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REVIEW ARTICLE

Ecotoxicological response of algae to contaminants in aquatic environments: a review

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Abstract

Algae play a vital role in aquatic ecosystems, contributing to oxygen production and serving as a foundational component of the food chain. Environment stress and contamination can lead to harmful algal blooms, depleting oxygen levels and creating dead zones in water bodies. When exposed to contaminants such as industrial chemicals, pharmaceuticals, pesticides, heavy metals, and synthetic nano/microparticles, algae can exhibit adverse responses, disrupting the balance of aquatic ecosystems. Furthermore, environmental issues related to ecotoxicology responses of algae include the disruption of biodiversity and the loss of crucial habitats, which can lead to health issues. We reviewed the response of algae exposed to contaminants in the aquatic environments, including ecotoxicology and environmental stresses. The major points are: (1) The accumulation of polycyclic aromatic hydrocarbons in food chains and ecosystems and their uptake is widely revealed as a major concern for environmental health and human beings. (2) Bisphenol A can negatively impact algae by inhibiting biochemical and physiological processes, in which half maximal effective concentration varies from 1.0 mg L^{-1} to 100 mg L^{-1}. (3) Though the level of per- and polyfluoroalkyl substances in the environment is generally low, ranging from ng L^{-1} to mg L^{-1}, the combined contaminant exposure leads to significantly more significant toxic effects than individual compounds. (4) An exposure level of 1000ng L is unsafe for the ecosystems, and per- and polyfluoroalkyl substances could lead to algal growth inhibition, e.g., damage to the photosynthetic, inhibition of deoxyribonucleic acid replication, and reactive oxygen species metabolism. (5) The ecotoxicity of chemicals to algae is influenced by chemical, biological, and physical factors, creating complex effects at the biological community level. (6) This research indicated the importance of the ecotoxicology response of algae to contaminants, emphasizing the necessity for monitoring and strategic interventions to protect the sustainability of aquatic ecosystems.

Keywords Ecotoxicology · Risk assessment · Pharmaceutical · Microplastic · Environmental stress · Sustainable development goals

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Introduction

In recent years, a critical emerging issue for ecosystems has been the increasing global pressure of chemical or micropollutant stressors (Reid et al. 2019; Schuijt et al. 2021; Xiao et al. 2023). The emergence of new pollutants in water sources is causing worldwide concern due to its potentially harmful environmental impact (Basheer 2018b; Basheer and Ali 2018). Environmental contaminants induced by anthropogenic sources have been highlighted to possess adverse effects that lead to ecological imbalance and environmental degradation (Basheer 2018a; Nguyen et al. 2022a). Emerging pollutants in aquatic ecosystems have received significant concern due to the various adverse influences on health issues and the natural environment. For example, petrochemicals, pharmaceuticals and personal care products, pesticides (organochlorine compounds), and heavy metals, e.g., arsenic (As), mercury (Hg), lead (Pb), and cadmium (Cd), have infiltrated aquatic ecosystems, causing habitat losses and vital species damage, even when released at low concentrations (Tsygankov 2019; Vardhan et al. 2019; Kreutzer et al. 2022). The occurrence of micropollutants in environmental matrices is of major attention for various reasons, such as their ecotoxicity to aquatic organisms. For this reason, to evaluate the potentially harmful effects of chemical mixtures on aquatic ecosystems, it is necessary to enhance stress monitoring and identify any adverse ecological impacts (Brack et al. 2019; Xin et al. 2021; Nguyen et al. 2023b).

Chemical stressors or environmental stress can directly impact population development and growth rates by reducing the birth rate and/or enhancing their mortality. Cai et al. (2020) investigated the algal toxicity *S. obliquus* caused by textile and dye wastewater streams. Prolonged exposure time could lead to adverse effects on algae, potentially causing their death (Cai et al. 2020; Othman et al. 2023). It was also found that tiny-sized polymers, e.g., microplastics, inhibited algae, and the interaction between algae and microplastics, might affect their photosynthesis and growth (Sjollema et al. 2016). Several chemicals released into the environmental matrices are genotoxic for aquatic life. Consequently, chemicals could indirectly and/or directly damage deoxyribonucleic acid structure (Schuijt et al. 2021). Exposure to these chemicals could cause compromised immune function in organisms. Thus, for organic and inorganic xenobiotics, microalgae contribute a critical role in the dispersal, chemical fate, transport, and bioaccumulation of toxic chemicals. Further, due to the low treatment performance in wastewater treatment plants, several micropollutants are discharged into water columns with high levels, then can accumulate and lead to high ecotoxicity to many aquatic organisms (Pessôa et al. 2021, Nguyen et al. 2022a, Tuan Tran et al. 2022a, b). Though the contents of pharmaceutical and personal care products are relatively low (ppm or ppb) in a natural environment, they have high durability and bioactivity that can have negative impacts (Arpin-Pont et al. 2016). Significantly, drug and pharmaceutical residues in water must be considered to predict the toxicities (Ali et al. 2009; Ky et al. 2023). Recent investigations have investigated the ecotoxicology of various pharmaceutical compounds in microalgae (Chia et al. 2021). More and more consideration has been attended to pesticides (e.g., organophosphorus compounds), which adversely affect aquatic organisms and threaten human health through the food chains (Xu et al. 2022). Also, many issues concerning the bioavailability of engineered micro/nanoparticles, their uptake by algae/microalgae, and the ecotoxicity mechanisms still need to be investigated. On this basis, the perspectives for ecotoxicity investigations about the contaminants in algal responses must be discussed. Thus far, numerous articles have explored micropollutant abundance and impacts; however, regarding their interaction and ecotoxicology associated with multi-contaminants in the aquatic environment, research explicitly focusing on the challenges remains limited (Azizullah et al. 2022; Banyoi et al. 2022; Othman et al. 2023; Xiao et al. 2023). This work remarks a state-of-the-art review of the current trend on the ecotoxicity of micropollutants to algae. The present investigation aimed to examine the adverse impacts of various micropollutants, e.g., petrochemicals, bisphenol A, pharmaceuticals (antibiotics and drugs), per- and polyfluoroalkyl substances, pesticides, heavy metals, and synthetic nano/microparticles on algae. Thus, ecotoxicology response of algae to contaminants in aquatic environments can establish a significant foundation for aquatic toxicological and risk assessments.

Environmental stress

Anthropogenic-induced disturbances lead to biodiversity degradation in water bodies among the most threatened and vulnerable ecosystems. Pollutants are a significant contributor to producing reactive oxygen species. Changes in cover and land-uses are strong drivers of global environmental degradation, and these human stressors can influence benthic algae (Fierro et al. 2019). Harmful algal blooms greatly damage marine ecosystem risk and human health (Griffith and Gobler 2020; Balaji-Prasath et al. 2022). The adverse impacts of agriculture on the aquatic biota and environment have been elucidated (Gerth et al. 2017). Increased expansion of marine pollution by high cadmium (Cd) contents has highly affected the growth and development of brown macroalga, namely *H. fusiforme* (Zhu et al. 2011). Adverse influences of nanoparticles on aquatic living organisms and the environment have also been given much special consideration (Farré et al. 2009). Nanoparticles could have a high threat and reach high levels, posing a significant risk to aquatic ecosystems. The increasing industrial use of nanomaterials poses potentially harmful threats to ecosystems, mainly living organisms in the environmental matrices. For example, Suman et al. (2015) illustrated that cytotoxic zinc oxide nanoparticles cause microalgae *C. vulgaris* and induce severe oxidative stress. Observations of Kumaresan et al. (2017) demonstrated that sulfate stress impacted the pigment level in blue-green algae *Spirulina* (*A. platensis*) with decreased their growth. It indicated that *A. platensis* could alter the gene expressions specifically included in sulfur-dependent pathways and sulfur metabolism.

While occurring contaminants are released into the environmental matrices, novel ones are being emitted continuously, e.g., engineered nanomaterials, pesticides, aromatic pollutants, pharmaceutical and personal care products, metals, and so on. The emerging concern of micropollutants discharged by municipal and domestic wastewater treatment plants can have an ecological effect on aquatic living organisms and surrounding environments. Consequently, water contamination and degradation have become unexpectedly complex (Lu et al. 2021). Environmental stress—sources, fate, and adverse effects on the aquatic ecosystem, is shown in Fig. 1. These persistent harmful compounds and their metabolites may raise ecotoxicological threats and risks. For instance, emerging micropollutants are illustrated in complex mixtures with various physicochemical characteristics, resulting in adverse health impacts (Archer et al. 2017; Nguyen et al. 2022a). Concerning the threats to health issues, one of the major examinations related to pharmaceutical and personal care products exposure via the aquatic pathway is that it can interfere with and alter the endocrine system. The triazophos residues, a chemical compound used in insecticides, could enter aquatic ecosystems by direct overspray on agricultural fields, surface runoff, and air deposition by rain (Xu et al. 2022). Therefore, these residues cause huge attention and concern for potential health threats to natural ecosystems and humans. Pesticides could inhibit the growth rate, photosynthetic damage, and oxidative stress on algal cells (Xu et al. 2022). The accumulation, distribution, and transfer of emerging micropollutants, e.g., nano/microplastics and persistent organic pollutants in the food chains and webs, is a critical benchmark for investigating its ecological risks (Zheng et al. 2016; Nguyen et al. 2023a, 2023b). The essential ecotoxicological mechanisms of pollutants to aquatic organisms, such as algae, have identified reactive oxygen species generation, cell activity reduction, cell structure damage, and deoxyribonucleic acid damage (Chen et al. 2019). Micropollutants discharged into aquatic ecosystems can trigger biochemical and physiological characteristics and algal ecological responses.

