornutum* have concluded that the activity of deoxyribonuclease, dehydrogenases, and POD is strongly affected by an increase in Cd^{2+} concentration within the nonlethal concentration range (0.25–1.5 mg/L $CdCl_2$). Meanwhile, cell division, the photosynthetic oxygen release rate, and cell membrane permeability were strongly inhibited [38].

2.1.4. Influence of heavy metals on the cell structure and metabolism of algae

Elevated concentration of Cu^{2+} could inhibit the growth and reproduction of algae, possibly because the permeability of the protoplasmic membrane was affected and the potassium was lost from the cell [39]. The metabolism of various compounds in normal algae cells would be affected to some extent and even some metabolic processes could be interrupted [39]. When copper ions surpass the toxic level, the structure of algal cells is damaged. Exposed to a high concentration of Cu^{2+}, *Chlorella* and *Scenedesmus* cells were deformed into those containing coarse particles. When transferred to a medium without Cu^{2+}, the large cells divided and were restored to their original morphology [40]. In addition, Cu^{2+} caused *Chlorella* and *Ankistrodesmus* sp. to form into giant cells and *Anacystis nidulansso* to become spherical, and thus completely different from its regular shape [40]. The ultrastructures of the chloroplasts, mitochondria, and cell nuclei of

Table 1
EC_{50} of various heavy metals on algae

Algae species		Heavy metal	EC_{50} (mg/L)			References
			48h-EC_{50}	72h-EC_{50}	96h-EC_{50}	
Bacillariophyta	*Phaeodactylum tricornutum*	Cd^{2+}			0.120	[8]
		Cu^{2+}		0.531 ± 0.037	0.017	[6,8]
		Zn^{2+}			0.363	[8]
		Pb^{2+}			0.468	[8]
	*Nitzschi*a sp.	Cr^{6+}		0.260		[9]
	Nitzschia closterium	Cr^{6+}		0.278		[10]
	Skeletonema costatum	Cu^{2+}		0.546 ± 0.068		[6]
	Chaetoceros muelleri	Cu^{2+}		0.326		[11]
		Cd^{2+}		0.386		[11]
Chrysophyta	*Dicrateria* sp.	Sn^{4+}		0.00058–0.00077		[12]
	Isochrysis galbana	Cu^{2+}	0.555		1.881	[13]
		Cd^{2+}	0.986		6.268	[13]
		Zn^{2+}	5.209		18.732	[13]
	*Isochrysis zhanjianggenesi*s sp. nov	Pb^{2+}			9.030	[14]
	Isochrysis galbana			8.830		[14]
	Monochrysis lutheri	Cd^{2+}		75		[15]
		Cu^{2+}		15		[15]
	Pavlova viridis	Cd^{2+}			7.777	[16]
					1.469	[17]
		Cu^{2+}			1.192	[16,17]
					7.079	[17]
		Zn^{2+}			3.548	[16]
					25.700	[17]
		Pb^{2+}			33.010	[16]
Cyanophyta	*Anabaena flos-aquae*	Cd^{2+}			0.0135	[18]
	Microcystis aeruginosa	Cu^{2+}			0.083	[19]
	Plectonema radiosum	Cu^{2+}			318	[20]
	Phormidium sp.	Cu^{2+}			339	[20]
	Spirulina platensis	Pb^{2+}		11.46		[21]
		Cr^{6+}			11.74	[22]
	Synechococcus sp.	Cr^{6+}			6.5	[22]
	Spirulina maxima	Cr^{6+}			11.16	[22]
Pyrrophyta	*Karenia mikimotoi*	Cu^{2+}	1.866		6.268	[14,23]
		Cd^{2+}	5.405		13.134	[14,23]
		Zn^{2+}	13.134		18.732	[14,23]
	Prorocentrum minimum	Cu^{2+}	0.514		1.125	[14,23]
		Cd^{2+}	0.835		4.376	[14,23]
		Zn^{2+}	4.376		7.976	[14,23]

(*Continued*)

Table 1 (*Continued*)

