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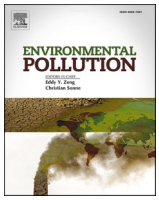

Review

Combined effects of microplastics and pharmaceutical and personal care products on algae: A critical review☆

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ABSTRACT

Microplastics (MPs) and pharmaceuticals and personal care products (PPCPs) are ubiquitous in aquatic environments. Algae play an important role in aquatic environments. Thus, it is important to study the response of algae to combined exposure of MPs and PPCPs. Here, we review the effects of MPs and PPCPs on algae. First, the individual effects of MPs and PPCPs on algae were summarized. Second, the combined effects of MPs and PPCPs on algae were systematically analyzed. (1) Antagonism: ① when the MPs are too large to enter the algal cells, the adsorption of PPCPs onto MPs results in decreased the contact of MPs and PPCPs with algae; ② PPCPs and MPs have opposing actions on the same biological target; ③ MPs increase the activity of metabolic enzymes in algae, thus promoting the PPCP degradation. (2) Synergy: ① when the MPs are small enough to enter algal cells, the adsorption of PPCPs on MPs promotes the entry of PPCPs; ② when MPs are negatively charged, the adsorption of positively charged PPCPs by MPs decreases the electrostatic repulsion, increasing the interaction between algae and MPs; ③ complementary modes of action between MPs and PPCPs show combined effects on the same biological target. Third, the relative importance of the factors that impact the combined effects are evaluated using the random forest model decreased in the following order: PPCP types > algal species > MP size > MP concentration > MP types > exposure time. Finally, future directions for the combined effects of MPs and PPCPs are proposed, which will facilitate a better understanding of the environmental fate and risks of both MPs and PPCPs.

1. Introduction

Plastics have long been utilized because of their abundance, affordability, lightness, strength, and adaptability (Bhagat et al., 2021). Plastic manufacturing has expanded tremendously over the past four decades, with the quantity growing from approximately 60 million tons in 1980 to 390 million metric tons in 2021 (Martín et al., 2022). Plastics may progressively break down into small fragments because of environmental and biological actions (Mao et al., 2020). Microplastics (MPs) are plastic pieces that are smaller than 5 mm in diameter (Mammo et al., 2020). Owing to their high production, persistence, exploitation, and disposal, MPs are frequently observed in aquatic environments (Table S1), including rivers (McCormick et al., 2014; Sanchez et al., 2014), lakes (Su et al., 2016; Wang et al., 2017) and ocean (Hu et al., 2022; Huang et al., 2021a; Su et al., 2022).

Pharmaceuticals and personal care products (PPCPs), comprise a range of compounds, such as prescription and non-prescription medications, veterinary pharmaceuticals and illicit drugs (Singh and Li, 2012). PPCPs have been detected in sediments and surface waters worldwide (Table S2). Trace amounts of PPCPs in aquatic environments can cause severe ecotoxicological issues and pose major risks to ecosystems and organisms (Zhou et al., 2020). Studies have revealed that PPCPs, which are residues in water, can accumulate in living organisms, potentially causing endocrine disruption (Czarny et al., 2019), drug resistance development (Wilkinson et al., 2017), primary productivity inhibition (Mackay et al., 2010), and long-term damage to aquatic

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ecosystems (Li et al., 2010).

MPs and several other contaminants share similar exposure routes, such as home sewage discharged from cities, wastewater and residues from chemical factories (Arshad and Zafar, 2020), mining and smelting industries (Nkoom et al., 2018). Additionally, the small size, large specific surface area, and diverse surface properties of MPs enable them to adsorb a variety of contaminants, making them be a vector for contaminant dissemination and altering their environmental behaviors (Du et al., 2021). Therefore, a complete understanding of their combined effects is required for ecological risk assessment.

Algae are vital to the aquatic environment. They play crucial roles in the functioning and structure of ecosystems, serving as essential primary producers in aquatic food chains (Xin et al., 2021). These organisms are involved in the nitrogen cycle and the synthesis of organic carbon (Chen et al., 2020). They are also sensitive to environmental stress, particularly to toxic substances present in the environment (Li et al., 2022; Zhang et al., 2017). Therefore, to assess the ecological risk of MPs and PPCPs, it is critical to investigate the response of algae to MPs and PPCPs. The effects of MPs on algae have been widely reported (Nguyen et al., 2023; Yang et al., 2024b), and mainly include heterogeneous-aggregation, photosynthetic inhibition and oxidative stress. The effects of PPCPs on algae have also been extensively studied (Fu et al., 2017; Mao et al., 2021; Miazek and Brozek-Pluska, 2019). For instance, Lee et al. (2024) reviewed the effects of triclosan on algae, including cellular structureal damage and photosynthetic inhibition. Miazek and Brozek-Pluska (2019) revealed the effects of sulphonamides on algae, including membrane destruction, genotoxicity and photosynthetic inhibition. The interaction between MPs and PPCPs can alter their respective environmental behaviors, thereby influencing their harmful effects (Ding et al., 2018). For example, polystyrene (PS) reduces the harmful effects of the triphenyltin (TPT) on algae. The 50% growth rate inhibition (IC_{50}) of TPT for algae was found to be 0.56 μg/L and increased to 0.85 μg/L with PS (Greven et al., 2016; Li et al., 2020a). Conversely, Prata et al. (2018) argued that PS enhances the harmful effects of procainamide. The 50% effective concentration (EC_{50}) of procainamide for algae was 143 mg/L, which decreased to 31 mg/L after PS treatment. Algae are diverse in terms of their species and structure, resulting in varying sensitivities to contaminants. Variations in the size and type of MPs and PPCPs will result in multiple interactions between coexisting pollutants and algae, influencing the combined effects of MPs and PPCPs on algae. Therefore, it is necessary to systematically analyze the combined effect and mechanism of MPs and PPCPs on algae.

Therefore, the objectives of this review were to (1) summarize the effects of MPs and PPCPs on algae respectively; (2) discuss the action mechanism of the MPs - PPCPs complex on algae elaborately; (3) examine the impact factors for the combined effects of MPs and PPCPs on algae using a random forest (RF) model; (4) identify the knowledge gaps in comprehending the combined impacts of MPs and PPCPs on algae.

2. Materials and methods

2.1. Literature screening

We performed a literature search on Web of Science, Scopus, and Elsevier and selected all the search results before June 2024. The following are keywords and their combinations used to identify appropriate studies: (microplastic OR nanoplastic OR plastic debris OR plastic polymers OR plastic particle) AND (PPCPs OR antibiotic OR pharmaceuticals OR herbicide OR drug OR biocide) AND (algae OR microalgae OR phytoplankton) AND (combined effect OR combined exposure OR joint OR mixture). A total of 160 articles were initially retrieved. To obtain the most representative literature and the most reliable data sets, all collected papers were further screened based on the following criteria.

(1) The study included the combined effects of MPs and PPCPs on algae;
(2) The data were related to the inhibition rate, PPCP types, algal species, MP size, MP types, MP concentration and exposure time;
(3) The units of all articles were uniform and could be converted to uniform units;
(4) The results were supported by reliable statistical analyses.

Based on the criteria mentioned above, 21 articles were selected for the RF model (Fig. S1, Table S3).

2.2. Data extraction

In this study, the data were extracted from the literature. The inhibition rate, PPCP types, MP size, MP types, MP concentration, algae species and exposure time were recorded for each study. Data were classified in the following manner.

(1) PPCP types: sulfamethoxazole (SMX), triclosan (TCS), ibuprofen (IBU), azithromycin (AZI), clarithromycin (CLA), ciprofloxacin (CIP), tetracycline (TC), triphenyltin chloride (TPTCl), triphenyltin (TPT), dibutyl phthalate (DBP) and chloramphenicol (CAP);
( ) 2Algal species: M. *aeruginosa*, S. *costatum*, C. *pyrenoidosa*, C. *reinhardtii*, *Anabaena* sp., *C. meneghiniana*, *Synechocystis* sp., *T. chuii*, *Dictyosphaerium* sp., *Chlorella* sp., C. *fluminea*;
(3) MPs size: <0.1, 0.1–0.5 μm, 0.5–1 μm, 1–5 μm, 5–10 μm and >10 μm;
(4) MPs types: polystyrene (PS), polyvinyl chloride (PVC), polyamide (PA), polyethylene (PE), polypropylene (PP), polyethylene glycol terephthalate (PET), and polylactic acid (PLA);
(5) MPs concentration: 0.5 mg/L, 5 mg/L, 10 mg/L, 20 mg/L, 50 mg/L, 100 mg/L;
(6) Exposure time: 72 h, 96 h and 168 h.

2.3. Analysis of the RF model

RF is a machine learning method based on the decision tree, which has high prediction accuracy, high tolerance to outliers, and a good fitting effect (Mahmoudzadeh et al., 2020). This method involves randomly dividing the data into a training set and a testing set, which is predicted by constructing a model consisting of multiple decision trees. When a prediction is made for a sample, the final result is then derived by counting the prediction results for each tree in the RF model (Kong et al., 2021). In addition, the RF model quantifies the relative importance of the influencing factors to reveal the deep relationships and underlying mechanisms within (Mao et al., 2024a).

In RF, each tree is built by a bootstrap sample from the overall data and the best partitions among a subset of attributes that are randomly selected for each node. The RF algorithm performs the predictions by aggregating the predictions of each tree, using the majority vote for classification and the average for regression (Ban et al., 2018). To measure the relative importance of factors, the percent increase in the RF mean square error (MSE) was calculated using the R package random forest. RF, as a data-driven model, includes two important parameters: Ntree, the number of trees in the forest; and Mtry, the number of attributes randomly selected for a subset at each node. The values of ntree and mtry for each study were adjusted to obtain the best predictive accuracy (Yang et al., 2024a). During tree construction, approximately 63% of the raw data were used to build the trees in each RF bootstrap sample, and the remaining out-of-bag data (not in the bootstrap samples) were used to validate the performance of the model. To measure the performance, the correlation coefficient (R^2) and root mean square error (RMSE) between the predictions and observations were calculated as predictive accuracy metrics (Li et al., 2023b). Training datasets (from 20% to 100%) were randomly selected from original datasets, with ten

repetitions, and the R^2 and RMSE were then calculated.

In this study, the RF model was employed to analyzed the relative importance of factors affecting the combined effects of MPS and PPCPs on algae. Theoretical framework and method route of the research process are detailed in the Supplementary Materials (Fig. S1). From the available research, we extracted data on inhibition rate of algae, MP size, MP concentration, MP types, PPCP types, algal species and exposure time. The inhibition rate of algae was used as the output variables, and the remaining variables were used as input variables. These data are provided in the Supplementary File (Table S3). By adjusting the values of Mtry and Ntree to optimize the model, the final set of the two random forest model hyperparameters were Ntree = 3 and Mtry = 480. The RF model was constructed using Python 3.10 and plot the relative importance of the influencing factors was plotted using Origin 2018.