In the global scope, more than 770 pharmaceutical active compounds and their transformative products have been recognized (Couto et al. 2022). The properties of pharmaceutical and personal care products and their risks to the environmental ecosystems and human health issues are determined. The uncontrolled release of polycyclic aromatic hydrocarbons into aquatic ecosystems has posed high risks to aquatic organisms. Polycyclic aromatic hydrocarbons are known as toxic, mutagenic effects, and carcinogenic, particularly by generating reactive oxygen species, including singlet oxygen, hydrogen peroxide, and others. For this reason, their occurrence is considered aquatic micropollutants as a severe concern. Risk assessment induced various hydrocarbons such as polycyclic aromatic hydrocarbons in marine

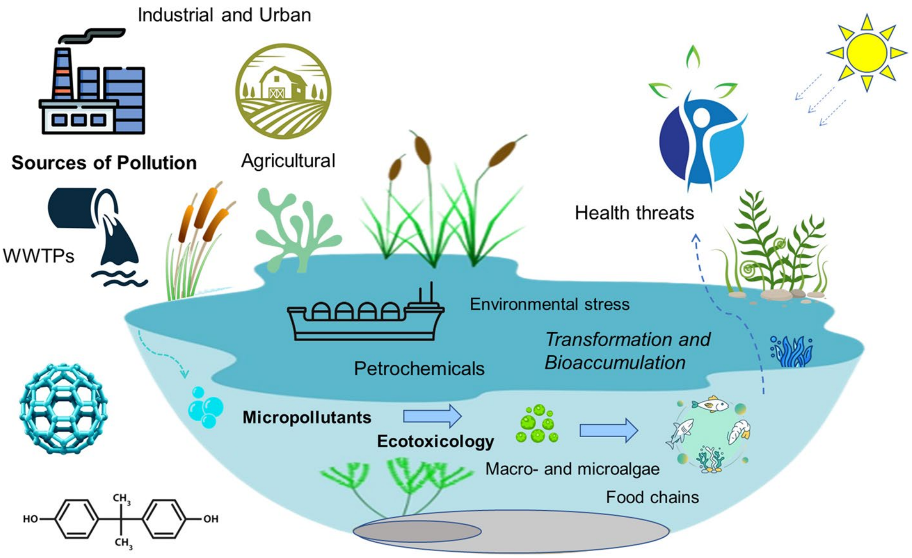

Fig. 1 Environmental stress sources, fate, and effects on the aquatic ecosystem. The environmental stress includes their origins, ecosystem pathways, and detrimental impacts on aquatic environments. The presence of hazardous substances and their by-products can increase ecological threats and risks significantly. WWTPs: wastewater treatment plants

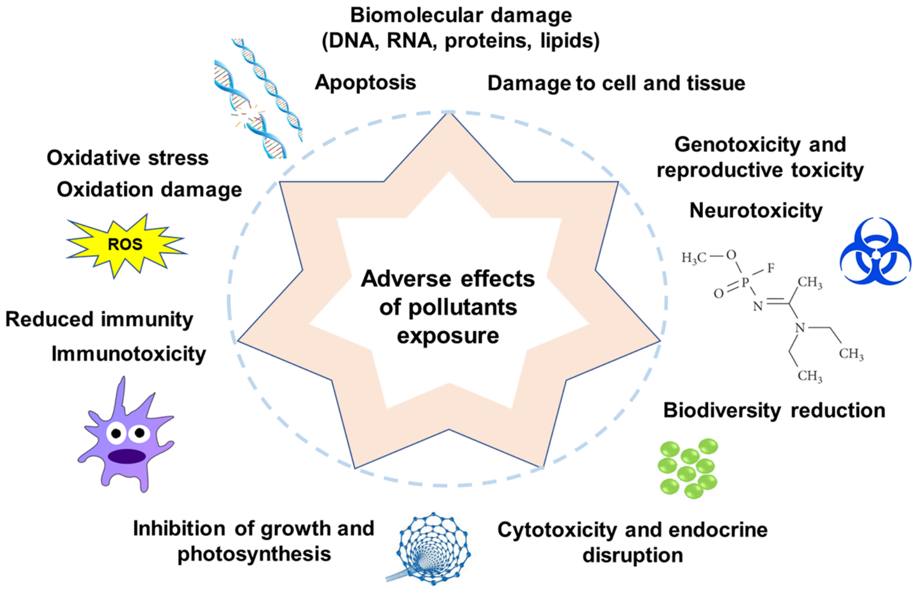

Fig. 2 Physiological and biochemical adverse effects of pollutant exposure on algae (ROS: reactive oxygen species, DNA: deoxyribonucleic acid, RNA: ribonucleic acid). Algae are susceptible to organic and inorganic chemical stressors, affecting them at various biological levels, including biochemical, cellular, community, and population. Micropollutants have the potential to accumulate within algae, resulting in adverse physiological and biochemical effects due to their prolonged exposure

waters can usefully predict the toxicity and their effects on the aquatic ecosystem (Softcheck 2021). Polycyclic aromatic hydrocarbons can inhibit the growth, biochemical, and physiological compositions of the various algal species (Asghari et al. 2020; Tomar and Jajoo 2021). The chemical structure of algal species depends on environmental factors; that is, they can alter to adapt under abiotic stress conditions (Tomar et al. 2022). For example, unfavorable environmental conditions, including pH, temperature, salinity, and nutrient variations, might cause changes in the levels of lipids, carbohydrates, and pigments for microalgae growth.

With increasing awareness of the ecological threats of micropollutants, many efforts have been examined in the past years. Environmental quality degradation and ecological risk have become critical global concerns (Tuan Tran et al. 2022a, b; Nguyen et al. 2023b). Sources of contamination, e.g., the discharge of industrial and domestic streams under uncontrol or improper management, runoff from agricultural and urban areas, and less effective treatment technology, cause an increase in various pollutants into water bodies and aquatic ecosystems (Couto et al. 2022; Nguyen et al. 2022b; Tran et al. 2022a). The biological uptake of persistent organic pollutants through marine phytoplankton has significantly influenced persistent organic pollutants levels in water bodies. The fate, behavior, and transportation of persistent organic pollutants in the marine ecosystem could be affected by algae bioaccumulation and adsorption. The persistent organic pollutants uptake and their accumulation process are involved in a complex manner by cell density and exposure time, as well as critical environmental parameters, i.e., pH, nutrient levels, contents of colloidal and dissolved organic matter, and phytoplankton characteristics (Rhee and Thompson 1992; Qiu et al. 2017).

Further, the biodiversity of ecosystems may be impacted by environmental pollution, which is caused by human activities and even invasive species, which can pose a high risk (Quetglas-Llabrés et al. 2020). For instance, the invasive red algae *L. lallemandii* induces oxidative stress and affects coastal marine ecosystems, e.g., sea urchin *P. lividus* (Quetglas-Llabrés et al. 2020). Another critical property that might harm aquatic ecosystems is contamination from human activities. After algae adsorb pollutants such as polycyclic aromatic hydrocarbons, pharmaceutical and personal care products, and heavy metals, they are ingested by higher trophic levels, such as fish and shrimp, which are enriched along the food chains. Thousands of toxic micropollutants have been discharged into the marine environment that can adversely impact their biological functions. Aquatic ecosystems can also be influenced differently, associated with the type of pollution, location, and chronic or acute exposure. Particularly, polycyclic aromatic hydrocarbons are recognized as priority micropollutants, e.g., some polycyclic aromatic hydrocarbons have been indicated as an essential concern for the environment and health risk in the European Union and the USA (Samanta et al. 2002; Othman et al. 2023). Therefore, the potential effects of ecological threats regarding various micropollutants on algae have drawn increasing interest. It required that aquatic ecotoxicology combines toxicology and ecology to integrate and examine the impacts of contaminants via biological levels, from the molecular to cellular levels, aquatic communities and even ecosystems (De Boeck et al. 2022).

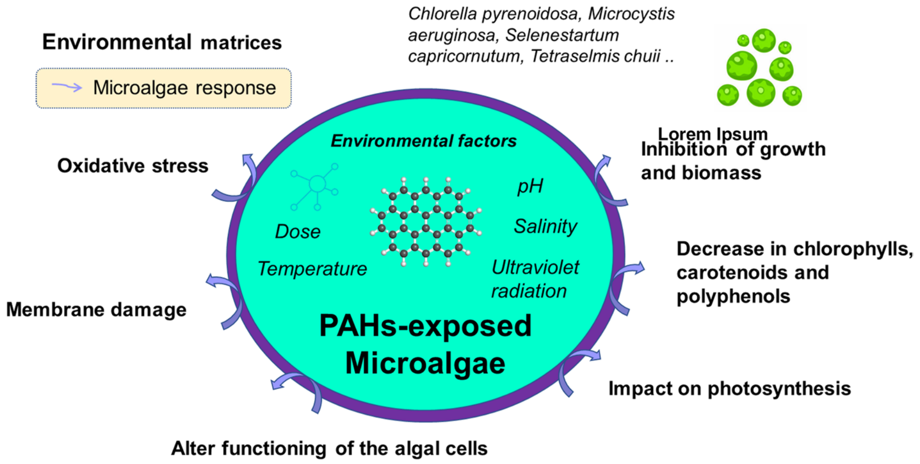

Fig. 3 Microalgae response to polycyclic aromatic hydrocarbons exposure (PAHs: polycyclic aromatic hydrocarbons). Exposure to polycyclic aromatic hydrocarbons induces significant stress responses in microalgae, leading to changes in enzymatic activities and biochemical compositions. Polycyclic aromatic hydrocarbons have the potential to modify cell membrane permeability by influencing lipids and proteins, indicating a negative impact on algal cells and their normal functioning. These effects depend on environmental factors such as pH, temperature, salinity, and ultraviolet radiation

Ecotoxicology response of algae to contaminants

Chemical, biological, and physical factors influence the ecotoxicity of chemicals to algae, leading to effects at the biological community level that can become complex (Genter 1996; Elersek et al. 2021; Ford et al. 2021). Organic and inorganic chemical stress impacts algae at biological organizations' biochemical, cellular, community, and population levels (Li et al. 2022; Pastorino et al. 2022; Zhang et al. 2023). Micropollutants can accumulate in algae, leading to physiological and biochemical adverse effects due to their exposure are shown in Fig. 2. The significance of transition heavy metals, e.g., chromium (Cr), copper (Cu), arsenic (As), and mercury (Hg), and pesticides, namely herbicides, insecticides, and fungicides along with oil products in the induction of oxidative stress in an aquatic ecosystem is also highlighted (Lushchak 2011; Xiao et al. 2023).

Polycyclic aromatic hydrocarbons

Global and local stressors highly threaten oil pollutants. Particularly, due to the incomplete combustion of living and fossil fuel types, petroleum processing or oil spills, industrial and urban runoff, and so on from human activities and natural sources that polycyclic aromatic hydrocarbons can enter aquatic ecosystems (Boehm and Page 2007; Nizzetto et al. 2008; Zhang et al. 2021). Uptake and polycyclic aromatic hydrocarbons accumulation in food chains and ecosystems have been recognized as significant health and environmental concerns. Figure 3 presents an illustration of microalgae response to polycyclic aromatic hydrocarbons exposure.

Several studies concluded that polycyclic aromatic hydrocarbons in the water column could cause an indirect impairment of aquatic environmental ecosystem health by these contaminations. More severe stress responses by polycyclic aromatic hydrocarbons-exposed microalgae could change enzymatic activities and biochemical contents (Othman et al. 2023). Due to the hydrophobic properties of polycyclic aromatic hydrocarbons, algal lipid level is influenced by this exposure and could cause damage to the cells. Depending on exposure doses, polycyclic aromatic hydrocarbon exposure to microalgae (e.g., single compounds and/or mixture) could lead to a decline in growth rates, photosynthetic, and biomass (Othman et al. 2023). These micropollutants can alter the functional absorption of photosystem II and the fluorescence yield, both critical proxies for the photosynthetic process. Furthermore, environmental conditions or factors, e.g., temperature and sunlight radiation, can also increase the algal community's ecotoxicity of polycyclic aromatic hydrocarbons.