Algae species		Heavy metal	EC_{50} (mg/L)			References
			48h-EC_{50}	72h-EC_{50}	96h-EC_{50}	
Chlorophyta	*Chlorella autotrophica*	La^{3+}			4.055	[24]
	Chlorella ellipsoidea	Cu^{2+}		1.452		[25]
		Zn^{2+}		61.988		[25]
		Ni^{2+}		6.908		[25]
		Cd^{2+}		10.512		[25]
	Chlorella pyrenoidosa	Cu^{2+}			0.067	[10,25]
		Zn^{2+}			0.473	[10]
		Mn^{2+}			0.017	[10]
		Cr^{6+}			4.96	[22]
	Chlorella sp.	Pb^{2+}			>20	[14]
		Cd^{2+}		26.992		[26]
		Cu^{2+}	1.11	18.496	0.77	[26,27]
		Zn^{2+}	1.1	20.020	0.85	[26,27]
		Hg^{2+}	0.002		0.005	[26,27]
	Closterium lunula	Cu^{2+}			0.200	[10]
					0.202	[28]
		Zn^{2+}			0.038	[10]
		Mn^{2+}			0.013	[10]
	Platymonas helgolandica var. tsingtaoensis	Cu^{2+}	1.041		0.671	[13]
		Zn^{2+}	23.274		5.773	[13]
		Cd^{2+}	16.25		1.188	[13]
	Tetraselmis tetrethele	Cd^{2+}		53.436		[26]
		Cu^{2+}		13.504		[26]
		Zn^{2+}		49.010		[26]
	Platymonas subcordifomis	Cd^{2+}		300		[11]
		Cu^{2+}		1.703		[11]
	Selenastrum capricornutum	Cr^{6+}			12.43	[22]
	Scenedesmus quadricauda	Cr^{6+}			20.89	[22]
	Scenedesmus obliquus	Cu^{2+}	0.029		0.050	[29]
		Zn^{2+}	0.230		0.567	[29]
		Pb^{2+}	0.122		0.759	[29]
		Mn^{2+}	20.95		29.22	[29]

Platymonas subcordiformis were destroyed to varying degrees after Cu^{2+} poisoning, and the pyrenoids disintegrated [41]. Cd^{2+} caused the outer layer of *Selenastrum minutum* cells to become detached. The chloroplast volume decreased, and the structure was changed to the appearance of a large vacuole with the enlargement of inclusion particles in cells [45]. After Ni^{2+} caused toxicity to *Ankistrodesmus*, the cytoderm thickened and deformed, evident plasmolysis appeared in the cytoplasm, and the laminated structure of the thylakoid was destroyed [42].

2.2. Coexistent heavy metals

Many heavy metal elements coexist in natural water. Algae are often affected by combinations of various heavy metals that influence their growth and reproduction and ultimately affect their physiological and biochemical functions. The combinations of heavy metals can be divided into four types: antagonism, synergism, addition, and sensitization [43]. Liu [29] indicated that when the heavy metal ions of Cu^{2+}, Zn^{2+}, Pb^{2+}, and Mn^{2+} were pairwise combined, the toxic effect of their

combination was different, embodied as synergistic or antagonistic. Regarding pairs of metals, different combinations yielded different effects. The effects of single combinations might also change over time [29]. The interactions between Cr^{2+}, Ni^{2+}, and Pd^{2+} on *Nostoc muscorum* were investigated, and the effects of the combinations of Cr^{2+} + Ni^{2+} and Cr^{2+} + Pb^{2+} on the growth of algae were antagonistic. However, the antagonistic effect of Cr^{2+} + Ni^{2+} was maintained only for 72 h and was followed by a synergistic effect. The effects of combining Ni^{2+} and Pb^{2+} were not considerably different from the individual effects of Ni^{2+} and Pb^{2+} [44]

3. Ecotoxicological effects of organic compounds on algae

3.1. Effective concentration of organic compounds on algae

Organic compounds such as phenolic compounds, pesticides, plasticizers, and surfactants have toxical impacts on algae. The plasticizer dibutyl phthalate (DBP) had highly harmful effect on *S. obliquus*, with a 96h-EC_{50} of 0.021 mg/L. The resistance of *S. obliquus* to phenol was strong, with a 96h-EC_{50} of 341 mg/L. *Chlorella* sp. was highly tolerant of lambda-cyhalothrin, with a 96h-EC_{50} of 105.71 mg/L (Table 2).