3. Effects of MPs and PPCPs on algae

3.1. Effects of MPs on algae

The primary manifestation of the effects of MPs on algae is their restriction of algal growth, as shown in Table S4. The inhibition of the algal growth increased with increasing MP concentrations. The widely acknowledged toxic mechanisms primarily involved heterogeneous-aggregation, photosynthetic inhibition and oxidative stress (Lagarde et al., 2016; Sjollema et al., 2016; Yang et al., 2024b).

3.1.1. Heterogeneous aggregation

Heterogeneous aggregation of algal cells and MPs has been frequently observed in previous studies (Huang et al., 2021b). The formation of heterogeneous aggregates is attributed to the secretion of extracellular polymeric substances (EPS) on the cell surface as a self-defense response to exogenous stimuli (Long et al., 2017). The formation of heterogeneous aggregates leads to the following outcomes: First, it results in close contact that easily causes mechanical damage to algal cells, e.g., cell wall damage and cell fragmentation, thereby compromising the integrity of the cell structure (Baudrimont et al., 2020). The adsorption of smaller-sized MPs on the surface of algae could cause membrane transport disorders and harm the cell structure, e.g., cytoplasmic separation, vacuolization, and distortion of the cell membrane structure (Lagarde et al., 2016). Second, the secreted EPS create a new layer on the surface of the MPs, known as the eco-corona, altering the surface charge and aggregation kinetics of the MPs and serving as a form of physical shielding (Su et al., 2023; Yang et al., 2021). Third, it hinders the entry and exit of substances into the cell, thereby blocking the exchange of substances and energy inside and outside the cell. For instance, the entry of oxygen and carbon dioxide into cells decreases and the elimination of harmful substances metabolized in cells becomes challenging, ultimately leading to algal cell death (Su et al., 2023).

3.1.2. Photosynthetic inhibition

Photosynthesis is a critical physiological mechanism for algal growth and reproduction. Previous studies have shown that the secondary KEGG pathway classification most frequently mentioned in algae affected by MPs was photosynthesis (Gao et al., 2023; Jin et al., 2022; Yang et al., 2021). Algal photosynthesis involves processes like light absorption, electron transfer, photosynthetic phosphorylation, and carbon assimilation (Gao et al., 2023; Jin et al., 2022). The partial size of MPs could have a shadowing impact on the water column, thereby diminishing light exposure to algae and thus affecting photosynthesis processes (Bhattacharya et al., 2010; Wang et al., 2017). In addition, MPs can decrease photosynthetic gene expression, resulting in a decrease in chlorophyll concentration (Zhang et al., 2019). Furthermore, by altering the electron transport chains, the photosystem II reaction center, and the electron donor site, MPs can hinder photosynthesis (Bhattacharya et al., 2010; Mao et al., 2018).

3.1.3. Oxidative stress

MPs induce oxidative stress in algal cells, causing an increase in the reactive oxygen species (ROS) content. Increased intracellular ROS levels result in lipid peroxidation and cell membrane structure disruption. These effects affect normal growth and metabolic processes, including the exchange of materials and energy inside and outside the cell (Mao et al., 2024b). The antioxidant systems of algae counteract MP-induced oxidative stress. When ROS damage algal cells, antioxidant activities are enhanced to eliminate ROS and maintain a dynamic balance to ensure normal algal growth (Venâncio et al., 2019). Additionally, algal cells reduce oxidative damage by upregulating arginine and proline metabolism. Arginine inhibits the increase in ROS and delays lipid peroxidation in cell membranes, whereas proline regulates cell membrane stability and balances osmotic pressure under exogenous stress (Fan et al., 2022).

3.2. Effects of PPCPs on algae

As shown in Table S5, PPCPs significantly inhibit algal growth. Widely acknowledged toxic mechanisms include membrane destruction, cell structure damage, genotoxicity, and photosynthetic inhibition.

3.2.1. Membrane destruction

PPCPs have been widely reported to cause algal cell death by damaging algal cell membranes. Some PPCPs specifically attack their membranes. Aminoglycosides interfere with bacterial protein synthesis by binding to the 30S subunit of the bacterial ribosome (Seoane et al., 2014), thereby causing the production of mistranslated proteins and, consequently, membrane damage and death. Furthermore, certain PPCPs target specific molecules (lipids). Exposure to specific PPCPs may either boost or impede the synthesis of certain biomolecules. For example, triclosan can affect the algal gene *FabI* and inhibit fatty acid synthesis (Lee et al., 2024). Carbamazepine can expand algal phospholipid bilayers, disturb membrane functions, and inhibit Na^+ and K^+ permeation (Suwalsky et al., 2006). Additionally, PPCPs can cause lipid peroxidation and damage the cell membranes of algae. The presence of organic components in PPCPs increases the ROS levels and can cause lipid peroxidation. Lipid peroxidation can, in turn, exacerbate oxidative stress through lipid-derived radical production, damaging algal cell membranes.

3.2.2. Cell structure damage

Morphology and ultrastructure can be used to observe and assess the interactions and sensitivity of algae to pollutants (Villain et al., 2016). The structural integrity of cells is essential for the successful execution of cellular activities (Guo et al., 2020), and PPCPs can impede the synthesis and metabolism of algae by disrupting the integrity of their plasmid structure. A previous study reported that the morphology and ultrastructure of *Phaeodactylum tricornutum* cells were seriously damaged by fungicides, with the pyrenoid and nucleus becoming severely blurred, the thylakoid and mitochondria disappearing, and large vacuoles appearing in the cells (Xin et al., 2017). Vacuoles are frequent reactions of algal cells to stress and have been detected in *Scenedesmus obliquus* under ibuprofen (IBU) stress (Xie et al., 2022). Damage to the thylakoid indicates that the photosynthetic enzyme system is compromised, thus preventing energy conversion and consequently inhibiting photosynthesis. This was further corroborated by the toxicity of tetracycline in freshwater green algae (Atugoda et al., 2021).

3.2.3. Genotoxicity

Several PPCPs are genotoxic compounds that can affect the mutation frequency and cause gene pool alterations. These alterations can change the population size and affect ecosystem sustainability (Ćesen et al., 2016). If algae are persistently exposed to genotoxic compounds, cracking may occur during normal homeostasis, causing irreversible damage and even death (Torres et al., 2008). Cyclophosphamide (CP),

carboxy-cyclophosphamide (CPCOOH) and their mixture caused gene pool alterations on *Pseudokirchneriella subcapitata* and *Synechococcus leopoliensis* (Česen et al., 2016). Quinolones interfere with DNA replication by inhibiting DNA gyrase and topoisomerase IV in *Prokaryota* (Aderemi et al., 2018). Sulfonamides inhibit dihydropteroate synthase, thereby interfering with the conversion of p-aminobenzoic acid to folic acid and consequently inhibiting DNA synthesis (Eguchi et al., 2004). Trimethoprim inhibits dihydrofolate reductase, thereby interfering with the conversion of dihydrofolic acid to tetrahydrofolic acid and consequently inhibiting DNA synthesis (Xiong et al., 2017).

3.2.4. Photosynthetic inhibition

Evidence has demonstrated that PPCPs can inhibit the rate of algal growth due to their effects on photosynthesis (Lee et al., 2024). First, PPCPs can impair the regular process of photosynthesis by reducing light absorption potential of algae. Chlorophyll is a key measure of photosynthetic potential (Villain et al., 2016). Previous studies have shown that PPCPs exposure can cause a reduction in the chlorophyll *a* content in algae, which impair the photosynthetic potential of algae (Zheng et al., 2021). Second, PPCPs can reduce the photosynthesis-related gene expression, which may reduce the amount of energy required for carbon assimilation (Gomaa et al., 2021). Third, the abnormal expression of *rbcL, psaB, and psbD* in diatoms exposed to a fungicide causes a reduction in photosynthetic electron transmission (Xin et al., 2017). Furthermore, transcriptomics were utilized to evaluate the toxicity of triclosan to *Raphidocelis subcapitata* (Fu et al., 2017), demonstrating that electron transport are sensitive targets for the effect of TCS on *R. subcapitata* photosynthesis system and further induced the generation of ROS.

4. Combined exposure to MPs and PPCPs

4.1. Growth effect

The interactions between MPs and PPCPs have been widely studied. Studies have shown that MPs can act as carriers by adsorbing hydrophobic pollutants (Wang et al., 2021), which is crucial to their combined effects. The adsorption mechanisms include hydrophobic interactions, hydrogen-bonding interactions, electrostatic interactions, partitioning, van der Waals interactions, π−π interactions, and microporous filling mechanisms (He et al., 2022; Wang et al., 2021). The interaction of MPs with PPCPs varies, modifying the compound effects on algae. Table 1 provides an overview of the toxicity of mixtures of MPs and PPCPs on algae, including antagonism and synergism. On the one hand, MPs and PPCPs have a synergistic effect on algae. Prata et al. (2018) reported that the *Tetraselmis chuii* growth rate was not significantly affected by MPs alone. However, the EC_{50} of doxycycline for *T. chuii* was 22 mg/L, which decreased to 11 mg/L with PS, demonstrating that the inhibitory effect of PS and doxycycline on algal growth was greater than the sum of their individual effects, inducing a synergistic effect. Qu et al. (2022) found that exposure to methamphetamine and PS caused more growth inhibition (42%) to algae than the sum of their individual effects, revealing the synergistic effects of MTA and PS on algae. However, several studies have shown antagonistic effects of MPs and PPCPs on algae. For example, PS and IBU showed antagonistic effects against *C. pyrenoidosa*. (Wang et al., 2020). The EC_{50} of IBU for *C. pyrenoidosa* was found to be 45.7 mg/L and increased to 63.9 mg/L with PS, revealing that the inhibitory impact of PS and IBU on algal growth was less than the sum of their individual effects. The complex interactions between MPs and PPCPs have different effects on the growth of algae. Therefore, the modes of action and influencing factors of MPs and PPCPs on algae were further studied in the following aspects.