Polycyclic aromatic hydrocarbons are toxic to organisms because they can interfere with the membrane functions of enzymes or proteins in cellular membranes. Regarding polycyclic aromatic hydrocarbons toxicity to microalgae, *S. capricornutum* (green microalgae) cultivated with anthracene illustrated a growth inhibition with a half-maximal inhibitory concentration of 16 µg L^{-1}, and the anthracene toxicity contributed to increasing the ultraviolet A light exposure of the alga (Gala and Giesy 1994). The microalgae *T. chuii* exposed to phenanthrene, anthracene, and naphthalene for 96 h reported a growth restraint that the ecotoxicity was, respectively, phenanthrene—anthracene—naphthalene, and this ecotoxicity was promoted by the increase of temperature (Vieira and Guilhermino 2012). Also, Kottuparambil and Park (2019) showed that the microalgae *E. agilis* cultivated with rising anthracene levels varied from 0.35 to 84 µM for 96 h, indicating a reduced in the content of carotenoids and chlorophylls, in photosynthetic efficiency, and in growth. The *Ulva lactuca* (known as green macroalga) exposed to gasoline involving naphthenic, paraffinic, aromatic, olefinic hydrocarbons, and isoparaffinic demonstrated a reduction in carotenoids, chlorophylls, and polyphenols contents (Pilatti et al. 2016). Anthracene caused a significant increase in lipoperoxides due to oxidative degradation reaching a 24-h maximal level, showing that oxidative stress caused *Chlorophyta's* membrane damage (González et al. 2021). The potentially toxic *M. aeruginosa* responded to anthracene contamination by altering the microcystin biosynthesis gene clusters (Bi et al. 2016). A substantial increase in microcystin level was demonstrated after 12-day exposure; consequently, the gene *mcyB* was repressed, indicating that polycyclic aromatic hydrocarbons pollution in the aquatic ecological community can cause unexpected alternations and harmful changes.

Polycyclic aromatic hydrocarbons are a group of organic chemical compounds comprising two or more joined-together aromatic rings categorized as persistent organic contaminants. Recently, the polycyclic aromatic hydrocarbon effects on microalgae have been carried out by Othman et al. (2023). Photosynthesis, the critical process conducted by algae, takes place to be the most influenced by polycyclic aromatic hydrocarbons exposure. Due to its hydrophobic nature, polycyclic aromatic hydrocarbons-related ecotoxicity effects on algae can interfere with cell biomolecules. Polycyclic aromatic hydrocarbons can cause severe stressors such as oxidative stress or membrane damage to algae. The influences of polycyclic aromatic hydrocarbons are determined by both species- and dose-dependent and are affected by environmental conditions, e.g., temperature, salinity, ultraviolet radiation, etc. (Othman et al. 2023). Further, Tomar et al. (2022) investigated the bioremediation of *Chlorella vulgaris* for several polycyclic aromatic hydrocarbons (such as naphthalene, anthracene, and pyrene) and their effects on the growth and photosynthesis of *C. vulgaris*. Under seven-day polycyclic aromatic hydrocarbons exposure, the growth of algae *C. vulgaris* was impacted within the order of pyrene—anthracene—naphthalene. Concerning biomolecules, polycyclic aromatic hydrocarbons experiments reported a notable reduction in lipid levels, especially the ecotoxic impact of pyrene was also marked. Polycyclic aromatic hydrocarbons might alter the permeability of cell membranes by influencing their lipids and proteins. This indicates that polycyclic aromatic hydrocarbons negatively affect the algal cells and can change their functioning.

Bisphenol A

In those days, high concentrations of serious toxicants were found in the ecosystems causing chronic and acute influences (Schmitt-Jansen et al. 2008). Prominent illustrations come from significant exposures to endocrine-disrupting chemicals such as bisphenol A. These ecotoxicants are usually characterized by long persistence, high toxicity, and bioaccumulation. For a comprehensive investigation, the molecular responses of algae related to bisphenol A exposure have been presented (Azizullah et al. 2022). Due to their extensive applications in industrial products, e.g., epoxy resins (polyepoxides) or polycarbonate plastics, bisphenol A is an emerging micropollutant, causing an increase in environmental pollution and detrimental influences on organisms. Bisphenol A negatively disturbs algae species by inhibiting various biochemical and physiological processes (Azizullah et al. 2022). They could induce cytotoxicity, neurotoxicity, genotoxicity, reproductive toxicity, and endocrine system disruption in exposed aquatic life (Bonefeld-Jørgensen et al. 2007; Yang and Hong 2012; Guo et al. 2017). For instance, after ten-day exposure, bisphenol A at 50 mg L^{-1} induced serious growth restraint of 18% in *C. mexicana* and 85% in *C. vulgaris* (Ji et al. 2014).

The half maximal effective concentration (EC_{50}) obtained 9.9 mg L^{-1} in *P. subcapitata* after 72-h exposure indicated that bisphenol A can inhibit the growth of *P. subcapitata* (Elersek et al. 2021). Bisphenol A exerted comparable toxic potential EC_{50} was below 3.5 mg L^{-1} in *D. subspicatus* (Tišler et al. 2016). Further, higher EC_{50} values were reported, varying from 20 to 89 mg L^{-1} for algae species such as *C. mexicana* and *C. vulgaris* (Ji et al. 2014). Findings also indicate that algal species are more sensitive to bisphenol A. Czarny-Krzymińska et al. (2022) examined microalgae in 14-day exposure time to bisphenol A that indicated EC_{50} varied from 42.1 to 42.5 mg L^{-1} and toxically adverse impacts to their structural congeners.

Due to widespread distribution and occurrence in aquatic ecosystems, bisphenol A can pose threats to the producers, typically algae (Czarny-Krzymińska et al. 2022). Previous investigations have indicated that bisphenol A harms aquatic living organisms and could lead to endocrine-disrupting impacts, especially potentially related to a variety of other contaminants, causing adverse health consequences (Liang et al. 2021; Wang et al. 2021). The effects of bisphenol A on chlorophyll level, cell growth, and oxidative stress of algae *C. pyrenoidosa* have been reported (Li et al. 2022). Thus, evaluating bisphenol A's influences on algae species in aquatic ecosystems gives essential data aid to investigating their potential threats. The level of bisphenol A affected the chlorophyll synthesis, recommending that oxidative stress may inhibit cell growth. Further, the increased negative impact caused by a mixture of chemicals poses a significant threat to microalgae.

Pharmaceutical and personal care products

Pharmaceutical and personal care products involve thousands of various chemical compounds, e.g., nonsteroidal anti-inflammatory drugs and antibiotics, prescription and/or nonprescription drugs, illegal drugs, veterinary drugs and their metabolites, hygiene products, cosmetics, bath, and hair products (Cizmas et al. 2015). Anthropogenic activities cause exposure of a living organism, such as algae, to active endocrine substances and endocrine disruptors. The primary sources of pharmaceutical and personal care products are the pharmaceutical industry, aquafarms, agricultural areas, wastewater treatment plants, and effluents, especially untreated sewage from hospitals (Luo et al. 2018; Lu et al. 2019; Tran et al. 2022b). Pharmaceutical and personal care products can cause unexpected impacts on algae species and their communities (Xin et al. 2021). Therefore, multiple algae endpoints can be applied to illustrate an entire assessment of the ecotoxicity of pharmaceutical and personal care products. Miazek and Brozek-Pluska (2019) conducted a review concentrating pharmaceutical and personal care products' ecotoxicity on microalgal growth and metabolism. Several algal species showed sensitive responses to pharmaceutical and personal care products contamination, e.g., *P. subcapitata, C. vulgaris, C. pyrenoidosa*, *S. obliquus* (Wang et al. 2016). pharmaceutical and personal care products can affect algal biochemical and physiological properties (Lushchak 2011). Algal metabolism is likely related to the transport and biochemical processes involved by pharmaceutical and personal care products. Several common reactive oxygen species, i.e., superoxide, hydroxyl radical, and hydrogen peroxide induced by pharmaceutical and personal care products, which could induce biomolecular damage, including ribonucleic acid, deoxyribonucleic acid, lipids, and proteins (Martín-Díaz et al. 2009; Lushchak 2011). Moreover, the influences of pharmaceutical and personal care products on the algae community can be assessed by toxicity and their bioaccumulation. Due to similar physicochemical characteristics, pharmaceutical and personal care products could cause impacts on algal communities, e.g., those with an octanol–water partition coefficient ≥ 3 to be bioaccumulated potential to algae (Van der Oost et al. 2003). Cytarabine, also known as cytosine arabinoside, is likely to be inhibited the growth and development of algae with EC_{50} varying from 53 to 100 mg L^{-1} (Zounkova et al. 2010).

As they are a fundamental group of emerging organic contaminants, there is a rising concern related to the severe impacts of pharmaceutical contamination. Antibiotics and nonsteroidal anti-inflammatory drugs are a group of fundamental drugs characterized, e.g., able to be highly persistent in the environmental matrices, are widely prescribed globally, and lead to long-term ecotoxicity. It also was investigated to examine the ecotoxicity in various living organisms (Magdaleno et al. 2015; Minguez et al. 2016; Wang et al. 2020). Similarly, De Boeck et al. (2022) investigated the ecotoxicity of various antibiotics and nonsteroidal anti-inflammatory drugs on green algal species, including *D. spinosus* and *Chlorella sp*. Based on the 96-h median effect concentration values, findings demonstrated that tetracycline was usually more toxic than other antibiotics such as amoxicillin and ciprofloxacin; meanwhile, paracetamol is considered to be a higher risk compared to diclofenac and ketoprofen. Pharmaceutical compounds cause adverse effects on microalgae metabolism and growth through disruption of the photosynthetic and gene expression, as well as dramatically enhancing reactive oxygen species formation and altering the activities and functions of antioxidant enzymes (Chia et al. 2021).

Per- and polyfluoroalkyl substances

Per- and polyfluoroalkyl substances are a kind of chemical compound used globally and approximately 4700 synthetic chemicals (Banyoi et al. 2022). They have been utilized in commercial and industrial products since the 1950s. These per- and polyfluoroalkyl substances are applied in various products and found in environmental matrices and living organisms around the world. From daily usage and manufacturing processes, and due to their high bioaccumulation and persistency in the environment, per- and polyfluoroalkyl substances distribute commonly in aquatic ecosystems, leading to potential ecotoxicity (Buck et al. 2011). Some per- and polyfluoroalkyl substances are a large family of persistent industrial chemical compounds with endocrine-disrupting characteristics that are harmful and considered as endocrine-disrupting chemicals. Per- and polyfluoroalkyl substances contamination can affect the algae and cause severe impacts on higher trophic organisms. Many investigations have illustrated the ecotoxicity of long-chain per- and polyfluoroalkyl substance on several aquatic life (e.g., fish, algae, or Daphnia, etc.), highlighting that algae are one of the most sensitive life forms to per- and polyfluoroalkyl substance-contaminated environments (Ding et al. 2012).

In the research of Niu et al. (2019), three concentrations (10 ng L^{-1} to 1000 ng L^{-1}) for these per- and polyfluoroalkyl substances were tested to examine the toxical response of algae *Chlorella sp.* for an exposure time of 14 days. The emerging per- and polyfluoroalkyl substances could affect aquatic ecosystems, these influences extremely inhibit the growth of algae *Chlorella sp*. For instance, per- and polyfluoroalkyl substances are conveyed from the inland to pose a potential risk to marine, these pollutants may induce oxidative stress and affect physiological processes and algal growth (Mallick and Mohn 2000; Niu et al. 2019). Liu et al. (2008) indicated that perfluorooctanesulfonic acid impeded the growth and development of algae *S. obliquus* with a 96-h median effect concentration of 99.9 mg L^{-1}. Per- and polyfluoroalkyl substances could enter the aquatic ecosystem from several sources, e.g., leakage from the production of fluorochemicals, atmospheric disposition, firefighting foams, industrial and household activities, and/or wastewater treatment plants (Evich et al. 2022).