3.2. Influence of organic compounds on the photosynthesis of algae

Three kinds of pharmaceuticals and personal care products (PPCPs), namely erythromycin lactobionate (ETM), diclofenac sodium (DCF), and polyoxyethylene nonylphenol ethers ($NPEO_{10}$) could significantly decrease the growth rate and inhibit the PSII function of *S. obliquus*. ETM was the most toxic, followed by $NPEO_{10}$ and DCF. Analysis of the chlorophyll fluorescence rapid response curve revealed that ETM deactivated the PSII reaction center and inhibited the donor and receptor sides of the PSII reaction center. However, the other two PPCPs mainly inhibited the electron transport process after the electron transport chain QA^- [54]. Two antibiotics, namely enrofloxacin and erythromycin thiocyanate, inhibited the growth of *M. aeruginosa* and hinder the photosynthesis process of *M. aeruginosa* and the synthesis of soluble proteins [55].

3.3. Influence of organic compounds on the enzyme activity of algae

Previous studies have shown that the effects of surfactants on the density of *S. obliquus* and POD activity are mainly due to the adsorption of quaternary ammonium salt on the cell's phospholipid bilayer membrane, which causes damage to the membrane structure and loss of function and damage to the chlorophyll and enzyme structure, affecting algae cell photosynthesis and enzyme activity and ultimately leading to cell death [56]. A study of the melamine toxicity of *S. obliquus* showed that the superoxide dismutase (SOD) activities of *S. obliquus* were initially stimulated and then inhibited with an increase in melamine concentration, reaching a peak at 200 mg/L and decreasing by 43.6% in 750 mg/L compared with the control group. The contents of malondialdehyde (MDA) and soluble sugar were inhibited significantly under moderate and high concentrations of melamine. The effects of melamine on the lipid peroxidation product MDA of *S. obliquus* and soluble sugar were consistent and decreased with an increase in melamine concentration [57].

3.4. Influence of organic compounds on the cell structure and chlorophyll content of algae

The plasticizer DBP could reduce the content of chlorophyll a, destroy the cell inclusions, prevent algal cell division, and mainly affect the number of cells and species for natural algae [58]. With an increase in the concentration of polychlorinated biphenyls (PCBs), the total quantity of *Chlorella pyrenoidosa* and *S. obliquus* cells showed a decreasing trend, and the growth of algae was inhibited. A low concentration (<0.4 ng/mL) exerted a minor effect on stimulating growth. At a high concentration (>10 ng/mL), algal cells grew slowly, even for negative growth, and the algae were yellow or colorless. Under a microscope, the chloroplast disintegrated, the cell structure was incomplete, and the percentage of broken cell debris was higher. The growth of algae was completely halted at 50 ng/mL [46]. With increase in the concentration of ionic liquid 1-butyl-3-methlimidazolium chloride ([BMIM]Cl), the inhibition rate of *S. obliquus* growth increased, leading to a decrease in chlorophyll content. Exposed to 80 mg/L (BMIM) Cl solution, the ultrastructure of *S. obliquus* cells showed the phenomenon of plasmolysis, chloroplast lamellae rupture, and mitochondrial ridge reduction [59,60].

4. Ecotoxicological effects of artificial nanomaterials on algae

With the development of nanotechnology, nanomaterials gradually start to affect people's lives and increasingly enter into the environment. Because of their unique special physical and chemical properties, nanomaterials pose a threat to the ecological environment and human health [61]. Studies of the environmental effects and biological safety of artificial nanomaterials have focused on nanometer oxides, carbon nanomaterials, and nanocrystalline metals because of the wide range of applications and high risks environmental exposure. Nanomaterials have a certain effect on the growth status, cell structure, photosynthetic pigment content, protein content, and enzyme activity of algae. The harmful effect is also related to the properties, morphology, size, and solubility of nanomaterials [62]. The harmful effect and the analyses and conclusions regarding such materials were displayed in Table 3.

4.1. Nanometer oxide

Research have demonstrated that nano-oxide can inhibit the growth of algae to block the synthesis of photosynthetic pigments and proteins, thereby halting antioxidant enzyme activity and exerting a great impact on the growth and physiology of algae. When exposed to nano-TiO_2, the growth of *S. obliquus* and synthesis of chlorophyll a were promoted at a low concentration (<5 mg/L) of nano-TiO_2. However, such growth and synthesis were inhibited at a high concentration (>10 mg/L) [67]. Nano-TiO_2 has an inhibitory effect on the growth of *Gymnodinium breve* with 72h-EC_{50} of 9.7 mg/L. The influence of nano-TiO_2 on the oxidation system and free oxygen radicals may be related to its algal inhibition