4.2. Influence mechanism

4.2.1. Antagonism

The antagonistic effects of PPCPs and MPs on algae can be attributed to the following factors. First, when the MPs are too large to enter algal cells, the adsorption of PPCPs by MPs leads to their antagonistic effect on algae (Hao et al., 2022). The adsorption of hydrophobic contaminants by MPs enhances their hydrophobicity, thereby promoting their aggregation (Li et al., 2023a; Thiagarajan et al., 2022). MPs can aggregate and be deposited in aquatic environments, which reduces the likelihood of contact with algae (Wang et al., 2020). Furthermore, the adsorption of PPCPs by MPs decreases the intake of PPCPs by algal cells, decreasing the direct toxicity of PPCPs (Cao et al., 2022; Ru et al., 2022). In addition, combined exposure to MPs and PPCPs promotes the secretion of EPS by algal cells (Qu et al., 2020). EPS can facilitate the accumulation of MPs around algal cells (Li et al., 2022). EPS and MPs around algal cells can form a barrier and reduce PPCPs exposure (Castro-Castellon et al., 2022; Li et al., 2020a). Second, certain PPCPs and MPs have opposing effects on the same biological targets. Heterogeneous aggregation is an important effect of MPs on algae and can downregulate the membrane lipid metabolism of algal cells. However, although quinolones can induce algal membrane disorders (Khondker et al., 2021), the resistance of microalgae cells to quinolones usually occurs through the upregulation of lipid metabolites (Redgrave et al., 2014). The opposing effects of MPs and quinolones on membrane targets lead to antagonistic effects For example, You et al. (2021b) found that phospholipids and glycerolipids are upregulated in response to CIP stress. Therefore, the inhibition caused by the combined exposure of algae to CIP and MPs was mitigated (the inhibition rate decreased to 18%) because of the adaptive responses of algae to CIP stress. Finally, low concentrations of MPs can induce hormesis in algae, which can increase the activity of metabolic enzymes, thus promoting the degradation of several PPCPs (Li et al., 2023a). The degradation of PPCPs reduces their accumulation in algae, thereby reducing their effects. For instance, 5 mg/L of PS upregulates the gene encoding the P450 enzyme in algae (You et al., 2021a). Research has indicated that P450 is a key catalyst in the breakdown of antibiotics by algae (You et al., 2021a). Therefore, the up-regulation of CYP enzyme promotes the degradation of sulfadiazine (SDZ).

4.2.2. Synergy

The synergistic effects of PPCPs and MPs on algae can be attributed to the following reasons (Fig. 2) (see Fig. 1). First, when the MPs are sufficiently small to enter algal cells, the adsorption of PPCPs by MPs creates a synergistic effect. MPs can carry PPCPs to algae through the adsorption of PPCPs, thereby increasing the bioaccumulation of PPCPs in algal cells (Lee et al., 2024; Li et al., 2023a). Second, when MPs are negatively charged, the adsorption of positively charged PPCPs by the MPs can reduce the electrostatic barrier between the MPs and algal cells. The reduction in electrostatic repulsion increases the likelihood of cell–particle interactions, leading to a synergistic combined effect (Zhang et al., 2022). Feng et al. (2020) reported that the addition of TC increased the zeta potential of PS-SO_3H from −27.33 to −10.00 mV. Thus, the electrostatic repulsion between PS-SO_3H and the algal cells was decreased, resulting in an increase in binary toxicity. Compared with *S. costatum* exposed to single PS-SO_3H system, the percentage of cell membrane damage in joint systems of tetracycline-saturated PS-SO_3H increased to 53.5%. Third, the combined effects of certain PPCPs and MPs on a same biological target could result in their synergy. At the boundary of algal cells, the contact between MPs and algae with weak barrier (e.g., green algae and cyanobacteria are more vulnerable than diatoms with silicate cell walls) can cause physical or oxidative damage to the cell membrane. Damage to the membrane makes it easier for PPCPs and MPs to enter cells (Prata et al., 2018), thereby enhancing the combined effects of PPCPs and MPs. For example, Yi et al. (2019a) reported that the presence of PS increased the toxicity of TPT-Cl, which could be attributed to the facilitated uptake of TPT-Cl by green algae after damaging the cell structure. Inside the algal cells, when MPs and PPCPs have similar or complementary toxic mechanisms, MPs and PPCPs show synergistic effects on the same biological target. ROS were confirmed to be an important mechanism by which MPs inhibit cell

Table 1
Effect of mixture of MPs and PPCPs on algae.

Algal species	MPs types	MPs size	MPs concentration	PPCPs	Exposure time	Effects	Maximum inhibition rate	Major findings	Ref
S. costatum	PS,PE and PVC	74 μm	50 mg/L	TCS	96 h	Antagonistic	21 % (96 h)	The adsorption of TCS by 74 μm MP decreases the intake of TCS by algal cells, decreasing the direct toxicity of TCS.	Zhu et al. (2019)
T. chuii	Red fluorescent polymer microspheres	1–5 μm	1.5 mg/L	Procainamide/ doxycycline	96 h	Synergistic	57% (96 h)	The contact between MPs and algae can cause physical damage to the cell membrane. Damage to the membrane makes it easier for doxycycline/procainamide and MPs to enter cells.	Prata et al. (2018)
S. costatum	PS-SO_3H	96.05 nm	20 mg/L, 200 mg/L	TC	24 h	Synergistic	53.5% (24 h)	The addition of TC increased the zeta potential of PS-SO_3H from −27.33 to −10.00 mV. Thus, the electrostatic repulsion between PS-SO_3H and the algal cells was decreased, resulting in an increase in binary toxicity.	Feng et al. (2020)
C. pyrenoidosa	PS	600 nm	1 mg/L	IBU	96 h	Antagonistic	28% (96 h)	Low concentrations of MPs can induce hormesis in algae, which can increase the activity of metabolic enzymes, thus promoting the degradation of several IBU. The degradation of PPCPs reduces their accumulation in algae, thereby reducing their effects.	Wang et al. (2020)
C. pyrenoidosa and C.cathayensis	PS	700 nm	20 mg/L	Methamphetamine	96 h	Synergistic	48% (96 h)	MPs at 700 nm can carry methamphetamine to algae through the adsorption of methamphetamine, thereby increasing the bioaccumulation of methamphetamine in algal cells.	Hao et al. (2022)
Dictyosphaerium sp.	PS	0.05–0.1 μm	50 mg/L	Nonylphenol	96 h	Antagonistic	26% (96 h)	Nonylphenol and MPs have opposing effects on the same biological targets. PS induce a mechanism of self-regulation of the algae to repair damage inside and defend invasion outside.	Jin et al. (2022)
C. pyrenoidosa	PS	0.55 μm, 5 μm	5 mg/L	Triphenyltin	96 h	Synergistic	48 % (96 h)	The exposure to 0.55 μm PS lead to damage on structure of algal cells, which could facilitated uptake of TPT-Cl	Yi et al. (2019a)
S. costatum	PS	0.1 μm, 5 μm	20 mg/L	Triphenyltin	96 h	Antagonistic	31 % (96 h)	The presence of PS might reduce the uptake of TPT by lowering the waterborne TPT levels, leading to the decreased toxicity of TPT.	Yi et al. (2019b)
Marine Chlorella sp.	PS	200 nm	10 μg/L	DCOIT	15 d	Antagonistic	11% (72 h)	Low concentrations of MPs can induce hormesis in algae and cause the inhibitory effect of DCOIT on marine *Chlorella* sp. to end early.	Ru et al. (2022)
Synechocystis sp.	PS	0.5 μm, 5 μm, 50 μm.	5, 50, 100 mg/ L	CIP	96 h	Antagonistic	18 % (96 h)	Heterogeneous aggregation is an important effect of MPs on algae and can downregulate the membrane lipid metabolism of algal cells. Phospholipids and glycerolipids are upregulated in response to CIP stress. The opposing effects of MPs and quinolones on membrane targets lead to antagonistic effects.	You et al. (2021b)
C. pyrenoidosa	PS	0.1 μm, 0.55 μm, 5 μm	0.5–64 mg/L	DBP	96 h	Synergistic and Antagonistic	38 % (96 h)	The interaction between PS and DBP was antagonistic at low concentrations of PS and synergistic at relatively high concentrations of PS	Li et al. (2020b)
M. aeruginosa	PS-NH_2	–	5 mg/L	Glyphosate	96 h	Antagonistic	21% (96 h)	The adsorption of PS-NH_2 decreased bioavailability of glyphosate for *M. aeruginosa*.	Thiagarajan et al. (2022)
C. meneghiniana and S. costatum	PS	0.6–1 μm	50 mg/L	Diuron	96 h	Synergistic	38% (96 h)	The adsorption behavior of MPs to diuron alleviated the intracellular damage to diatoms caused by diuron, and the oxidative stress induced by diuron enhanced the physical damage to diatoms caused by MPs.	Garrido et al. (2019)
Anabaena sp.	PET, PLA, PS, POM	–	20 mg/L	AZI, CLA	72 h	Antagonistic	16% (72 h)	The more hydrophobic AZI showed the highest sorption on all MPs.	González-Pleiter et al. (2021)
C. pyrenoidosa	PA6	75 μm	1.5 mg/L	SMX, DCB	60 d	Antagonistic	25 % (96 h)	The adsorption of SMX by 75 μm PA6 decreases the intake of TCS by algal cells, decreasing the direct toxicity of TCS.	Yang et al. (2020)
M. aeruginosa	PS	1 μm	10, 20, 50 mg/ L	CAP	96 h	Synergistic	44% (96 h)	The synergistic effect of CAP and PS could be explained by the common photosynthetic toxicity target of CAP and MPs as well as oxidative stress.	Li et al. (2023a)
C. pyrenoidosa	PS	3 μm	50 mg/L	Amphetamine	96 h	Synergistic	42 % (96 h)	MPs were observed to increase the toxicity of amphetamine to algae and reduce algae cell growth.	Qu et al. (2022)

(*continued on next page*)

Table 1 (*continued*)

Algal species	MPs types	MPs size	MPs concentration	PPCPs	Exposure time	Effects	Maximum inhibition rate	Major findings	Ref
S. costatum	PLA	1 μm	20 mg/L	TC, CIP	96 h	Synergistic	51 % (96 h)	PLA can carry antibiotics to algae through the adsorption of antibiotics, thereby increasing the bioaccumulation of antibiotics in algal cells.	Zhu et al. (2019)
I. galbana	PE	4.1 μm	10 mg/L	CPF	72 h	Antagonistic	31 % (72 h)	A reduction in the bioavailability of CPF due to their adsorption onto MP (4.1 μm) surfaces.	Garrido et al. (2019)
C. fluminea	PS, PVC	6 μm	10 mg/L	CIP	96 h	Antagonistic	27% (96 h)	MPs lower the toxicity of CIP by reducing its bioavailable	Ye et al. (2023)
S. costatum	PS, PE, PET, PP, PLA	–	50 mg/L	SMX	96 h	Antagonistic	18.2% (96 h)	The co-exposure of SMX and PS alleviated the perturbation of alanine, aspartate and glutamate metabolism of algae compared with SMX.	Li et al. (2022)

-: Data not reported.
Abbreviations: polystyrene (PS), polyvinyl chloride (PVC), polyamide (PA), polyethylene (PE), polypropylene (PP), polyethylene glycol terephthalate (PET), polylactic acid (PLA), sulfamethoxazole (SMX), triclosan (TCS), ibuprofen (IBU), azithromycin (AZD), clarithromycin (CLA), ciprofloxacin (CIP), tetracycline (TC), triphenyltin chloride (TPTCl), triphenyltin (TPT), dibutyl phthalate (DBP), chloramphenicol (CAP).

survival. Algal cells eliminate the adverse effects of excessive ROS production by producing antioxidant enzymes (Aderemi et al., 2018). However, inhibitors of protein synthesis, such as azithromycin, doxycycline, florfenicol, chloramphenicol, and oxytetracycline, can inhibit the synthesis of antioxidant enzymes. The complementary effects of MPs and PCPPs on the oxidative stress targets led to synergistic effects. For example, Li et al. (2023a) reported that PS induces algae to produce excess ROS. Proteomic analysis revealed that chloramphenicol inhibits SOD synthesis. Thus, the down-regulation of SOD caused by CAP enhanced the lipid peroxidation caused by PS. The complementary toxic mechanisms of PS and CAP result in their synergistic effects on oxidative stress.