Among per- and polyfluoroalkyl substances, perfluorooctane sulfonic acid and perfluorooctanoic acid were determined to be the two main kinds discharged to the environment. Per- and polyfluoroalkyl substance, particularly those with longer carbon chains, particularly perfluorooctanoic acid or perfluorooctane sulfonic acid, have been reported to be environmentally persistent, with ecotoxic impacts associated with bioaccumulation potential (DeWitt et al. 2012; Fenton et al. 2021). Emerging per- and polyfluoroalkyl substance mixture can interrupt photosynthesis, reactive oxygen species metabolism, and deoxyribonucleic acid replication in algae *C. pyrenoidosa*, demonstrating the environmental threats and risks (Liu et al. 2022). Although these per- and polyfluoroalkyl substance levels in the environmental matrices are relatively low (ng L^{-1}–mg L^{-1}), the exposure to per- and polyfluoroalkyl substances mixture caused exhibits more substantial toxic impacts than individual per- and polyfluoroalkyl substance on algae. Under the per- and polyfluoroalkyl substances mixture exposure, the gene expression linked to deoxyribonucleic acid replication was interrupted, inhibiting the algae growth. The wide use and persistent occurrence of emerging per- and polyfluoroalkyl substances in the aquatic ecosystem could cause toxical influences, particularly some per- and polyfluoroalkyl substance such as GenX chemicals, which could disorder the metabolism of algae *C. pyrenoidosa* (Li et al. 2021; Liu et al. 2021b).

Pesticides

In agricultural activities, widespread use of pesticides, e.g., organophosphorus compounds, leads to massive residues in environmental matrices, especially in aquatic ecosystems. Regarding pesticide accumulation, pesticide levels in the aquatic environment have increased over time. Pesticides can cause indirect and/or direct ecotoxicity to microalgae. For instance, *Chlorella pyrenoidosa* has been applied as an algal species in ecotoxicological investigations for risk examination of organophosphorus compounds (Chen et al. 2016). Du et al. (2023) illustrated that temperate and Arctic microalgae were sensitive to insecticides, e.g., such as trifluralin and chlorpyrifos, regarding pesticide ecotoxicity. Furthermore, the growth of temperate microalgae, e.g., *M. bravo, C. neogracile*, and Arctic microalgae, e.g., *M. polaris, C. neogracilis*, was acutely inhibited at the chlorpyrifos concentrations at 500 µg L^{-1} and 200 µg L^{-1} (Du et al. 2023).

Several herbicides adversely impact photosynthesis due to damaging cellular oxidative induced by reactive oxygen species accumulation and formation. It was illustrated that the oxidative stress and sensitivity caused by pesticides to algal species (Medithi et al. 2021). The 96-h acute toxic effects of triazophos (1.0 and 10 mg L^{-1}) on the algae *Chlorella pyrenoidosa* were also reported (Xu et al. 2022). Findings indicate that the algal cellular structure was damaged by triazophos exposure, and the growth of algae *C. pyrenoidosa* was dramatically reduced by pesticides such as triazophos. More significantly, it was shown that the inhibition rates were decreased by 25.7% (1.0 mg L^{-1}) and 39.5% (10 mg L^{-1}) after 96-h exposure, respectively. Also, results showed that oxidative stress damage in *C. pyrenoidosa* and their growth was notably inhibited by triazophos with the 96 h-EC_{50} was 12.79 mg L^{-1}. The growth inhibition of algae was accordant with the raised intracellular reactive oxygen species, malondialdehyde level, and activity of antioxidant enzymes illustrating lipid peroxidation and oxidative damage in the algal cells. Further, the toxic response of the freshwater algae *S. obliquus* has experimented with herbicides, e.g., fenhexamid, atrazine, and lactofen (Mofeed and Mosleh 2013; Cheng et al. 2015). Kurade et al. (2016) described that the green microalgae *C. vulgaris* responded to diazinon by enhancing the algal enzymatic antioxidant in 12-day exposure time. Therefore, ecotoxicology is essential to investigate an in-depth knowledge of their toxicity, the action mode of pesticides, and the adverse effects at the population and/or organism level.

Heavy metals

Heavy metals originated from wastewater treatment plants and industrial activities contaminating the environment, and they are long-standing due to their non-biodegradable properties, which are ecotoxic to ecosystem threat and human health (Phan et al. 2020; Zamani-Ahmadmahmoodi et al. 2020; Xiao et al. 2023). Heavy metals have been recognized as an adverse global environmental risk due to their wide occurrence, distribution, high bioaccumulation, and biotransformation. The occurrence, distribution, and fate of heavy metal contaminants in aquatic environments critically rely on the characteristics of industrial fields, e.g., mining, paint, metallurgy, battery, hair dye, machinery, electroplating process, and so on, and daily urban activities, e.g., traffic emissions, air deposition, and domestic waste streams (Hepburn et al. 2018; Saleem et al. 2019). Heavy metals can be accumulated in microalgae and then aggregate transfer at higher trophic organisms via the food chains and webs.

Moreover, heavy metals can alter important cofactors in proteins and enzymes, leading to abnormal metabolism in algae (Lu et al. 2021). These peculiar processes produce excessive reactive oxygen species, an important cause that induces adverse impacts. Consequently, they can severely damage cellular components, i.e., proteins, lipids, nucleic acids, amino acids, and lipid membranes (Qian et al. 2011; Jamers et al. 2013; Byeon et al. 2021). More seriously, heavy metals severely impact the algal community and may lead to their death (Xiao et al. 2023). However, the harmful impacts are associated with heavy metal species, levels, and environmental factors. For instance, the growth of *Chlorella vulgaris* can be inhibited at 60 µmol L^{-1} Zn(II) and 80 µmol L^{-1} Cd(II) (Leong and Chang 2020). Growth inhibition is also associated with the microalgae species and the exposure time to metals. Concerning response to cadmium (Cd) exposure of brown algae *S. fusiforme*, Zhang et al. (2015) reported that an increase in Cd ion could lead to a significant reduce in algae growth rate. Cd-related ecotoxicity could disrupt and alter membrane integrity, and inactivate the enzymes of multiple metabolic processes, consequently the disturbances in response inhibition of algal physiological activities (Lee and Shin 2003; Zhang et al. 2015).

Microalgae respond to a toxic environment by altering intracellular ultrastructure and cell morphology, e.g., cellular size, cellular debris, cytoplasmic vacuolation, starch accumulation by granules, and electron-dense granules (Xiao et al. 2023). The critical responses of microalgae to heavy metal stress were previously examined, e.g., *Scenedesmu*, *Chlorella*, *Chlamydomonas reinhardtii, Cyanobacterium*, etc. (Pradhan et al. 2019; Gu et al. 2020; Geng et al. 2021). The ecotoxicological responses vary between microalgae species and heavy metals (Table 1). Major challenges in aquatic ecotoxicology are that communities are exposed to multiple stressors. It shows heavy metals cause significantly influence the physiological and biochemical processes of microalgae. Under heavy metal-induced stress, living organisms such as microalgae can generate several extracellular polymeric substances, i.e., proteins, lipids, polysaccharides, non-polymeric substances, uronic acids, etc. For detail, associated with the characters of the functional groups and cell surface, extracellular polymeric substances could be engaged in the sorption of heavy metal ions (Naveed et al. 2019). Moreover, high heavy metal levels strongly impact algae's biochemical and physiological processes, including cell ultrastructure, photosynthesis, growth, the composition of fatty acids, and protein content (Xiao et al. 2023). Heavy metals can cause the formation of critical reactive oxygen species (e.g., singlet oxygen, hydroxyl radicals, and hydrogen peroxide) in cells, which primarily induces the oxidation damage of lipid, protein, and thiol peptides, as well as activation of the antioxidant system (Fig. 4). Heavy metals exert a toxic influence on algae at molecular and cellular levels (Priyadarshini et al. 2019). The high contamination of heavy metals damages the cellular system, and further alters its populations. Interaction between algae and toxic heavy metals adversely impacted their physiological, biochemical, and enzymatic activities, ultimately causing their death.

Synthetic nano/microparticles

Over the last few years, an increase in reports on the unexpected effects of nano/microparticles on algae has been demonstrated (Middepogu et al. 2018; Pereira et al. 2020; Pastorino et al. 2022; Minh-Ky et al. 2023). Carbon-based nanomaterials, e.g., carbon nanotubes, graphene, and fullerenes, have been recognized in aquatic ecosystems. The literature search revealed that the presence of nanoparticles such as carbon nanotubes would enter natural aquatic environments in combination with other organic compounds. For instance, exposed to carbon nanotube of *Pseudokirchneriella subcapitata* with EC_{50} up to 17.95–20 mg L^{-1} regarding the toxicity sensitivities (Schwab et al. 2011; Lukhele et al. 2015). Kwok et al. (2010) conducted *Thalassiosira pseudonana* exposure to multi-walled carbon nanotubes, leading to growth and development inhibition of microalgae reaching EC_{50} of 1.9 mg L^{-1}.

Among engineered nanoparticles, metal oxide nanoparticles are commonly used in various commercial products and are causing concerns about their potentially harmful influences on environmental health and human beings (Aschberger et al. 2011; Banu et al. 2021; Grasso et al. 2022). To observe the ecotoxicity mechanism, algae *C. vulgaris* were tested with 50, 100, 200, and 300 mg L^{-1} zinc oxide nanoparticles for exposure of 24 h and 72 h (Suman et al. 2015). The cytotoxicity assay measure indicated a substantial decrease in the viability that depended on the exposure time and dose. The cell wall damage and substantial morphological alternations were confirmed by Suman et al. (2015). Investigations of the zinc oxide nanoparticles biotoxicity illustrate critical mechanisms of nanoparticle influence, indicating their potentiality to release free Zn(II) ions, which could synergistically promote reactive oxygen species production, resulting in oxidative damage in cells. Overproduction of reactive oxygen species is reported to be the most important mechanism of nanoparticle toxicity (Sharifi et al. 2012; Pastorino et al. 2022). In this manner, chemical reactions occur, leading to increasing formation and accumulation of reactive oxygen species, such as superoxide radicals, causing oxidative stress.