Table 2
EC_{50} for various organic compounds on algae

Algae species	Organic compounds		EC_{50}(mg/L)			References
			48h-EC_{50} (mg/L)	72h-EC_{50} (mg/L)	96h-EC_{50} (mg/L)	
Scenedesmus obliquus	Phenols	Phenol			341	[45]
		o-Chlorophenol			85	[45]
		2,4-Dichloro-phenol			25	[45]
		Pentachlorophe-nol			1.50	[45]
		PCBs			21.62	[46]
		1,2,4-Trichloro-benzene			341	[47]
	Plasticizer	DBP	15.49	1.95	2.21	[48]
	Surfactants	Cetyl trimethyl ammonium bromide	1.8	2.4		[23]
		Linear alkylbenzene sulfonates	142.3	153.3		[23]
		TX-100	171.2	164.7		[23]
	Pesticide	Cypermethrin			45.75;112.45 (acetone),112.81 (ethyl acetate)	[49,50]
		Methamidophos			12.31	[49]
		Acephate	667.7	523.0		[51]
		Atrazine	0.03	0.022	0.021	[52]
Chlorella sp.	Pesticide	Lambda-cyhalo-thrin			105.71	[53]
		Parathion	3.6	7	6	[24]
		Dichlorvos	15.4	15.8	11.7	[24]
		Methamidophos	76.7	92.3	104.5	[24]
		Omethoate	77	90	57	[24]
		Phoxim	1.5	1.205	1.12	[24]
		Isocarbophos	9.3	13.4	6.5	[24]
		Metribuzin			0.021	[11]
	Pesticide	Puma super			0.937	[11]
		Alachlor			5.54	[11]
Chlorella pyrenoidosa	Phenols	PCBs			7.73	[46]
Microcystis aeruginosa	Drug	Enrofloxacin	0.085			[11]
		Erythromycin	0.048			[11]

mechanism [65]. Hollow glass microspheres of coated nano-TiO_2 could inhibit the photosynthesis of cyanobacteria and diatom, thereby showing potential applications of nanomaterials for inhibiting algal overgrowth. Nano-ZnO significantly promoted the growth of *S. obliquus* at a low concentration (5 mg/L) and gradually inhibited growth at an increased concentration. At its highest concentration (50 mg/L), the cytochrome content was reduced and the protein content and antioxidant enzyme activity decreased significantly, causing significant cell oxidative damage [5].

4.2. Nanocrystalline metals

Four nanometal additives, namely Cu, Al, Zn, and Ti, had certain levels of biological toxicity for luminous bacteria, and biotoxicity increased with their addition. In addition, biological toxicity was evidently enhanced by the synergistic effect of metal when combined with a multimetal additive [68]. Two kinds of nano-Cu powders with different grain sizes, inhibited the survival of *S. obliquus*, *Chlorella ellipsoide*, and *Tetraselmis tetrethele* to different degrees, and the inhibition

Table 3
Toxicological effects of artificial nanomaterials on algae

Nanomaterials	Algae	Effect	Determination index	References
Nano-CeO_2	*Scenedesmus obliquus*	Promoted in the low concentration inhibited in the middle concentration, obviously inhibited in the high concentration.	Photosynthetic pigment, SOD, MDA	[63]
Nano-TiO_2	*S. obliquus*	Promoted in the low concentration, inhibited in the high concentration, SOD activity firstly increased and decreased then, MDA content gradually increased.	Cell density, chlorophyll a, SOD, MDA	[64]
	Gymnodinium breve	72h-EC_{50} is 9.7mg/L, SOD activity seriously decreased, CAT activity, hydroxyl radical and hyper anion obviously increased.	SOD, CAT, MDA	[65]
	Chlorella sp.	In the concentration of 0.01–500mg/L, without obvious inhibition.	EC_{50}	[5]
Nano-NiO_2	*Scenedesmus quadricauda* *Chlorella* sp. *Selenastrum capricornutum*	The content of chlorophyll a, antioxidant activity and protein decreased, the content of MDA increased, stronger resistance to nano-NiO_2	Growth status, chlorophyll a, protein, MDA, SOD, CAT	[66]
SWCNTs	*Chlorella* sp.	Obvious inhibition, its 96h-EC_{50} is 261.5mg/L.	EC_{50}	[5]
CNTs	*Chlorella* sp.	The toxicities of CNTs in the following order: SWCNTs > short SWCNTs > DWCNTs > short DWCNTs	Photosynthetic pigments, soluble protein, SOD, POD	[67]

of several microalgae of nano-Cu powder was considerably heavier than that of ordinary Cu powder with the same content or even ten or one hundred times as much [69]. A total of 1 mg/L nano-Ag particles significantly inhibited the growth of *M. aeruginosa*, with an inhibition rate of 87% [70]. Fe was a crucial factor in the synthesis of chlorophyll, the effect of nano-Fe on algae was no significant, and the appropriate amount of Fe facilitated the growth of algae.