4.3. Factors

To determine the relative importance of the different parameters for the combined toxicity, the relative importance of the parameters was ranked in the RF model (Fig. 3). The RF analysis identified PPCP types and algal species as the significant factors.

Different PPCPs have different modes of action and the physicochemical properties of different PPCPs affect their adsorption by MPs. Thus, the type of PPCP is a critical factor in determining the combined effects of MPs and PPCPs on algae. If certain types of PPCPs and MPs have similar modes of action, exposure to such combinations can result in synergistic overall effects. Yi et al. (2019a) found that PS and TPT-Cl have synergistic effects on algae because of the disruption of the cell structure, facilitating the uptake of TPT-Cl by algae (Yi et al., 2019a). However, the different modes of action of certain PPCPs and MPs on algae may lead to antagonistic effects (Yi et al., 2019b). According to You et al. (2021b), the combined action of CIP and MPs results in antagonistic effects because the adaptive responses of algae to CIP stress mitigated the attack of PS on algal membrane. Second, the physicochemical properties of different PPCPs affect their interactions with MPs. González-Pleiter et al. (2021) reported that AZI exhibited stronger hydrophobicity and a higher adsorption ratio than clarithromycin (CLA) by MPs, resulted in more synergistic effects.

Additionally, algal species are significant factors affecting the combined effects of MPs and PPCPs on algae (Fig. 3). This can be attributed to the following reasons. First, the metabolic activities of algae affected by MPs and PPCPs vary depending on the algal species. For example, Almeida et al. (2017) reported that ZnO nanoparticles induce higher oxidative stress in the diatom *P. tricornutum* than in the green algae *Tetraselmis suecica*. The malondialdehyde (MDA) content of *P. tricornutum* was 2.2 times higher than that of *T. suecica*. A high MDA content led to higher growth inhibition. The EC_{50} values of nano-ZnO were 1.09 mg Zn/L toward diatoms and 3.91 mg Zn/L toward green microalgae. Second, the effect of MPs on algae depends on the size of the algal cells. Larger algae are more susceptible to MP inhibition. For larger algae, more MPs are able to enter the cells, resulting in greater growth inhibition. For instance, Ye et al. (2023) investigated the response of 12 species of algae (<8 μm; 8–15 μm; >15 μm) to PS MPs. The inhibition rates of *Desmodesmus* sp. (<8 μm), *Scenedesmus* sp. (8–15 μm) and *Cyclotella* sp. (>15 μm) were 1.09%, 2.10%, and 14.24% respectively. Therefore, the growth inhibition rate of large algae was significantly higher than that of small algae exposed to the same pollutant. Third, structural differences in algal cells may result in distinct responses to pollutant stress, which amplify the disparity in their combined effects. A recent study found that exposing *C. pyrenoidosa* to MPs could cause the cell wall to separate from the plasma membrane or direct physical damage to the membrane structure, resulting in cytotoxicity to algal cells (Mao et al., 2018). Nevertheless, the diatom cell wall consists of biogenic silica, which is thicker and denser than organic matter (Zhu et al., 2019). Therefore, green algae are more vulnerable to pollutants than diatoms. For example, Baudrimont et al. (2020) found that the growth-inhibition rates of the freshwater green alga *S. subspicatus* and marine diatom *T. weissiflogii* were 12.13% and 3.34%, respectively. The

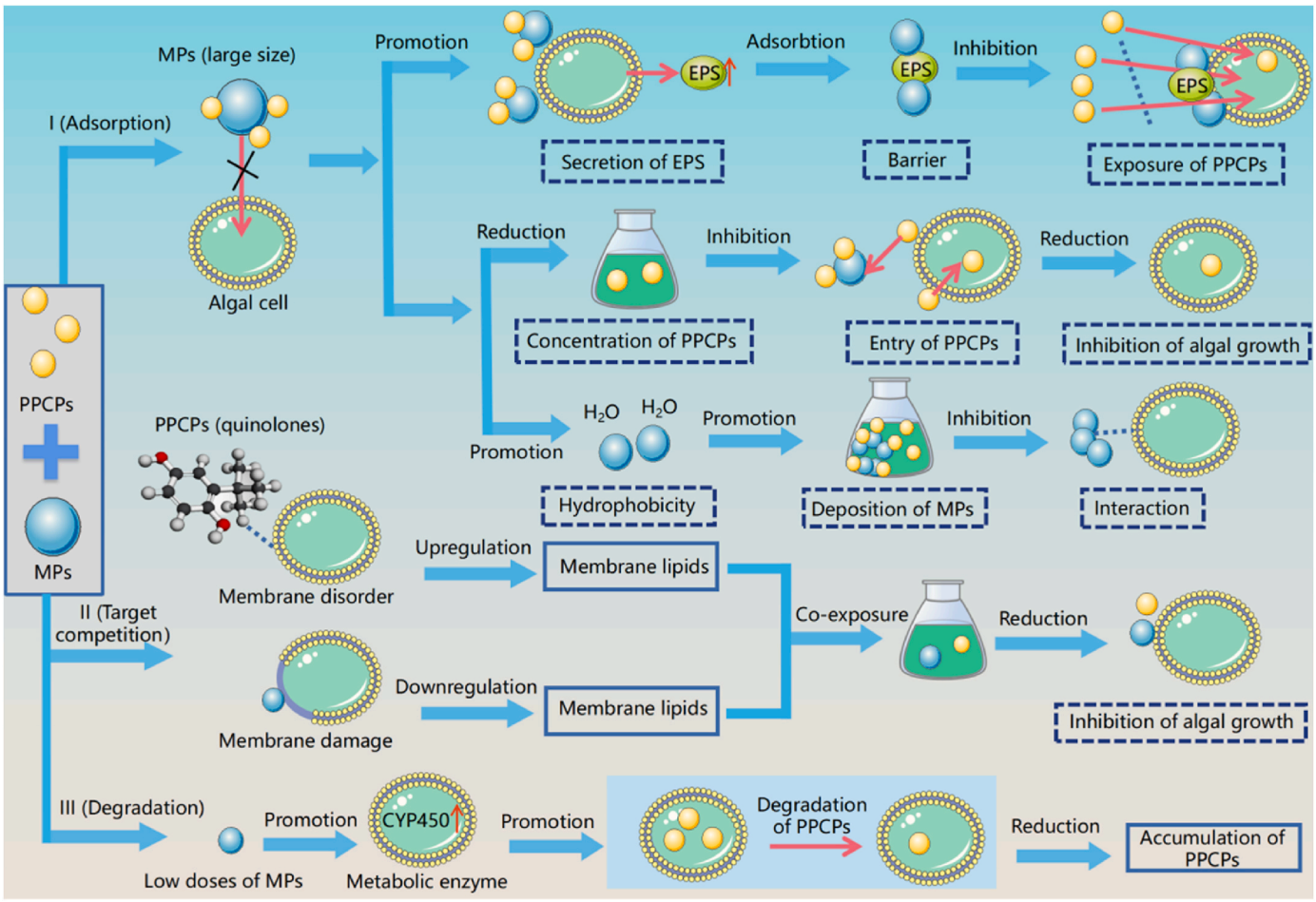

Fig. 1. Mechanism of antagonistic effect of MPs and PPCPs on algae.

unique effects of MPs and PPCPs on distinct algae amplify the disparity in their combined effects. For example, PS cannot destroy the cell walls of diatoms, but can damage those of *C. pyrenoidosa*. The damage caused by MPs to *C. pyrenoidosa* cell walls causes the MPs to carry more PPCPs into the algal cells, resulting in higher growth inhibition. Therefore, PS enhances the inhibition of TPT on *C. pyrenoidosa* but reduces the inhibition of diatoms by TPT (Yi et al., 2019a).

It has been established that the size and concentration of MPs can also influence the combined effects of MPs and PPCPs on algae. Generally, smaller MPs have a greater combined impact than larger ones because smaller MPs have higher adsorption capabilities for PPCPs, which enhances their entry into algal cells. For example, PS (5 μm) does not considerably alter the harmful effects of TPT-Cl on *C. pyrenoidosa*, while PS (550 nm) enhances those effects (Yi et al., 2019a). Moreover, the concentration of MPs can influence these combined effects (Hong et al., 2022). When the PS concentration is below 10 mg/L, PS and dibutyl phthalate (DBP) exert antagonistic effects on *C. pyrenoidosa*. At a PS concentration of >10 mg/L, PS and DBP exert synergistic effects on *C. pyrenoidosa* (Li et al., 2020b).

Differences in the chemical structures of different types of MPs (e.g., chemical bonds and chains) can affect the adsorption of PPCPs and thus affect joint toxicity (Pinto et al., 2023). PVC has a greater adsorption capacity for TCS, resulting in fewer harmful effects on *S. costatum* than those of PE and PS (Zhu et al., 2019). Nevertheless, the influence of MP type on co-toxicity is not as strong as that of MPs size and concentration, and the type of does not affect co-toxicity. Therefore, the type of PPCPs and algae and concentration and size of MPs are more important than the type of MPs when considering their relative importance. The toxicities of different types of MPs may vary over time, leading to different combined effects. Yang et al. (2020) found that the inhibitory effect in a 48-h combined toxicity experiment decreased in the following order: NP > PE > PE1000 > PA > PA1000. However, in a 96-h combined toxicity trial, the inhibitory effect decreased in the order of: NP > PE1000 > PE > PA1000 > PA (Yang et al., 2020). The highest adsorption capacity of PA1000 significantly decreased the toxicity of NPs on algae; however, some MPs initially cause severe damage to algal cells. Nevertheless, with a prolonged exposure time, the toxicity of NPs to algae decreased, whereas the toxicity of PA1000 MPs to algae became more severe, resulting in lower algal density in the PA1000 group than in the PA group after 96 h.