Toxic influences on green alga *A. superbus* were investigated and supported on various associations of nano-zinc oxide, Degussa P25-titanium dioxide, and antimicrobial agents (i.e., triclosan) under multiple illuminations (Xin et al. 2020). Degussa P25 is primary for the antioxidant enzyme, lipid peroxidation, and oxidative stress. Degussa

Table 1 Ecotoxicological response of algae to contaminants in aquatic environments

Category	Algae	Pollutants	Influences	Remarks	References
Polycyclic aromatic hydrocarbons	*Ulva lactuca* (Chlorophyta)	Anthracene	Indicated that oxidative stress caused membrane damage	Anthracene induces oxidative stress	González et al. (2021)
Bisphenol A	*Chlorella vulgaris*	Anthracene Naphthalene Pyrene	Impact on photosynthetic, biochemical properties/functions and their bioremediation With regard to biomolecules, illustrate a significant reduction in lipid level Alternations in microalgae cells	Tested polycyclic aromatic hydrocarbons at 5 mg L^{-1} invoked a biochemical response in *C. vulgaris* Toxic influence of pyrene was more pronounced	Tomar et al. (2022)
	Phaeodactylum tricornutum	Fluoranthene	The marine microalgae to be applied as a model in ecotoxicity testing T-iso indicates higher sensitivity for most toxicants	$EC_{50} = 2838$ μg L^{-1} under the 72 h-growth inhibition	Tato and Beiras (2019)
	Chlorella vulgaris	Fluoranthene	Alternations in growth, physiological compositions, and biochemical characteristics of the algae Adversely impacted by the higher level of fluoranthene	Fluoranthene = 5 μM and 25 μM $EC_{50} > 5000$ μg L^{-1}	Tomar and Jajoo (2021)
	Raphidocelis subcapitata	Phenanthrene	The growth inhibition of the algae *R. subcapitata* caused by polycyclic aromatic hydrocarbons Polycyclic aromatic hydrocarbons indicated inhibiting effects on the algal growth	The growth inhibition test over 72 h $EC_{50} = 120$ μg L^{-1} These organic micropollutants may pose to the ecosystem	Kreutzer et al. (2022)
	Tetraselmis suecica, *Selenastrum capricornutum, Picocystis sp.*	Bisphenol A	Bisphenol A negatively impacts algae by inhibiting biochemical and physiological processes Bisphenol A can be categorized as harmful and toxic to algae	EC_{50} in the variation between 1–10 and 10–100 mg L^{-1}	Azizullah et al. (2022)
	Pseudokirchneriella subcapitata	Bisphenol A	Toxic to algae *P. subcapitata* Bisphenol A represents an environmental risk	Tested bisphenol A = 5 mg L^{-1} Growth inhibition of *P. subcapitata* over 72 h exposure $EC_{50} = 9.9$ mg L^{-1}	Elersek et al. (2021)

Table 1 (continued)

Category	Algae	Pollutants	Influences	Remarks	References
	Chlorella vulgaris	Bisphenol A	Exposure to bisphenol A and its combined structural congeners cause synergistic impacts Potential ecological risk Poses a serious threat to microalgae	Tested compounds were added 5–100 mg L^{-1} of bisphenol A $EC_{50} = 42.3$ mg L^{-1} (period of 14 d)	Czarny-Krzymińska et al. (2022)
Pharmaceutical and personal care products	*Chlamydomonas reinhardtii*	Triclosan/antimicrobial	Highly toxic to algae Inhibition of algal growth	$EC_{50} = 184$ µg L^{-1} in the duration of exposure 24 h	de Almeida et al. (2017)
	Desmodesmus subspicatus	17α-ethinylestradiol/Hormones	Toxic effects occurred for *D. subspicatus*	Exposed to algae at a level of 0.01–3.2 mg L^{-1} $EC_{50} = 0.04$ mg L^{-1} (duration of 24 h)	Salomão et al. (2014)
	Chlamydomonas reinhardtii	Benzophenone-3/Ultraviolet filter	Benzophenone-3 might regulate the growth of *C. reinhardtii* such as influencing pigment production	The test was exposed to concentrations of BP-3 for 10 d, at levels between 0.01 and 5000 µg L^{-1} $EC_{50} = 1.8$ mg L^{-1}	Mao et al. (2017)
Per- and polyfluoroalkyl substances	*Chlorella* sp.	Per- and polyfluoroalkyl substances	Per- and polyfluoroalkyl substance reduced the growth of marine *Chlorella sp.* 1000 ng L^{-1} exposure could lead to the serious growth reduction	Emerging per- and polyfluoroalkyl substances are not safe for the ecosystems	Niu et al. (2019)
	Chlorella pyrenoidosa	Per- and polyfluoroalkyl substances	Certain growth inhibitory effects on *C. pyrenoidosa* Per- and polyfluoroalkyl substance mixture interrupted photosynthesis, reactive oxygen species metabolism, and deoxyribonucleic acid replication in algae Exposure of 100 mg L^{-1}: inhibition rate of algae 33.16–39.92%	Damage to the photosynthetic, inhibition of deoxyribonucleic acid replication, and obstruction of reactive oxygen species metabolism Environmental risk of emerging per- and polyfluoroalkyl substance Concentrations = 100 ng L^{-1}, 10 µg L^{-1}, 1 mg L^{-1}, 20 mg L^{-1}, and 100 mg L^{-1} Treatment period: 12 d	Liu et al. (2022)
	Chlorella vulgaris	Perfluorooctane sulfonic acid	Mainly exhibited as antagonistic for *C. vulgaris*	Exposure level was set at 0.01 mg L^{-1} to 500 mg L^{-1} $EC_{50} = 117.4$ mg L^{-1} Ecological risks of emerging polyfluorinated compounds	Zhang et al. (2023)

Table 1 (continued)

Category	Algae	Pollutants	Influences	Remarks	References
Pesticides	Chlorella pyrenoidosa	Triazophos/ Insecticide	The morphology of thylakoid chloroplast (algal cells) was damaged Triazophos indicates potential ecotoxicity and environmental threats Triazophos can inhibit the energy metabolism of *Chlorella pyrenoidosa*	The 96 h-acute toxic influences of 1 and 10 mg L^{-1} triazophos 96 h-EC_{50} obtained at 12.8 mg L^{-1}	Xu et al. (2022)
	Chlorella vulgaris	Diazinon/Insecticides	Diazinon affected the biochemical properties of *C. vulgaris*	The degradation rate of diazinon (0.5–100 mg L^{-1}) ranged between 0.23 and 0.05 d^{-1}	Kurade et al. (2016)
Heavy metals	*Chlorella vulgaris*, *C. sorokiniana*,*C. ellipsoidea*, C.*pyrenoidosa*, *Scenedesmus dimorphus*, *C. reinhardtii*, *S.obliquus, Aphanothece* sp.	Cu, Cr, Pb, Cd	Physiological effect on growth Pb (II) causes oxidative stress in *S. obliquus* cells	Microalgae is a promising method for the bioremediation of heavy metal-polluted water	Danouche et al. (2020)
	Phaeodactylum tricornutum	Cd	Impact on cell morphology and ultrastructure	Characterize the morphology-dependent Cd homeostasis and detoxification	Ma et al. (2021)
	Chlorella vulgaris	Cd, Zn	Physiological effect on growth Cell damage at a high level Cd bioaccumulation in algal cells and severe harm to *C. vulgaris*	*C. vulgaris* can be used as an early warning indicator of Cd pollution	Geng et al. (2021)
Nano/micro-particles	*Chlorella pyrenoidosa*	Nano-titanium dioxide	n-titanium dioxide inhibited algal growth Threat to the photosynthesis of algae	*Chlorella pyrenoidosa* was exposed to different concentrations (0, 0.1, 1, 5, 10, and 20 mg L^{-1}) $EC_{50}=9.1$ mg L^{-1}	Middepogu et al. (2018)
	Chlorella sp., *Raphidocelis subcapitata*, *Dunaliella tertiolecta*	Carbon-based nanomaterials	Slightly toxic for most aquatic organisms Algae are known as one of the sensitive aquatic organisms to carbon-based nanomaterials	$EC_{50}=23.7\pm28.9$ mg L^{-1}	Freixa et al. (2018)

EC_{50}: Half maximal effective concentration

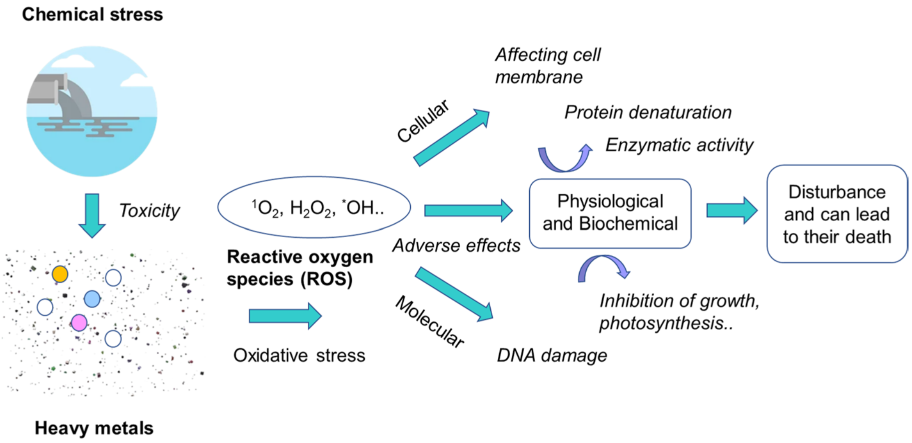

Fig. 4 Toxic influence on algae induced by heavy metals (DNA: deoxyribonucleic acid, $^1O_2$: singlet oxygen, H_2O_2: hydrogen peroxide, *OH: hydroxyl radicals). Heavy metals have the potential to generate harmful reactive oxygen species, such as singlet oxygen ($^1O_2$), hydroxyl radicals (*OH), and hydrogen peroxide (H_2O_2). This process primarily leads to oxidative damage in lipids, proteins, and thiol peptides. The levels of heavy metals significantly affect various biochemical and physiological processes in algae, including alterations in cell structure, photosynthesis, growth, fatty acid composition, and protein content

P25*nano-zinc oxide is the critical interaction of micropollutants, influencing lipid peroxidation, macromolecules, and photosynthesis. When nano-zinc oxide, Degussa P25, and triclosan enter into natural ecosystems simultaneously or individually, they could cause various impacts on aquatic algae. Similarly, various aquatic organisms also can exhibit sensitivity to nanomaterials. Trace levels at 10 µg L^{-1} of silver nanoparticles can activate the growth and development of algae in experiments (Lu et al. 2020). The ecotoxicity of silver nanoparticles was reported to result in interactions of the dissolution, particle uptake, and cause of oxidative stress for living organisms (Liu et al. 2021a). It showed the bio uptake, physiological responses, and metabolic perturbations related to interactions of citrate-coated silver nanoparticles (20 nm) with the alga *P. malhamensis*. The silver nanoparticle exposure increased with time and induced meaningful bioaccumulation of Ag into an algal cell. Also, other results showed high sensitivity to a broad range of toxic nanoparticles, such as n-titanium dioxide and n-zinc oxide to algae species *C. tenuissimus* (Pastorino et al. 2022).