4.3. Carbon nanomaterials

As representatives of carbon nanomaterials, fullerene, metallofullerene, and carbon nanotubes (CNTs) are playing an increasingly irreplaceable and crucial role in human production and life. They also exert certain ecological impact. CNTs inhibited the growth of *S. obliquus.* First, the harmful effect of CNTs on *S. obliquus* was connected to the number of graphene layers. In particular, single-walled carbon nanotubes (SWCNTs) had higher toxicities than double-walled carbon nanotubes (DWCNTs). The toxicity of CNTs was associated with their length. The long nanotubes were more toxic than the short ones [71]. Research on the harmful effect of three types of multivalent carbon nanotubes (MWCNTs) on *Chlorella* sp. showed that MWCNTs strongly inhibited algae growth under light or dark conditions and their inhibitory effects were dose dependent. Algal toxicity of MWCNTs was mainly explained by the three major mechanisms of shading effect, physical interaction, and oxidative damage [63].

5. Conclusions and prospects

Typical pollutants such as heavy metals, organic compounds, and artificial nanomaterials had stimulating effects on the growth of algae in the low concentration range, and the growth of algae was in a highly inhibited in the high concentration. The toxic mechanisms of different pollutants of algae are summarized in terms of three aspects: photosynthesis, enzyme activity, and metabolism and cell structure. Heavy metals and organic compounds can inhibit the growth of algae by blocking the synthesis of photosynthetic pigments and membrane permeability, affecting the activity of PSII reaction center or inhibit the electron transport process of photoelectron transfer chain, destroying the structure and function of algal cell membrane and damage the ultrastructure of algal cells thereby halting antioxidant enzyme activity and exerting a great impact on the growth and physiology of alga. Nanomaterials can inhibit the growth of algae by release of a large number of reactive oxygen species on algal cells to produce oxidative stress and inhibit algal cell growth, contacting with the physical damage of algae cells

and result in algal cytoplasmic wall separation, cracking, and agglomeration with algal cells, affecting the normal swimming of the cells and their absorption of light energy, nutrients, and gas exchange.

Although previous research has been demonstrated that typical pollutants have certain impact on algae growth, enzyme activity, photosynthesis, cell structure, and metabolism. Further in-depth research work can be carried out from the following aspects with regard to ecotoxicological effects of typical pollutants on algae. For example, there are various indexes, such as algae growth characteristics, chlorophyll fluorescence characteristics, enzyme activity, etc. that can be used for characterization of toxic effect on algae. However, this index system in previous is not systematic enough and a widely accepted testing system, and standard have not been established. Therefore, the establishment of a systematic and standard ecotoxicological testing system is one of the problems to be solved.

In terms of toxicity test method, most previous research only carried out acute toxicity experiments, and few conducted long-term continuous observation of algae toxicity and carried out chronic toxicity experiments. Although algae have the characteristics of fast growth and short growth cycle, whether it can find other test ways and methods for long-term serial chronic toxicity is a direction that can be explored in the future. Single or two of the same pollutants (such as the combined toxic effect of two heavy metals) were often used for investigating ecotoxicological effects of typical pollutants on algae. However, there are many kinds of pollutants in the actual polluted water and ecotoxicological effects are often caused by multiple pollutants. For example, whether there is interaction between nanomaterials and existing pollutants (heavy metals, persistent organic pollutants, etc.) in the water ecosystem, and the extent of such interaction, is of great significance to further research.

Acknowledgments

This research was financially supported by the National Key Research and Development Program (Grant No. 2016YFC0502201); the Special Scientific Research Foundation of Public Welfare Profession of the Ministry of Water Resources, China (Grant No. 201401042); and the special fund for basic scientific research business of central public research institutes (Grant No. CKSF2017026/SH, CKSF2017045+SH, CKSF2016270/SH).

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