5. Conclusion and future research recommendations

In this review, we discussed the effects of PPCPs and MPs on algae in aquatic environments. First, the individual effects of MPs and PPCPs on algae were summarized. The effects of MPs on algae included heterogeneous aggregation, and photosynthetic and oxidative damage. The effects of PPCPs on algae included membrane, cell structure, genotoxicity, and photosynthetic damage. Second, the effects and modes of the combined exposure of algae to MPs and PPCPs were then systematically reviewed. The antagonistic effect was attributed to the following factors: ① when MPs are too large to enter algal cells, the adsorption of PPCPs on MPs reduces the contact of MPs and PPCPs with algae; ② PPCPs and MPs have opposing actions on the same biological target; ③ MPs increase the activity of metabolic enzymes in algae, thus promoting the PPCP degradation. The synergistic effect is attributed to the following factors: ① when the MPs are small enough to enter algal cells, the adsorption of PPCPs on MPs promotes the entry of PPCPs; ② when MPs are negatively

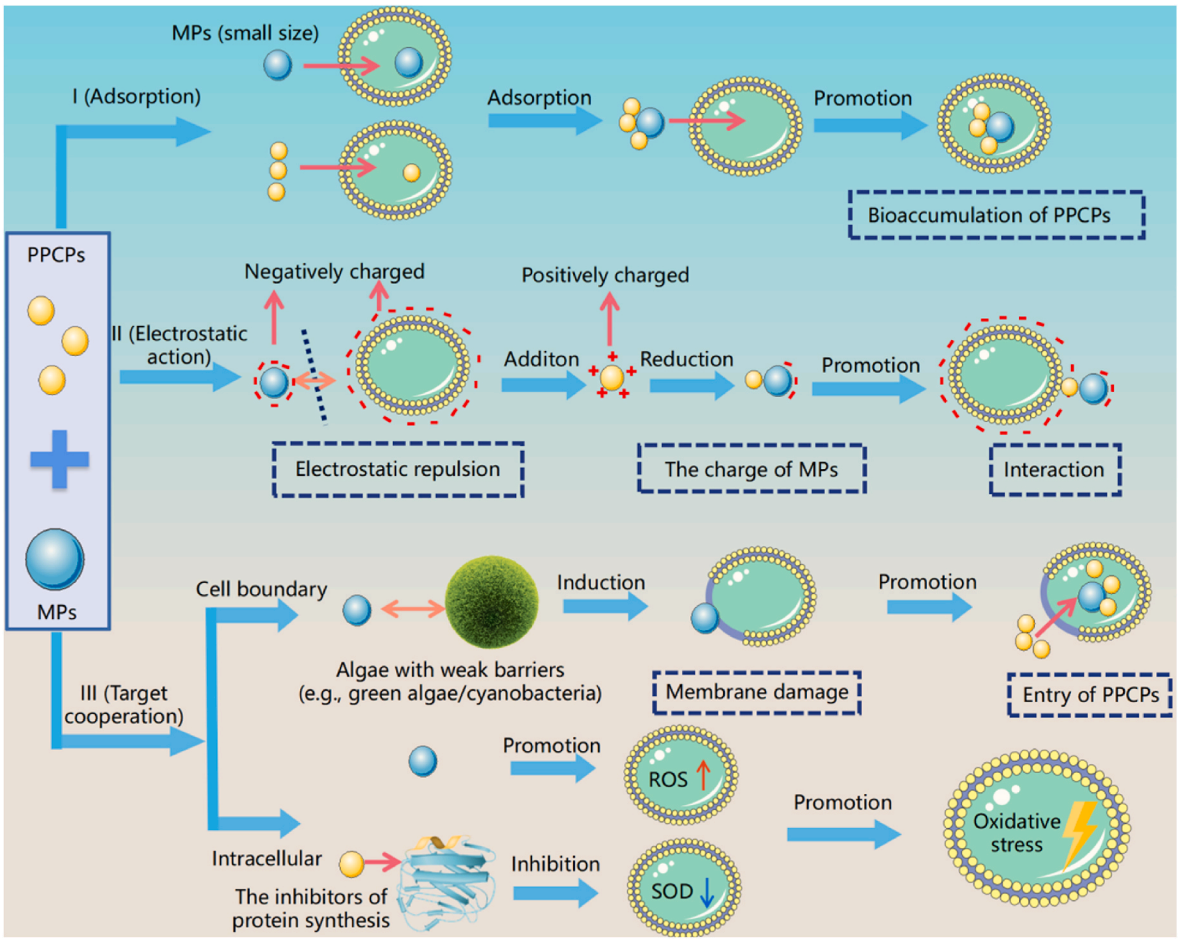

Fig. 2. Mechanism of synergy effect of MPs and PPCPs on algae.

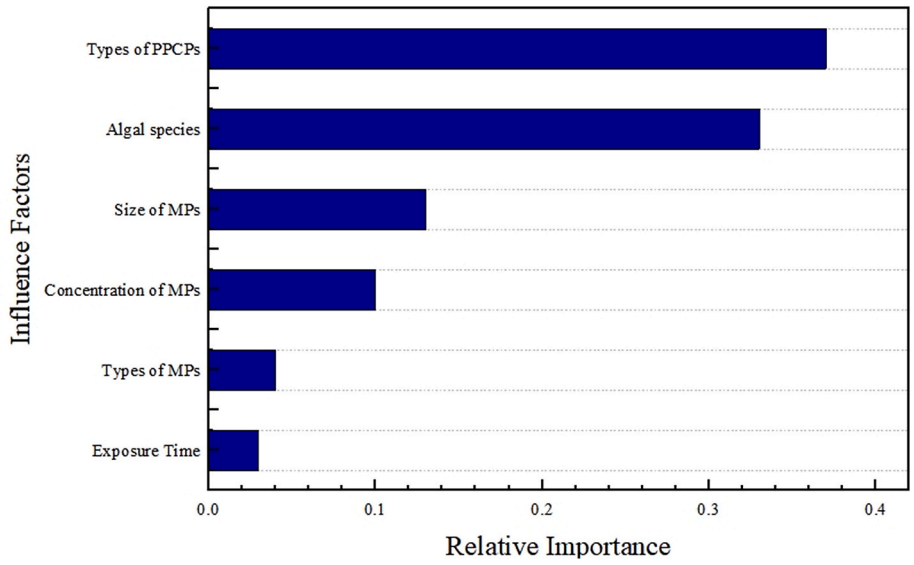

Fig. 3. Order of importance of the RF model variables of joint toxicity of MPs and PPCPs on algae.

charged, the adsorption of positively charged PPCPs by MPs decreases electrostatic repulsion, increasing the interaction between algae and MP; ③ complementary modes of action of MPs and PPCPs show a combined effect on the same biological target. Finally, the impact factors of the combined effects of MPs and PPCPs on algae were analyzed using the RF model. PPCP types and algal species are the important factors leading to different compound effects of MPs and PPCPs on algae. However, there remains a gap regarding the combined effects of MPs and PPCPs on algae. Further studies on the following aspects should be conducted.

1) This study indicates that the combined effects of MPs and PPCPs on algae include both antagonistic and synergistic effects. The synergistic effect of MPs and PPCPs can cause greater growth inhibition in algae, resulting in more serious harm to the aquatic environment. Therefore, it is essential to reduce the synergistic effects of MPs and PPCPs. Specific regulation and control measures could be as follows: First, previous studies have shown that high concentrations of MPs can significantly inhibit the growth of algae (Gao et al., 2023). Hormesis can be induced by exposure to low concentrations of MPs, which can increase the activity of metabolic enzymes in algae, thus promoting the degradation of several PPCPs and leading to antagonistic effects (Wang et al., 2021). Therefore, additional strategies should be adopted to remove MPs, which more successfully reduce the combined effect of MPs and PPCPs on algae. Second, studies indicate that small MPs can transfer PPCPs to algae owing to the adsorption of PPCPs on their surfaces, thus increasing the bioaccumulation of PPCPs in algal cells (Yi et al., 2019a). Therefore, small MPs can induce a synergistic effect with PPCPs. However, recent studies have shown that plastic products can be continuously decomposed into small fragments that are difficult to completely degrade (Nava and Leoni, 2021). Although methods capable of analyzing MPs <10 μm are still lacking (Mishra et al., 2024), the particle size and abundance of MPs detected by now available methods are inversely proportional in aquatic environment (Yang et al., 2024a). Hence, small MPs are expected to widely distributed in aquatic environment. Therefore, for the removal of MPs, it is important to focus on the control of small-sized MPs released into aquatic environments. Third, RF model revealed that PPCP types are the significant factor affecting combined effect. Previous studies have shown that synergistic effects can occur with the combined exposure to MPs and specific PPCPs. For example, inhibitors of protein synthesis (e.g., azithromycin, doxycycline, florfenicol, chloramphenicol, and oxytetracycline) can inhibit the synthesis of antioxidant enzymes, which enhance the oxidative stress of MPs on algae, resulting in synergistic effects (Li et al., 2023a). Therefore, better management measures should be implemented to mitigate the co-emissions of MPs and these pollutants.
2) Biodegradable plastics have gained popularity as a means to improve the efficiency of plastic waste treatment. Biodegradable polymers decompose more easily than ordinary plastics and totally disintegrate during composting at high temperatures (55–175 °C) (Malafeev et al., 2023). However, it is difficult to achieve complete deterioration under natural environmental conditions, particularly in aquatic habitats. Instead, they have a high probability of generating a significant number of smaller MPs. (Podbielska and Szpyrka, 2023). Therefore, the potential environmental impact of biodegradable plastics remains unclear. Several algal species may use MPs as a carbon source via enzymatic breakdown, which promotes algal development. The effects of micro-sized biodegradable polymers on *M. aeruginosa* were investigated by Song et al. (2023). The results showed that, after extended contact, the chemicals in biodegradable plastic leachates promoted *M. aeruginosa* development. In addition, compared with non-biodegradable plastics, biodegradable plastics have different surface potentials and functional groups, thus changing their interactions with other pollutants (Shi et al., 2022). Therefore, the combined effects of biodegradable plastics and PPCPs on algae require further study.

CRediT authorship contribution statement

Wei Yang: Writing – original draft. **Hao Zhang:** Writing – original draft, Data curation. **Shengfa Yang:** Conceptualization. **Yi Xiao:** Writing – review & editing. **Kailai Ye:** Investigation. **Ruixu He:** Methodology. **Yao Liu:** Investigation. **Zuoyuan Hu:** Data curation. **Wenshu Guo:** Formal analysis. **Qin Zhang:** Visualization. **Han Qu:** Writing – review & editing, Supervision. **Yufeng Mao:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Aderemi, A.O., Novais, S.C., Lemos, M.F.L., Alves, L.M., Hunter, C., Pahl, O., 2018. Oxidative stress responses and cellular energy allocation changes in microalgae following exposure to widely used human antibiotics. Aquat. Toxicol. 203, 130–139. https://doi.org/10.1016/j.aquatox.2018.08.008.

Almeida, A.C., Gomes, T., Langford, K., Thomas, K.V., Tollefsen, K.E., 2017. Oxidative stress in the algae Chlamydomonas reinhardtii exposed to biocides. Aquat. Toxicol. 189, 50–59. https://doi.org/10.1016/j.aquatox.2017.05.014.

Arshad, M., Zafar, R., 2020. Chapter 9 - antibiotics, AMRs, and ARGs: fate in the environment. In: Hashmi, M.Z. (Ed.), Antibiotics and Antimicrobial Resistance Genes in the Environment. Elsevier, pp. 138–154. https://doi.org/10.1016/B978-0-12-818882-8.00009-7.

Atugoda, T., Vithanage, M., Wijesekara, H., Bolan, N., Sarmah, A.K., Bank, M.S., You, S., Ok, Y.S., 2021. Interactions between microplastics, pharmaceuticals and personal care products: implications for vector transport. Environ. Int. 149, 106367 https://doi.org/10.1016/j.envint.2020.106367.