Regarding the impacts of combined exposures of nano/microplastic particles and chemicals, these particles can facilitate the bioaccumulation of micropollutants into exposed organisms. Previous investigations demonstrated that tiny particle sizes of microplastics had higher ecotoxicity in the microalgal community (Chae and An 2017; Alimi et al. 2018; Natarajan et al. 2022). Microplastic items are well highlighted as directly great risks to freshwater organisms, e.g., microalgae, they also indirectly affect the aquatic ecosystem by adsorbing and acting as a significant pathway for the fate and transportation of toxic micropollutants. In addition, the combination of various microplastics (e.g., polyethylene, polystyrene, and polyvinyl chloride) and antibiotic drugs (e.g., triclosan) resulted in oxidative stress and antagonistic effect on growth inhibition on algae *S. costatum* (Zhu et al. 2019). Findings indicate that the distribution of organic micropollutants can affect the microplastic influences, and the ecotoxicity of microplastics on microalgae mainly causes physical damage. Thus, the interaction of microplastics and antibiotic drugs could potentiate toxic impacts on aquatic living organisms.

It is documented that the ecotoxicity regarding carbon-based nanomaterials to algae cells could be included in direct exposure and indirect effects, e.g., negative effects on photosynthesis, light absorption, and nutrient depletion (Long et al. 2012; Zhao et al. 2017). For example, Zhao et al. (2017) examined the ecotoxicity of graphene-based nanomaterials and showed a substantially reduced membrane integrity of freshwater algae cells *C. pyrenoidosa*. A similar observed result was exposed to carbon nanotube for *Pseudokirchneriella subcapitata* with EC_{50} of 17.95 mg L^{-1} (Lukhele et al. 2015). Micro- or nanoparticles, including carbon nanotubes and silver nanoparticles, promoted reactive oxygen species production, leading to oxidative stress in microalgae and inhibition of algal growth (Zhang et al. 2017).

For more details, nanoparticles often carry various functional groups, resulting in strong adsorption capacities to other toxic pollutants. The wide application of nanomaterials or their technology causes the emission of engineered nanoparticles discharged into aquatic ecosystems. Entrapping nanotitanium dioxide of algal cells plays an important role, leading to ecotoxicity to algae *Pseudokirchneriella subcapitata* (Aruoja et al. 2009). In particular, nanoparticles (1–100 nm) can transport pollutants and alter their mobility, toxicity, transformation, and bioavailability (Besha et al.

2020). Ecotoxicological research is a critical task to examine interactions between micropollutants and develop mostly organism-based ecotoxicity testing for chemical compounds. It is well recognized that a high amount of nanoparticles could lead to significant alternations in the morphology of the algae cells and cause significant ecotoxicity effects (Pereira et al. 2020; Rana and Kumar 2022). Nanoparticles act as primary convey vectors into the ecosystems and promote the entry of nanoparticle-sorbed micropollutants into organism cells and potential toxic impacts (Kahru and Dubourguier 2010; Huang et al. 2022). Furthermore, it also reported that the elevated reactive oxygen species caused growth reduction of algal cell density by about 38%, and their ecotoxicity was associated with the engineered nanoparticles dose and type (Chen et al. 2019).

Perspective

To date, the ecotoxicology response of algae to contaminants has become a growing concern due to their environmental persistence and potential health threats. Our study indicates some significant challenges and future perspectives (Table 2).

1. Microalgae are often used as a model organism in ecotoxicological research owing to ecological relevance, their sensitivity to micropollutants, and their easy culturing and maintenance in laboratory-scale environments. They are deemed helpful tools for studying the effects of pollutants on aquatic ecosystems. To better understand the challenges and opportunities in using behavioral toxicology for regulatory ecotoxicology and threat assessment, future research should include various fields such as behavioral ecology, ecotoxicology, regulatory ecotoxicology, neurotoxicology, and risk assessment and should expand from laboratory studies to field-scale investigations.
2. Research has shown that nano/microparticles in aquatic ecosystems can positively act as critical carriers of chemical compounds and can combine with other pollutants such as heavy metals, persistent organic pollutants, hydrophobic organic chemicals, and others. Therefore, understanding the ecotoxicity of persistent organic pollutants, such as polycyclic aromatic hydrocarbons, toward important marine species would be valuable as open ocean and coastal ecosystems are becoming increasingly polluted globally. Further studies on toxicokinetics are needed to give a higher accurate and sensitive assessment of the risks and threats posed by

Table 2 Challenges, future perspectives, and solutions related to the ecotoxicological response of algae to contaminants in aquatic environments

Challenges	Perspectives and solutions	References
Algae sensitivity to micropollutants	An in-depth understanding of the new challenges, prospects, and opportunities for behavioral ecotoxicology Risk assessments are critical	Ford et al. (2021)
Vectors of chemical contaminants can combine with other pollutants such as persistent organic pollutants and heavy metals	Ecotoxicokinetic investigations are still a must to ensure a more accurate and sensitive threat assessment	(Zhu et al. 2019; Othman et al. 2023)
Provide useful predictions of influences at community and/or population levels	Need to be explored more environmental factors and their combined effects Better predict the potential threats and risks	(Rohr et al. 2016; Lu et al. 2021; Schuijt et al. 2021)
Enhanced EC_{50} acute toxicity values	Design and develop the next generation of tools to assess ecotoxicity rapidly	(Freixa et al. 2018; Tato and Beiras 2019)
To ensure more accurate biomarkers and in vitro bioassays	Combination of ecotoxicological experiments, testing, models, and tools for monitored aquatic systems	(Torres et al. 2008; De Baat et al. 2019)
A need to better understand and assess how chemical stressors	Ecological threats assessment associated with chemical stress and their influences	Schuijt et al. (2021)
To make better progress in commercial and industrial applications	Critical developments based on green technological approaches	Yap et al. (2021)
Seeking to overcome potential ecotoxicological issues	Phytoremediation and microalgae-based approaches are required	(Leong and Chang 2020; Tomar et al. 2022)
The adverse influences of abiotic environmental conditions or factors	Needs more further investigation in combination with mesocosm scales of the ecotoxicity, their mechanisms	(Kurade et al. 2016; Lu et al. 2021)

EC_{50}: Half maximal effective concentration persistent organic pollutants in aquatic ecosystems and environments.

3. A major challenge in ecological threat assessment is the ability to predict impacts at the community and population level, which are typically the most relevant for protecting aquatic ecosystems. A priority for research is to study the fate and transport of micropollutants in aquatic environments and to explore the mechanisms of how algae respond to ecotoxicity. Scientists need to further examine the influences of environmental conditions and factors on microalgae ecotoxicity. To improve predictions of the potential risks and threats posed by micropollutants to aquatic ecosystems and human health, research on the ecotoxicological effects of these compounds on microalgae must be increased (Lu et al. 2021).
4. The term "ecotoxicology" relates to the potential for physical, biological, or chemical stressors that impact ecosystems. The acute toxicity values showed that the algae application is one of the most sensitive aquatic organism groups (Freixa et al. 2018). However, it needs to be designed to develop the next generation to detect and assess rapid toxicity response. Developing new ecotoxicity tools and/or models for rapidly intelligent quantification of biological impacts and responses of organisms to micropollutants is needed in further studies.
5. The findings demonstrated that pharmaceutical and personal care products could influence algae species and their communities unexpectedly. Besides, the algae also can be used as a helpful model species in aquatic ecotoxicity. The impacts of toxins on the algal population, as well as the indirect effects on higher trophic level organisms, can be applied to investigate to reveal the overall ecotoxicity on the ecosystems. By applying in vitro bioassays, or biomarkers, ecotoxicity properties of environmental samples can be accumulated, and caused ecotoxicological risks could be estimated for monitored ecosystems (De Baat et al. 2019). Ultimately, to overcome these challenges, combining ecotoxicological experiments, tools, and models that give for high-performance will lead to a more comprehensive risk investigation of the influences of chemical stress on ecosystems.
6. It is crucial to have an in-depth understanding and evaluation of how chemical and non-chemical stressors and their mixtures could affect aquatic ecosystems. While there have been notable advancements in the design and development of ecotoxicological tests, significant challenges still need to be addressed before they can be widely used in risk assessments (Schuijt et al. 2021). These challenges include the need for more research on the effects of chemical mixtures on aquatic living forms, the development of sustainable approaches in measuring the impacts of chemicals at the ecosystem and population levels, and the need for better ways to predict the influences of toxic chemicals on the environment. The investigated micropollutants, such as pharmaceutical compounds, were considered as harmful and toxic to the algae. Therefore, to overcome concerns about mechanisms, that means the following approaches need to be introduced to link chemical exposure and its effects in ecological threat assessment.
7. The microalgae-aided technologies should be further integrated flexibly into wastewater treatment plants to make better progress in full-scale (or commercial) applications. Developing low-cost and sustainable wastewater treatment plants approaches to remove pollutants is essential. Considering the environment, microalgae have been attended to and applied extensively (Zhang et al. 2020). These solutions provide relevant and valuable basics that could be applied to excellent strategies for suitable development principles and targeted phytoremediation purposes. Critical green technology with the employment of natural materials is becoming more popular, and this novel method is compatible with the current trend toward sustainable development.
8. Seeking solutions to overcome potential ecotoxicological risks or problems, it is necessary to conduct green technologies for micropollutant remediation. The phytoremediation and microalgae-based approaches are promising solutions for the bioremediation of toxic and persistent compounds such as pharmaceutical and personal care products, heavy metals, nano/microplastics, and pesticides from the environmental matrices (Ky et al. 2020; Leong and Chang 2020; Pessôa et al. 2021; Tomar et al. 2022). Also, it must provide further trends for its application for the bioremediation approach of hydrocarbon-containing compounds. For example, several algae, such as *C. vulgaris*, could be applied for bioremediation of a polycyclic aromatic hydrocarbon-polluted ecosystem (Tomar et al. 2022).
9. In ecotoxicology research, the influence of environmental conditions or chemicals, e.g., pH, temperature, nitrogen (N), phosphorous (P) levels, and so on, can greatly impact the toxicity of micropollutants that must be noted (Lu et al. 2021). These responses can influence aquatic organisms, particularly algae, which are sensitive, reasonable, and suitable for monitoring and early warning. Responses to chemical compounds and/or environmental stressors can be used as ecological indicators, and indices are frequently applied to investigate the impacts of toxic stressors on the community-scale level. In the future, low-cost approaches should be explored for eco-

toxicology, which can significantly contribute toward the Sustainable Development Goals.

Conclusion

This work's findings significantly contributed to improving the understanding of ecotoxicity of various micropollutants, e.g., polycyclic aromatic hydrocarbons, bisphenol A, pharmaceutical and personal care products, per- and polyfluoroalkyl substance, pesticides, heavy metals, and nano/microparticles in an aquatic ecosystem, and the interactions between these micropollutants and their joint toxicity on algae. Reports about the adverse impacts of various pollutants in various algae across trophic chains provide the necessary contribution to encourage the current emergency of ecotoxicity. Algae, especially microalgae, can be applied for investigating and assessing ecotoxicology risks related to pollutants in aquatic ecosystems. This finding indicates several algal strains routinely used in ecotoxicity investigation. They are susceptible to environmental changes and respond quickly to contaminants and/or environmental stressors, making them excellent bioindicators for ecotoxicity assessments, which is indeed a valuable and environmentally friendly approach. Knowledge domain about ecotoxicity and environmental threats; therefore, ecotoxicology needs to be updated for intelligent environmental designing and planning toward Sustainable Development Goals. Furthermore, a novel generation must be developed to examine rapid and accurate ecotoxicity response. It provides the capability that enables cost-effective and fast assessment of the bioavailability and toxicity of micropollutants in ecosystems for government and industry areas. In the future, scientists still need further investigation on ecotoxicity; their mechanisms of emerging pollutants in the environmental matrices should be examined in associated with the mesocosm scale.

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References

Ali I, Singh P, Aboul-Enein HY, Sharma B (2009) Chiral analysis of ibuprofen residues in water and sediment. Anal Lett 42(12):1747–1760. https://doi.org/10.1080/00032710903060768

Alimi OS, Farner Budarz J, Hernandez LM, Tufenkji N (2018) Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ Sci Technol 52(4):1704–1724

Archer E, Petrie B, Kasprzyk-Hordern B, Wolfaardt GM (2017) The fate of pharmaceuticals and personal care products (PPCPs), endocrine disrupting contaminants (EDCs), metabolites and illicit drugs in a WWTW and environmental waters. Chemosphere 174:437–446

Arpin-Pont L, Bueno MJM, Gomez E, Fenet H (2016) Occurrence of PPCPs in the marine environment: a review. Environ Sci Pollut Res 23(6):4978–4991

Aruoja V, Dubourguier H-C, Kasemets K, Kahru A (2009) Toxicity of nanoparticles of CuO, ZnO and TiO_2 to microalgae *Pseudokirchneriella subcapitata*. Sci Total Environ 407(4):1461–1468

Aschberger K, Micheletti C, Sokull-Klüttgen B, Christensen FM (2011) Analysis of currently available data for characterising the risk of engineered nanomaterials to the environment and human health—lessons learned from four case studies. Environ Int 37(6):1143–1156

Asghari S, Rajabi F, Tarrahi R, Salehi-Lisar SY, Asnaashari S, Omidi Y, Movafeghi A (2020) Potential of the green microalga Chlorella vulgaris to fight against fluorene contamination: evaluation of antioxidant systems and identification of intermediate biodegradation compounds. J Appl Phycol 32(1):411–419

Azizullah A, Khan S, Gao G, Gao K (2022) The interplay between bisphenol A and algae—a review. J King Saud Univ Sci 34(5):102050. https://doi.org/10.1016/j.jksus.2022.102050

Balaji-Prasath B, Wang Y, Su YP, Hamilton DP, Lin H, Zheng L, Zhang Y (2022) Methods to control harmful algal blooms: a review. Environ Chem Lett 20(5):3133–3152. https://doi.org/10.1007/s10311-022-01457-2

Banu AN, Kudesia N, Raut AM, Pakrudheen I, Wahengbam J (2021) Toxicity, bioaccumulation, and transformation of silver nanoparticles in aqua biota: a review. Environ Chem Lett 19(6):4275–4296. https://doi.org/10.1007/s10311-021-01304-w

Banyoi S-M, Porseryd T, Larsson J, Grahn M, Dinnétz P (2022) The effects of exposure to environmentally relevant PFAS concentrations for aquatic organisms at different consumer trophic levels: Systematic review and meta-analyses. Environ Pollut 315:120422. https://doi.org/10.1016/j.envpol.2022.120422

Basheer AA (2018a) Chemical chiral pollution: impact on the society and science and need of the regulations in the 21st century. Chirality 30(4):402–406

Basheer AA (2018b) New generation nano-adsorbents for the removal of emerging contaminants in water. J Mol Liq 261:583–593. https://doi.org/10.1016/j.molliq.2018.04.021

Basheer AA, Ali I (2018) Stereoselective uptake and degradation of (±)-o, p-DDD pesticide stereomers in water-sediment system. Chirality 30(9):1088–1095

Besha AT, Liu Y, Fang C, Bekele DN, Naidu R (2020) Assessing the interactions between micropollutants and nanoparticles in engineered and natural aquatic environments. Crit Rev Environ Sci Technol 50(2):135–215

Bi X, Dai W, Zhou Q, Wang Y, Dong S, Zhang S, Qiao X, Zhu G (2016) Effect of anthracene (ANT) on growth, microcystin (MC) production and expression of MC synthetase (mcy) genes in *Microcystis aeruginosa*. Water Air Soil Pollut 227(8):1–8

Boehm PD, Page DS (2007) Exposure elements in oil spill risk and natural resource damage assessments: a review. Hum Ecol Risk Assess 13(2):418–448

Bonefeld-Jørgensen EC, Long M, Hofmeister MV, Vinggaard AM (2007) Endocrine-disrupting potential of bisphenol A, bisphenol A dimethacrylate, 4-n-nonylphenol, and 4-n-octylphenol in vitro: new data and a brief review. Environ Health Perspect 115(Suppl 1):69–76

Brack W, Aissa SA, Backhaus T, Dulio V, Escher BI, Faust M, Hilscherova K, Hollender J, Hollert H, Müller C (2019) Effect-based methods are key. The European collaborative Project SOLUTIONS recommends integrating effect-based methods for diagnosis and monitoring of water quality. Environ Sci Europe 31(1):1–6

Buck RC, Franklin J, Berger U, Conder JM, Cousins IT, De Voogt P, Jensen AA, Kannan K, Mabury SA, van Leeuwen SPJ (2011) Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins. Integr Environ Assess Manag 7(4):513–541

Byeon E, Kang H-M, Yoon C, Lee J-S (2021) Toxicity mechanisms of arsenic compounds in aquatic organisms. Aquat Toxicol 237:105901. https://doi.org/10.1016/j.aquatox.2021.105901

Cai H, Liang J, Ning X-a, Lai X, Li Y (2020) Algal toxicity induced by effluents from textile-dyeing wastewater treatment plants. J Environ Sci 91:199–208. https://doi.org/10.1016/j.jes.2020.01.004

Chae Y, An Y-J (2017) Effects of micro-and nanoplastics on aquatic ecosystems: current research trends and perspectives. Mar Pollut Bull 124(2):624–632

Chen S, Chen M, Wang Z, Qiu W, Wang J, Shen Y, Wang Y, Ge S (2016) Toxicological effects of chlorpyrifos on growth, enzyme activity and chlorophyll a synthesis of freshwater microalgae. Environ Toxicol Pharmacol 45:179–186

Chen F, Xiao Z, Yue L, Wang J, Feng Y, Zhu X, Wang Z, Xing B (2019) Algae response to engineered nanoparticles: current understanding, mechanisms and implications. Environ Sci Nano 6(4):1026–1042

Cheng C, Huang L, Ma R, Zhou Z, Diao J (2015) Enantioselective toxicity of lactofen and its metabolites in Scenedesmus obliquus. Algal Res 10:72–79

Chia MA, Lorenzi AS, Ameh I, Dauda S, Cordeiro-Araújo MK, Agee JT, Okpanachi IY, Adesalu AT (2021) Susceptibility of phytoplankton to the increasing presence of active pharmaceutical ingredients (APIs) in the aquatic environment: a review. Aquat Toxicol 234:105809

Cizmas L, Sharma VK, Gray CM, McDonald TJ (2015) Pharmaceuticals and personal care products in waters: occurrence, toxicity, and risk. Environ Chem Lett 13(4):381–394

Couto E, Assemany PP, Assis Carneiro GC, Ferreira Soares DC (2022) The potential of algae and aquatic macrophytes in the pharmaceutical and personal care products (PPCPs) environmental removal: a review. Chemosphere 302:134808. https://doi.org/10.1016/j.chemosphere.2022.134808

Czarny-Krzymińska K, Krawczyk B, Szczukocki D (2022) Toxicity of bisphenol A and its structural congeners to microalgae *Chlorella vulgaris* and *Desmodesmus armatus*. J Appl Phycol 34(3):1397–1410. https://doi.org/10.1007/s10811-022-02704-3

Danouche M, El Ghachtouli N, El Baouchi A, El Arroussi H (2020) Heavy metals phycoremediation using tolerant green microalgae: enzymatic and non-enzymatic antioxidant systems for the management of oxidative stress. J Environ Chem Eng 8(5):104460

de Almeida ACG, Petersen K, Langford K, Thomas KV, Tollefsen KE (2017) Mixture toxicity of five biocides with dissimilar modes of action on the growth and photosystem II efficiency of *Chlamydomonas reinhardtii*. J Toxicol Environ Health A 80(16–18):971–986

De Baat ML, Kraak MHS, Van der Oost R, De Voogt P, Verdonschot PFM (2019) Effect-based nationwide surface water quality assessment to identify ecotoxicological risks. Water Res 159:434–443

De Boeck G, Rodgers E, Town RM (2022) Chapter 3 - Using ecotoxicology for conservation: from biomarkers to modeling. In: Fangue NA, Cooke SJ, Farrell AP, Brauner CJ, Eliason EJ (eds) Fish physiology, vol 39. Academic Press, London, pp 111–174

DeWitt JC, Peden-Adams MM, Keller JM, Germolec DR (2012) Immunotoxicity of perfluorinated compounds: recent developments. Toxicol Pathol 40(2):300–311

Ding G, Wouterse M, Baerselman R, Peijnenburg WJGM (2012) Toxicity of polyfluorinated and perfluorinated compounds to lettuce (*Lactuca sativa*) and green algae (*Pseudokirchneriella subcapitata*). Arch Environ Contam Toxicol 62(1):49–55

Du J, Izquierdo D, Naoum J, Ohlund L, Sleno L, Beisner BE, Lavaud J, Juneau P (2023) Pesticide responses of Arctic and temperate microalgae differ in relation to ecophysiological characteristics. Aquat Toxicol 254:106323. https://doi.org/10.1016/j.aquatox.2022.106323

Elersek T, Notersberg T, Kovačič A, Heath E, Filipič M (2021) The effects of bisphenol A, F and their mixture on algal and cyanobacterial growth: from additivity to antagonism. Environ Sci Pollut Res 28(3):3445–3454. https://doi.org/10.1007/s11356-020-10329-7

Evich MG, Davis MJB, McCord JP, Acrey B, Awkerman JA, Knappe DRU, Lindstrom AB, Speth TF, Tebes-Stevens C, Strynar MJ (2022) Per-and polyfluoroalkyl substances in the environment. Science 375(6580):eabg065

Farré M, Gajda-Schrantz K, Kantiani L, Barceló D (2009) Ecotoxicity and analysis of nanomaterials in the aquatic environment. Anal Bioanal Chem 393(1):81–95

Fenton SE, Ducatman A, Boobis A, DeWitt JC, Lau C, Ng C, Smith JS, Roberts SM (2021) Per-and polyfluoroalkyl substance toxicity and human health review: current state of knowledge and strategies for informing future research. Environ Toxicol Chem 40(3):606–630

Fierro P, Valdovinos C, Arismendi I, Díaz G, Jara-Flores A, Habit E, Vargas-Chacoff L (2019) Examining the influence of human stressors on benthic algae, macroinvertebrate, and fish assemblages in Mediterranean streams of Chile. Sci Total Environ 686:26–37. https://doi.org/10.1016/j.scitotenv.2019.05.277