Ban, Z., Zhou, Q., Sun, A., Mu, L., Hu, X., 2018. Screening priority factors determining and predicting the reproductive toxicity of various nanoparticles. Environ. Sci. Technol. 52 (17), 9666–9676. https://doi.org/10.1021/acs.est.8b02757.

Baudrimont, M., Arini, A., Guégan, C., Venel, Z., Gigault, J., Pedrono, B., Prunier, J., Maurice, L., Ter Halle, A., Feurtet-Mazel, A., 2020. Ecotoxicity of polyethylene nanoplastics from the North Atlantic oceanic gyre on freshwater and marine organisms (microalgae and filter-feeding bivalves). Environ. Sci. Pollut. Control Ser. 27 (4), 3746–3755. https://doi.org/10.1007/s11356-019-04668-3.

Bhagat, J., Nishimura, N., Shimada, Y., 2021. Toxicological interactions of microplastics/nanoplastics and environmental contaminants: current knowledge and future perspectives. J. Hazard Mater. 405, 123913 https://doi.org/10.1016/j.jhazmat.2020.123913.

Bhattacharya, P., Lin, S., Turner, J.P., Ke, P.C., 2010. Physical adsorption of charged plastic nanoparticles affects algal photosynthesis. J. Phys. Chem. C 114 (39), 16556–16561. https://doi.org/10.1021/jp1054759.

Cao, J., Liao, Y., Yang, W., Jiang, X., Li, M., 2022. Enhanced microalgal toxicity due to polystyrene nanoplastics and cadmium co-exposure: from the perspective of physiological and metabolomic profiles. J. Hazard Mater. 427, 127937 https://doi.org/10.1016/j.jhazmat.2021.127937.

Castro-Castellon, A.T., Horton, A.A., Hughes, J.M.R., Rampley, C., Jeffers, E.S., Bussi, G., Whitehead, P., 2022. Ecotoxicity of microplastics to freshwater biota: considering exposure and hazard across trophic levels. Sci. Total Environ. 816, 151638 https://doi.org/10.1016/j.scitotenv.2021.151638.

Česen, M., Eleršek, T., Novak, M., Žegura, B., Kosjek, T., Filipič, M., Heath, E., 2016. Ecotoxicity and genotoxicity of cyclophosphamide, ifosfamide, their metabolites/transformation products and their mixtures. Environ. Pollut. 210, 192–201. https://doi.org/10.1016/j.envpol.2015.12.017.

Chen, Q., Li, Y., Li, B., 2020. Is color a matter of concern during microplastic exposure to Scenedesmus obliquus and Daphnia magna? J. Hazard Mater. 383, 121224 https://doi.org/10.1016/j.jhazmat.2019.121224.

Czarny, K., Szczukocki, D., Krawczyk, B., Skrzypek, S., Zieliński, M., Gadzała-Kopciuch, R., 2019. Toxic effects of single animal hormones and their mixtures on the growth of Chlorella vulgaris and Scenedesmus armatus. Chemosphere 224, 93–102. https://doi.org/10.1016/j.chemosphere.2019.02.072.

Ding, J., Ma, T., Cui, M., Shao, R., Guan, R., Wang, P., 2018. Gas phase dehydration of glycerol to acrolein over Cs2.5H0.5PW12O40/Zr-MCM-41 catalysts prepared by supercritical impregnation. Mol. Catal. 461, 1–9. https://doi.org/10.1016/j.mcat.2018.09.021.

Du, J., Zhou, Q., Li, H., Xu, S., Wang, C., Fu, L., Tang, J., 2021. Environmental distribution, transport and ecotoxicity of microplastics: a review. J. Appl. Toxicol. 41 (1), 52–64. https://10.1002/jat.4034.

Eguchi, K., Nagase, H., Ozawa, M., Endoh, Y.S., Goto, K., Hirata, K., Miyamoto, K., Yoshimura, H., 2004. Evaluation of antimicrobial agents for veterinary use in the ecotoxicity test using microalgae. Chemosphere 57 (11), 1733–1738. https://doi.org/10.1016/j.chemosphere.2004.07.017.

Fan, Y., Liu, T., Qian, X., Deng, L., Rao, W., Zhang, Q., Zheng, J., Gao, X., 2022. Metabolic impacts of polystyrene microplastics on the freshwater microalga Microcystis aeruginosa. Sci. Total Environ. 836, 155655 https://doi.org/10.1016/j.scitotenv.2022.155655.

Feng, L.-J., Shi, Y., Li, X.-Y., Sun, X.-D., Xiao, F., Sun, J.-W., Wang, Y., Liu, X.-Y., Wang, S.-G., Yuan, X.-Z., 2020. Behavior of tetracycline and polystyrene nanoparticles in estuaries and their joint toxicity on marine microalgae Skeletonema costatum. Environ. Pollut. 263, 114453 https://doi.org/10.1016/j.envpol.2020.114453.

Fu, L., Huang, T., Wang, S., Wang, X., Su, L., Li, C., Zhao, Y., 2017. Toxicity of 13 different antibiotics towards freshwater green algae Pseudokirchneriella subcapitata and their modes of action. Chemosphere 168, 217–222. https://doi.org/10.1016/j.chemosphere.2016.10.043.

Gao, L., Su, Y., Mehmood, T., Bao, R., Peng, L., 2023. Microplastics leachate may play a more important role than microplastics in inhibiting microalga Chlorella vulgaris growth at cellular and molecular levels. Environ. Pollut. 328, 121643 https://doi.org/10.1016/j.envpol.2023.121643.

Garrido, S., Linares, M., Campillo, J.A., Albentosa, M., 2019. Effect of microplastics on the toxicity of chlorpyrifos to the microalgae Isochrysis galbana, clone t-ISO. Ecotoxicol. Environ. Saf. 173, 103–109. https://doi.org/10.1016/j.ecoenv.2019.02.020.

Gomaa, M., Zien-Elabdeen, A., Hifney, A.F., Adam, M.S., 2021. Phycotoxicity of antibiotics and non-steroidal anti-inflammatory drugs to green algae Chlorella sp. and Desmodesmus spinosus: assessment of combined toxicity by Box–Behnken experimental design. Environ. Technol. Innovat. 23, 101586 https://doi.org/10.1016/j.eti.2021.101586.

González-Pleiter, M., Pedrouzo-Rodríguez, A., Verdú, I., Leganés, F., Marco, E., Rosal, R., Fernández-Piñas, F., 2021. Microplastics as vectors of the antibiotics azithromycin and clarithromycin: effects towards freshwater microalgae. Chemosphere 268, 128824. https://doi.org/10.1016/j.chemosphere.2020.128824.

Greven, A.C., Merk, T., Karagöz, F., Mohr, K., Klapper, M., Jovanović, B., Palić, D., 2016. Polycarbonate and polystyrene nanoplastic particles act as stressors to the innate immune system of fathead minnow (Pimephales promelas). Environ. Toxicol. Chem. 35 (12), 3093–3100. https://doi.org/10.1002/etc.3501.

Guo, J., Peng, J., Lei, Y., Kanerva, M., Li, Q., Song, J., Guo, J., Sun, H., 2020. Comparison of oxidative stress induced by clarithromycin in two freshwater microalgae Raphidocelis subcapitata and Chlorella vulgaris. Aquat. Toxicol. 219, 105376 https://doi.org/10.1016/j.aquatox.2019.105376.

Hao, B., Wu, H., Zhang, S., He, B., 2022. Individual and combined toxicity of microplastics and diuron differs between freshwater and marine diatoms. Sci. Total Environ. 853, 158334 https://doi.org/10.1016/j.scitotenv.2022.158334.

He, Y., Wei, G., Tang, B., Salam, M., Shen, A., Wei, Y., Zhou, X., Liu, M., Yang, Y., Li, H., Mao, Y., 2022. Microplastics benefit bacteria colonization and induce microcystin degradation. J. Hazard Mater. 431, 128524 https://doi.org/10.1016/j.jhazmat.2022.128524.

Hong, J., Huang, X., Wang, Z., Luo, X., Huang, S., Zheng, Z., 2022. Combined toxic effects of enrofloxacin and microplastics on submerged plants and epiphytic biofilms in high nitrogen and phosphorus waters. Chemosphere 308, 136099. https://doi.org/10.1016/j.chemosphere.2022.136099.

Hu, L., Zhao, Y., Xu, H., 2022. Trojan horse in the intestine: a review on the biotoxicity of microplastics combined environmental contaminants. J. Hazard Mater. 439, 129652 https://doi.org/10.1016/j.jhazmat.2022.129652.

Huang, W., Song, B., Liang, J., Niu, Q., Zeng, G., Shen, M., Deng, J., Luo, Y., Wen, X., Zhang, Y., 2021a. Microplastics and associated contaminants in the aquatic environment: a review on their ecotoxicological effects, trophic transfer, and potential impacts to human health. J. Hazard Mater. 405, 124187 https://doi.org/10.1016/j.jhazmat.2020.124187.

Huang, W., Zhao, T., Zhu, X., Ni, Z., Guo, X., Tan, L., Wang, J., 2021b. The effects and mechanisms of polystyrene and polymethyl methacrylate with different sizes and concentrations on Gymnodinium aeruginosum. Environ. Pollut. 287, 117626 https://doi.org/10.1016/j.envpol.2021.117626.

Jin, Z., Du, L., Cheng, Q., Jiang, Y., Hui, C., Xu, L., Zhao, Y., Jiang, H., 2022. Physiological and transcriptional responses of Dictyosphaerium sp. under co-exposure of a typical microplastic and nonylphenol. Environ. Res. 204, 112287 https://doi.org/10.1016/j.envres.2021.112287.

Khondker, A., Bider, R.-C., Passos-Gastaldo, I., Wright, G.D., Rheinstädter, M.C., 2021. Membrane interactions of non-membrane targeting antibiotics: the case of aminoglycosides, macrolides, and fluoroquinolones. Biochim. Biophys. Acta Biomembr. 1863 (1), 183448 https://doi.org/10.1016/j.bbamem.2020.183448.

Kong, L., Guo, Z., Peng, C., Xiao, X., He, Y., 2021. Factors influencing the effectiveness of liming on cadmium reduction in rice: a meta-analysis and decision tree analysis. Sci. Total Environ. 779, 146477 https://doi.org/10.1016/j.scitotenv.2021.146477.

Lagarde, F., Olivier, O., Zanella, M., Daniel, P., Hiard, S., Caruso, A., 2016. Microplastic interactions with freshwater microalgae: hetero-aggregation and changes in plastic density appear strongly dependent on polymer type. Environ. Pollut. 215, 331–339. https://doi.org/10.1016/j.envpol.2016.05.006.

Lee, J.-S., Lee, J.-S., Kim, H.S., 2024. Toxic effects of triclosan in aquatic organisms: a review focusing on single and combined exposure of environmental conditions and pollutants. Sci. Total Environ. 920, 170902 https://doi.org/10.1016/j.scitotenv.2024.170902.

Li, N., Zeng, Z., Zhang, Y., Zhang, H., Tang, N., Guo, Y., Lu, L., Li, X., Zhu, Z., Gao, X., Liang, J., 2023a. Higher toxicity induced by co-exposure of polystyrene microplastics and chloramphenicol to Microcystis aeruginosa: experimental study and molecular dynamics simulation. Sci. Total Environ. 866, 161375 https://doi.org/10.1016/j.scitotenv.2022.161375.

Li, S., Wang, P., Zhang, C., Zhou, X., Yin, Z., Hu, T., Hu, D., Liu, C., Zhu, L., 2020a. Influence of polystyrene microplastics on the growth, photosynthetic efficiency and aggregation of freshwater microalgae Chlamydomonas reinhardtii. Sci. Total Environ. 714, 136767 https://doi.org/10.1016/j.scitotenv.2020.136767.

Li, W., Li, X., Tong, J., Xiong, W., Zhu, Z., Gao, X., Li, S., Jia, M., Yang, Z., Liang, J., 2023b. Effects of environmental and anthropogenic factors on the distribution and abundance of microplastics in freshwater ecosystems. Sci. Total Environ. 856, 159030 https://doi.org/10.1016/j.scitotenv.2022.159030.

Li, X., Ying, G.-G., Su, H.-C., Yang, X.-B., Wang, L., 2010. Simultaneous determination and assessment of 4-nonylphenol, bisphenol A and triclosan in tap water, bottled water and baby bottles. Environ. Int. 36 (6), 557–562. https://doi.org/10.1016/j.envint.2010.04.009.

Li, Z., Dong, S., Huang, F., Lin, L., Hu, Z., Zheng, Y., 2022. Toxicological effects of microplastics and sulfadiazine on the microalgae chlamydomonas reinhardtii. Front. Microbiol. 13 https://doi.org/10.3389/fmicb.2022.865768.

Li, Z., Yi, X., Zhou, H., Chi, T., Li, W., Yang, K., 2020b. Combined effect of polystyrene microplastics and dibutyl phthalate on the microalgae Chlorella pyrenoidosa. Environ. Pollut. 257, 113604 https://doi.org/10.1016/j.envpol.2019.113604.

Long, M., Paul-Pont, I., Hégaret, H., Moriceau, B., Lambert, C., Huvet, A., Soudant, P., 2017. Interactions between polystyrene microplastics and marine phytoplankton lead to species-specific hetero-aggregation. Environ. Pollut. 228, 454–463. https://doi.org/10.1016/j.envpol.2017.05.047.

Mackay, D., Barnthouse, L.J.I.e.a., management, 2010. Integrated risk assessment of household chemicals and consumer products: addressing concerns about triclosan. Integrated Environ. Assess. Manag. 6 (3), 390–392. https://doi.org/10.1002/ieam.73.

Mahmoudzadeh, H., Matinfar, H.R., Taghizadeh-Mehrjardi, R., Kerry, R., 2020. Spatial prediction of soil organic carbon using machine learning techniques in western Iran. Geoderma Regional 21, e00260. https://doi.org/10.1016/j.geodrs.2020.e00260.

Malafeev, K.V., Apicella, A., Incarnato, L., Scarfato, P., 2023. Understanding the impact of biodegradable microplastics on living organisms entering the food chain: a review. Polymers 15 (18), 3680. https://doi.org/10.3390/polym15183680.

Mammo, F.K., Amoah, I.D., Gani, K.M., Pillay, L., Ratha, S.K., Bux, F., Kumari, S., 2020. Microplastics in the environment: interactions with microbes and chemical contaminants. Sci. Total Environ. 743, 140518 https://doi.org/10.1016/j.scitotenv.2020.140518.

Mao, Y., Ai, H., Chen, Y., Zhang, Z., Zeng, P., Kang, L., Li, W., Gu, W., He, Q., Li, H., 2018. Phytoplankton response to polystyrene microplastics: perspective from an entire growth period. Chemosphere 208, 59–68. https://doi.org/10.1016/j.chemosphere.2018.05.170.

Mao, Y., Hu, Z., Li, H., Zheng, H., Yang, S., Yu, W., Tang, B., Yang, H., He, R., Guo, W., Ye, K., Yang, A., Zhang, S., 2024a. Recent advances in microplastic removal from drinking water by coagulation: removal mechanisms and influencing factors. Environ. Pollut. 349, 123863 https://doi.org/10.1016/j.envpol.2024.123863.

Mao, Y., Li, H., Huangfu, X., Liu, Y., He, Q., 2020. Nanoplastics display strong stability in aqueous environments: insights from aggregation behaviour and theoretical calculations. Environ. Pollut. 258, 113760 https://doi.org/10.1016/j.envpol.2019.113760.

Mao, Y., Ye, K., Yang, S., Salam, M., Yu, W., He, Q., He, R., Li, H., 2024b. Repeated exposure enhanced toxicity of clarithromycin on microcystis aeruginosa versus single exposure through photosynthesis, oxidative stress, and energy metabolism shift. Environ. Sci. Technol. 58 (9), 4070–4082. https://doi.org/10.1021/acs.est.3c07008.

Mao, Y., Yu, Y., Ma, Z., Li, H., Yu, W., Cao, L., He, Q., 2021. Azithromycin induces dual effects on microalgae: roles of photosynthetic damage and oxidative stress. Ecotoxicol. Environ. Saf. 222, 112496 https://doi.org/10.1016/j.ecoenv.2021.112496.

Martín, J., Santos, J.L., Aparicio, I., Alonso, E., 2022. Microplastics and associated emerging contaminants in the environment: analysis, sorption mechanisms and effects of co-exposure. Trends in Environmental Analytical Chemistry 35, e00170. https://doi.org/10.1016/j.teac.2022.e00170.

McCormick, A., Hoellein, T.J., Mason, S.A., Schluep, J., Kelly, J.J., 2014. Microplastic is an abundant and distinct microbial habitat in an urban river. Environ. Sci. Technol. 48 (20), 11863–11871. https://doi.org/10.1021/es503610r.

Miazek, K., Brozek-Pluska, B., 2019. Effect of PHRs and PCPs on microalgal growth, metabolism and microalgae-based bioremediation processes: a review. Int. J. Mol. Sci. 20 (10), 2492. https://doi.org/10.3390/ijms20102492.
Mishra, S., Ren, Y., Sun, X., Lian, Y., Singh, A.K., Sharma, N., 2024. Microplastics pollution in the Asian water tower: source, environmental distribution and proposed mitigation strategy. Environ. Pollut. 356, 124247 https://doi.org/10.1016/j.envpol.2024.124247.
Nava, V., Leoni, B., 2021. A critical review of interactions between microplastics, microalgae and aquatic ecosystem function. Water Res. 188, 116476 https://doi.org/10.1016/j.watres.2020.116476.
Nguyen, M.-K., Lin, C., Nguyen, H.-L., Le, V.-G., Haddout, S., Um, M.-J., Chang, S.W., Nguyen, D.D., 2023. Ecotoxicity of micro- and nanoplastics on aquatic algae: facts, challenges, and future opportunities. J. Environ. Manag. 346, 118982 https://doi.org/10.1016/j.jenvman.2023.118982.
Nkoom, M., Lu, G., Liu, J., 2018. Occurrence and ecological risk assessment of pharmaceuticals and personal care products in Taihu Lake, China: a review. Environ. Sci. J. Integr. Environ. Res.: Process. Impacts 20 (12), 1640–1648. https://doi.org/10.1039/C8EM00327K.
Pinto, E.P., Paredes, E., Bellas, J., 2023. Influence of microplastics on the toxicity of chlorpyrifos and mercury on the marine microalgae Rhodomonas lens. Sci. Total Environ. 857, 159605 https://doi.org/10.1016/j.scitotenv.2022.159605.
Podbielska, M., Szpyrka, E., 2023. Microplastics – an emerging contaminants for algae. Critical review and perspectives. Sci. Total Environ. 885, 163842 https://doi.org/10.1016/j.scitotenv.2023.163842.
Prata, J.C., Lavorante, B.R.B.O., B S M, Montenegro, M.d.C., Guilhermino, L., 2018. Influence of microplastics on the toxicity of the pharmaceuticals procainamide and doxycycline on the marine microalgae Tetraselmis chuii. Aquat. Toxicol. 197, 143–152. https://doi.org/10.1016/j.aquatox.2018.02.015.
Qu, H., Ma, R., Barrett, H., Wang, B., Han, J., Wang, F., Chen, P., Wang, W., Peng, G., Yu, G., 2020. How microplastics affect chiral illicit drug methamphetamine in aquatic food chain? From green alga (Chlorella pyrenoidosa) to freshwater snail (Cipangopaludian cathayensis). Environ. Int. 136, 105480 https://doi.org/10.1016/j.envint.2020.105480.
Qu, H., Wang, F., Barrett, H., Wang, B., Han, J., Wu, J., Huang, X., Hu, Y., Yu, G., 2022. Synthetical effect of microplastics and chiral drug amphetamine on a primary food source algae Chlorella pyrenoids. Food Chem. Toxicol. 169, 113415 https://doi.org/10.1016/j.fct.2022.113415.
Redgrave, L.S., Sutton, S.B., Webber, M.A., Piddock, L.J.V., 2014. Fluoroquinolone resistance: mechanisms, impact on bacteria, and role in evolutionary success. Trends Microbiol. 22 (8), 438–445. https://doi.org/10.1016/j.tim.2014.04.007.
Ru, J.-C., Zhao, X.-L., Cao, Z.-H., Chen, C.-Z., Li, P., Li, Z.-H., 2022. Chronic toxic effects of polystyrene micro-plastics, DCOIT and their combination on marine Chlorella sp. Comp. Biochem. Physiol. C Toxicol. Pharmacol. 261, 109426 https://doi.org/10.1016/j.cbpc.2022.109426.
Sanchez, W., Bender, C., Porcher, J.-M., 2014. Wild gudgeons (Gobio gobio) from French rivers are contaminated by microplastics: preliminary study and first evidence. Environ. Res. 128, 98–100. https://doi.org/10.1016/j.envres.2013.11.004.
Seoane, M., Rioboo, C., Herrero, C., Cid, Á., 2014. Toxicity induced by three antibiotics commonly used in aquaculture on the marine microalga Tetraselmis suecica (Kylin) Butch. Mar. Environ. Res. 101, 1–7. https://doi.org/10.1016/j.marenvres.2014.07.011.
Shi, K., Zhang, H., Xu, H., Liu, Z., Kan, G., Yu, K., Jiang, J., 2022. Adsorption behaviors of triclosan by non-biodegradable and biodegradable microplastics: kinetics and mechanism. Sci. Total Environ. 842, 156832 https://doi.org/10.1016/j.scitotenv.2022.156832.
Singh, S., Li, S.S.-L., 2012. Epigenetic effects of environmental chemicals bisphenol A and phthalates. Int. J. Mol. Sci. 13 (8), 10143–10153. https://doi.org/10.3390/ijms130810143.
Sjollema, S.B., Redondo-Hasselerharm, P., Leslie, H.A., Kraak, M.H.S., Vethaak, A.D., 2016. Do plastic particles affect microalgal photosynthesis and growth? Aquat. Toxicol. 170, 259–261. https://doi.org/10.1016/j.aquatox.2015.12.002.
Song, W., Fu, C., Fang, Y., Wang, Z., Li, J., Zhang, X., Bhatt, K., Liu, L., Wang, N., Liu, F., Zhu, S., 2023. Single and combined toxicity assessment of primary or UV-aged microplastics and adsorbed organic pollutants on microalga Chlorella pyrenoidosa. Environ. Pollut. 318, 120925 https://doi.org/10.1016/j.envpol.2022.120925.
Su, L., Xue, Y., Li, L., Yang, D., Kolandhasamy, P., Li, D., Shi, H., 2016. Microplastics in taihu lake, China. Environ. Pollut. 216, 711–719. https://doi.org/10.1016/j.envpol.2016.06.036.
Su, X., Yuan, J., Lu, Z., Xu, J., He, Y., 2022. An enlarging ecological risk: review on co-occurrence and migration of microplastics and microplastic-carrying organic pollutants in natural and constructed wetlands. Sci. Total Environ. 837, 155772 https://doi.org/10.1016/j.scitotenv.2022.155772.
Su, Y., Gao, L., Peng, L., Diao, X., Lin, S., Bao, R., Mehmood, T., 2023. Heterogeneous aggregation between microplastics and microalgae: may provide new insights for microplastics removal. Aquat. Toxicol. 261, 106638 https://doi.org/10.1016/j.aquatox.2023.106638.
Suwalsky, M., Mennickent, S., Norris, B., Villena, F., Sotomayor, C.P., 2006. Effects of the antiepileptic drug carbamazepine on human erythrocytes. Toxicol. Vitro 20 (8), 1363–1369. https://doi.org/10.1016/j.tiv.2006.05.010.
Thiagarajan, V., Seenivasan, R., Jenkins, D., Chandrasekaran, N., Mukherjee, A., 2022. Mixture toxicity of TiO2 NPs and tetracycline at two trophic levels in the marine ecosystem: Chlorella sp. and Artemia salina. Sci. Total Environ. 812, 152241 https://doi.org/10.1016/j.scitotenv.2021.152241.
Torres, M.A., Barros, M.P., Campos, S.C.G., Pinto, E., Rajamani, S., Sayre, R.T., Colepicolo, P., 2008. Biochemical biomarkers in algae and marine pollution: a review. Ecotoxicol. Environ. Saf. 71 (1), 1–15. https://doi.org/10.1016/j.ecoenv.2008.05.009.
Venâncio, C., Ferreira, I., Martins, M.A., Soares, A.M.V.M., Lopes, I., Oliveira, M., 2019. The effects of nanoplastics on marine plankton: a case study with polymethylmethacrylate. Ecotoxicol. Environ. Saf. 184, 109632 https://doi.org/10.1016/j.ecoenv.2019.109632.
Villain, J., Minguez, L., Halm-Lemeille, M.-P., Durrieu, G., Bureau, R., 2016. Acute toxicities of pharmaceuticals toward green algae. mode of action, biopharmaceutical drug disposition classification system and quantile regression models. Ecotoxicol. Environ. Saf. 124, 337–343. https://doi.org/10.1016/j.ecoenv.2015.11.009.
Wang, F., Wang, B., Qu, H., Zhao, W., Duan, L., Zhang, Y., Zhou, Y., Yu, G., 2020. The influence of nanoplastics on the toxic effects, bioaccumulation, biodegradation and enantioselectivity of ibuprofen in freshwater algae Chlorella pyrenoidosa. Environ. Pollut. 263, 114593 https://doi.org/10.1016/j.envpol.2020.114593.
Wang, W., Ndungu, A.W., Li, Z., Wang, J., 2017. Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Sci. Total Environ. 575, 1369–1374. https://doi.org/10.1016/j.scitotenv.2016.09.213.
Wang, Y., Yang, Y., Liu, X., Zhao, J., Liu, R., Xing, B., 2021. Interaction of microplastics with antibiotics in aquatic environment: distribution, adsorption, and toxicity. Environ. Sci. Technol. 55 (23), 15579–15595. https://doi.org/10.1021/acs.est.1c04509.
Wilkinson, J., Hooda, P.S., Barker, J., Barton, S., Swinden, J., 2017. Occurrence, fate and transformation of emerging contaminants in water: an overarching review of the field. Environ. Pollut. 231, 954–970. https://doi.org/10.1016/j.envpol.2017.08.032.
Xie, Z., Wang, X., Gan, Y., Cheng, H., Fan, S., Li, X., Tang, J., 2022. Ecotoxicological effects of the antidepressant fluoxetine and its removal by the typical freshwater microalgae Chlorella pyrenoidosa. Ecotoxicol. Environ. Saf. 244, 114045 https://doi.org/10.1016/j.ecoenv.2022.114045.
Xin, X., Huang, G., Liu, X., An, C., Yao, Y., Weger, H., Zhang, P., Chen, X., 2017. Molecular toxicity of triclosan and carbamazepine to green algae Chlorococcum sp.: a single cell view using synchrotron-based Fourier transform infrared spectromicroscopy. Environ. Pollut. 226, 12–20. https://doi.org/10.1016/j.envpol.2017.04.007.
Xin, X., Huang, G., Zhang, B., 2021. Review of aquatic toxicity of pharmaceuticals and personal care products to algae. J. Hazard Mater. 410, 124619 https://doi.org/10.1016/j.jhazmat.2020.124619.
Xiong, J.-Q., Kurade, M.B., Jeon, B.-H., 2017. Ecotoxicological effects of enrofloxacin and its removal by monoculture of microalgal species and their consortium. Environ. Pollut. 226, 486–493. https://doi.org/10.1016/j.envpol.2017.04.044.
Yang, L., Kang, S., Luo, X., Wang, Z., 2024a. Microplastics in drinking water: a review on methods, occurrence, sources, and potential risks assessment. Environ. Pollut. 348, 123857 https://doi.org/10.1016/j.envpol.2024.123857.
Yang, W., Gao, P., Li, H., Huang, J., Zhang, Y., Ding, H., Zhang, W., 2021. Mechanism of the inhibition and detoxification effects of the interaction between nanoplastics and microalgae Chlorella pyrenoidosa. Sci. Total Environ. 783, 146919 https://doi.org/10.1016/j.scitotenv.2021.146919.
Yang, W., Gao, P., Ye, Z., Chen, F., Zhu, L., 2024b. Micro/nano-plastics and microalgae in aquatic environment: influence factor, interaction, and molecular mechanisms. Sci. Total Environ. 934, 173218 https://doi.org/10.1016/j.scitotenv.2024.173218.
Yang, W., Gao, X., Wu, Y., Wan, L., Tan, L., Yuan, S., Ding, H., Zhang, W., 2020. The combined toxicity influence of microplastics and nonylphenol on microalgae Chlorella pyrenoidosa. Ecotoxicol. Environ. Saf. 195, 110484 https://doi.org/10.1016/j.ecoenv.2020.110484.
Ye, S., Rao, M., Xiao, W., Zhou, J., Li, M., 2023. The relative size of microalgal cells and microplastics determines the toxicity of microplastics to microalgae. Process Saf. Environ. Protect. 169, 860–868. https://doi.org/10.1016/j.psep.2022.11.077.
Yi, X., Chi, T., Li, Z., Wang, J., Yu, M., Wu, M., Zhou, H., 2019a. Combined effect of polystyrene plastics and triphenyltin chloride on the green algae Chlorella pyrenoidosa. Environ. Sci. Pollut. Res. 26, 15011–15018. https://doi.org/10.1007/s11356-019-04865-0.
Yi, X., Wang, J., Li, Z., Zhang, Z., Chi, T., Guo, M., Li, W., Zhou, H., 2019b. The effect of polystyrene plastics on the toxicity of triphenyltin to the marine diatom Skeletonema costatum—influence of plastic particle size. Environ. Sci. Pollut. Res. 26, 25445–25451. https://doi.org/10.1007/s11356-019-05826-3.
You, M., You, X., Hu, J., Yang, X., Sun, W., 2021a. Carbon nanotubes influence the toxic effects of chloramphenicol and tetracycline on cyanobacterium Synechocystis sp. in different ways. Environ. Sci.: Nano 8 (3), 634–646. https://doi.org/10.1039/D0EN01204A.
You, X., Cao, X., Zhang, X., Guo, J., Sun, W., 2021b. Unraveling individual and combined toxicity of nano/microplastics and ciprofloxacin to Synechocystis sp. at the cellular and molecular levels. Environ. Int. 157, 106842 https://doi.org/10.1016/j.envint.2021.106842.
Zhang, C., Chen, X., Wang, J., Tan, L., 2017. Toxic effects of microplastic on marine microalgae Skeletonema costatum: interactions between microplastic and algae. Environ. Pollut. 220, 1282–1288. https://doi.org/10.1016/j.envpol.2016.11.005.
Zhang, W., Sun, S., Du, X., Han, Y., Tang, Y., Zhou, W., Shi, W., Liu, G., 2022. Toxic impacts of microplastics and tetrabromobisphenol A on the motility of marine microalgae and potential mechanisms of action. Gondwana Res. 108, 158–170. https://doi.org/10.1016/j.gr.2021.08.011.

Zhang, Y., Hu, K., Zhou, Y., Xia, Y., Yu, N., Wu, G., Zhu, Y., Wu, Y., Huang, H., 2019. A facile, one-step synthesis of silicon/silicon carbide/carbon nanotube nanocomposite as a cycling-stable anode for lithium ion batteries. Nanomaterials 9 (11), 1624. https://doi.org/10.3390/nano9111624.

Zheng, X., Zhang, W., Yuan, Y., Li, Y., Liu, X., Wang, X., Fan, Z., 2021. Growth inhibition, toxin production and oxidative stress caused by three microplastics in Microcystis aeruginosa. Ecotoxicol. Environ. Saf. 208, 111575 https://doi.org/10.1016/j.ecoenv.2020.111575.

Zhou, R., Lu, G., Yan, Z., Jiang, R., Bao, X., Lu, P., 2020. A review of the influences of microplastics on toxicity and transgenerational effects of pharmaceutical and personal care products in aquatic environment. Sci. Total Environ. 732, 139222 https://doi.org/10.1016/j.scitotenv.2020.139222.

Zhu, Z.-l., Wang, S.-c., Zhao, F.-f., Wang, S.-g., Liu, F.-f., Liu, G.-z., 2019. Joint toxicity of microplastics with triclosan to marine microalgae Skeletonema costatum. Environ. Pollut. 246, 509–517. https://doi.org/10.1016/j.envpol.2018.12.044.