Ford AT, Ågerstrand M, Brooks BW, Allen J, Bertram MG, Brodin T, Dang Z, Duquesne S, Sahm R, Hoffmann F, Hollert H, Jacob S, Klüver N, Lazorchak JM, Ledesma M, Melvin SD, Mohr S, Padilla S, Pyle GG, Scholz S, Saaristo M, Smit E, Steevens JA, van den Berg S, Kloas W, Wong BBM, Ziegler M, Maack G (2021) the role of behavioral ecotoxicology in environmental protection. Environ Sci Technol 55(9):5620–5628. https://doi.org/10.1021/acs.est.0c06493

Freixa A, Acuña V, Sanchís J, Farré M, Barceló D, Sabater S (2018) Ecotoxicological effects of carbon based nanomaterials in aquatic organisms. Sci Total Environ 619:328–337

Gala WR, Giesy JP (1994) Flow cytometric determination of the photoinduced toxicity of anthracene to the green alga *Selenastrum capricornutum*. Environ Toxicol Chem Int J 13(5):831–840

Geng W, Xiao X, Zhang L, Ni W, Li N (2022) Li Y (2021) Response and tolerance ability of Chlorella vulgaris to cadmium pollution stress. Environmental Technology 43(27):4391–4401

Genter RB (1996) Ecotoxicology of inorganic chemical stress to algae. In: Stevenson RJ, Bothwell ML, Lowe RL (eds) Algal ecology. Academic Press, San Diego, pp 403–468

Gerth WJ, Li J, Giannico GR (2017) Agricultural land use and macroinvertebrate assemblages in lowland temporary streams of the Willamette Valley, Oregon, USA. Agr Ecosyst Environ 236:154–165

González A, Vidal C, Espinoza D, Moenne A (2021) Anthracene induces oxidative stress and activation of antioxidant and detoxification enzymes in *Ulva lactuca* (Chlorophyta). Sci Rep 11(1):7748. https://doi.org/10.1038/s41598-021-87147-5

Grasso A, Ferrante M, Moreda-Piñeiro A, Arena G, Magarini R, Oliveri Conti G, Cristaldi A, Copat C (2022) Dietary exposure of zinc oxide nanoparticles (ZnO-NPs) from canned seafood by single particle ICP-MS: balancing of risks and benefits for human health. Ecotoxicol Environ Saf 231:113217. https://doi.org/10.1016/j.ecoenv.2022.113217

Griffith AW, Gobler CJ (2020) Harmful algal blooms: a climate change co-stressor in marine and freshwater ecosystems. Harmful Algae 91:101590

Gu P, Li Q, Zhang W, Zheng Z, Luo X (2020) Effects of different metal ions (Ca, Cu, Pb, Cd) on formation of cyanobacterial blooms. Ecotoxicol Environ Saf 189:109976

Guo R, Du Y, Zheng F, Wang J, Wang Z, Ji R, Chen J (2017) Bioaccumulation and elimination of bisphenol a (BPA) in the alga *Chlorella pyrenoidosa* and the potential for trophic transfer to the rotifer *Brachionus calyciflorus*. Environ Pollut 227:460–467

Hepburn E, Northway A, Bekele D, Liu G-J, Currell M (2018) A method for separation of heavy metal sources in urban groundwater using multiple lines of evidence. Environ Pollut 241:787–799

Huang Y, Gao M, Wang W, Liu Z, Qian W, Chen CC, Zhu X, Cai Z (2022) Effects of manufactured nanomaterials on algae: implications and applications. Front Environ Sci Eng 16(9):122. https://doi.org/10.1007/s11783-022-1554-3

Jamers A, Blust R, De Coen W, Griffin JL, Jones OAH (2013) An omics based assessment of cadmium toxicity in the green alga *Chlamydomonas reinhardtii*. Aquat Toxicol 126:355–364

Ji M-K, Kabra AN, Choi J, Hwang J-H, Kim JR, Abou-Shanab RAI, Oh Y-K, Jeon B-H (2014) Biodegradation of bisphenol A by the freshwater microalgae *Chlamydomonas mexicana* and *Chlorella vulgaris*. Ecol Eng 73:260–269

Kahru A, Dubourguier H-C (2010) From ecotoxicology to nanoecotoxicology. Toxicology 269(2):105–119. https://doi.org/10.1016/j.tox.2009.08.016

Kottuparambil S, Park J (2019) Anthracene phytotoxicity in the freshwater flagellate alga *Euglena agilis* Carter. Sci Rep 9(1):1–11

Kreutzer A, Faetsch S, Heise S, Hollert H, Witt G (2022) Passive dosing: assessing the toxicity of individual PAHs and recreated mixtures to the microalgae *Raphidocelis subcapitata*. Aquatic Toxicol 249:106220

Kumaresan V, Nizam F, Ravichandran G, Viswanathan K, Palanisamy R, Bhatt P, Arasu MV, Al-Dhabi NA, Mala K, Arockiaraj J (2017) Transcriptome changes of blue-green algae, *Arthrospira* sp. in response to sulfate stress. Algal Res 23:96–103. https://doi.org/10.1016/j.algal.2017.01.012

Kurade MB, Kim JR, Govindwar SP, Jeon B-H (2016) Insights into microalgae mediated biodegradation of diazinon by *Chlorella vulgaris*: microalgal tolerance to xenobiotic pollutants and metabolism. Algal Res 20:126–134

Kwok KWH, Leung KMY, Flahaut E, Cheng J, Cheng SH (2010) Chronic toxicity of double-walled carbon nanotubes to three marine organisms: influence of different dispersion methods. Nanomedicine 5(6):951–961

Ky NM, Hung NTQ, Manh NC, Lap BQ, Dang HTT, Ozaki A (2020) Assessment of nutrients removal by constructed wetlands using reed grass (*Phragmites australis* L.) and Vetiver Grass (*Vetiveria Zizanioides* L.). J Fac Agric Kyushu Univ 65(1):149–156

Ky NM, Lin C, Nguyen H-L, Hung NTQ, La DD, Nguyen XH, Chang SW, Chung WJ, Nguyen DD (2023) Occurrence, fate, and potential risk of pharmaceutical pollutants in agriculture: challenges and environmentally friendly solutions. Sci Total Environ 899:165323. https://doi.org/10.1016/j.scitotenv.2023.165323

Lee MY, Shin HW (2003) Cadmium-induced changes in antioxidant enzymes from the marine alga *Nannochloropsis oculata*. J Appl Phycol 15(1):13–19

Leong YK, Chang J-S (2020) Bioremediation of heavy metals using microalgae: recent advances and mechanisms. Biores Technol 303:122886

Li Y, Liu X, Zheng X, Yang M, Gao X, Huang J, Zhang L, Fan Z (2021) Toxic effects and mechanisms of PFOA and its substitute GenX on the photosynthesis of *Chlorella pyrenoidosa*. Sci Total Environ 765:144431

Li J, Wang Y, Li N, He Y, Xiao H, Fang D, Chen C (2022) Toxic effects of bisphenol A and bisphenol S on *Chlorella Pyrenoidosa* under single and combined action. Int J Environ Res Public Health 19(7):4245

Liang X, Yang R, Yin N, Faiola F (2021) Evaluation of the effects of low nanomolar bisphenol A-like compounds' levels on early human embryonic development and lipid metabolism with human embryonic stem cell in vitro differentiation models. J Hazard Mater 407:124387

Liu W, Chen S, Quan X, Jin YH (2008) Toxic effect of serial perfluorosulfonic and perfluorocarboxylic acids on the membrane system of a freshwater alga measured by flow cytometry. Environ Toxicol Chem Int J 27(7):1597–1604

Liu W, Majumdar S, Li WW, Keller AA, Slaveykova VI (2021a) Impact of silver nanoparticles on the biouptake, physiological responses and metabolic perturbations in freshwater alga *Poterioochromonas malhamensis*. Toxicol Lett 350:S181. https://doi.org/10.1016/S0378-4274(21)00668-8

Liu X, Li Y, Zheng X, Zhang L, Lyu H, Huang H, Fan Z (2021b) Antioxidant mechanisms of *Chlorella pyrenoidosa* under acute GenX exposure. Sci Total Environ 797:149005

Liu X, Zheng X, Zhang L, Li J, Li Y, Huang H, Fan Z (2022) Joint toxicity mechanisms of binary emerging PFAS mixture on algae (*Chlorella pyrenoidosa*) at environmental concentration. J Hazard Mater 437:129355. https://doi.org/10.1016/j.jhazmat.2022.129355

Long Z, Ji J, Yang K, Lin D, Wu F (2012) Systematic and quantitative investigation of the mechanism of carbon nanotubes' toxicity toward algae. Environ Sci Technol 46(15):8458–8466

Lu G-H, Piao H-T, Gai N, Shao P-W, Zheng Y, Jiao X-C, Rao Z, Yang Y-L (2019) Pharmaceutical and personal care products in surface waters from the inner city of Beijing, China: influence of hospitals and reclaimed water irrigation. Arch Environ Contam Toxicol 76(2):255–264

Lu T, Qu Q, Lavoie M, Pan X, Peijnenburg W, Zhou Z, Pan X, Cai Z, Qian H (2020) Insights into the transcriptional responses of a microbial community to silver nanoparticles in a freshwater microcosm. Environ Pollut 258:113727

Lu T, Zhang Q, Zhang Z, Hu B, Chen J, Chen J, Qian H (2021) Pollutant toxicology with respect to microalgae and cyanobacteria. J Environ Sci 99:175–186. https://doi.org/10.1016/j.jes.2020.06.033

Lukhele LP, Mamba BB, Musee N, Wepener V (2015) Acute toxicity of double-walled carbon nanotubes to three aquatic organisms. J Nanomater 2015:3

Luo Y, Liang J, Zeng G, Chen M, Mo D, Li G, Zhang D (2018) Seed germination test for toxicity evaluation of compost: its roles, problems and prospects. Waste Manage 71:109–114

Lushchak VI (2011) Environmentally induced oxidative stress in aquatic animals. Aquat Toxicol 101(1):13–30

Ma J, Zhou B, Chen F, Pan K (2021) How marine diatoms cope with metal challenge: insights from the morphotype-dependent metal tolerance in *Phaeodactylum tricornutum*. Ecotoxicol Environ Saf 208:111715

Magdaleno A, Saenz ME, Juárez AB, Moretton J (2015) Effects of six antibiotics and their binary mixtures on growth of

Pseudokirchneriella subcapitata. Ecotoxicol Environ Saf 113:72–78

Mallick N, Mohn FH (2000) Reactive oxygen species: response of algal cells. J Plant Physiol 157(2):183–193

Mao F, He Y, Kushmaro A, Gin KY-H (2017) Effects of benzophenone-3 on the green alga *Chlamydomonas reinhardtii* and the cyanobacterium *Microcystis aeruginosa*. Aquat Toxicol 193:1–8

Martín-Díaz ML, Gagné F, Blaise C (2009) The use of biochemical responses to assess ecotoxicological effects of pharmaceutical and personal care products (PPCPs) after injection in the mussel *Elliptio complanata*. Environ Toxicol Pharmacol 28(2):237–242

Medithi S, Jonnalagadda PR, Jee B (2021) Predominant role of antioxidants in ameliorating the oxidative stress induced by pesticides. Arch Environ Occup Health 76(2):61–74

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

Middepogu A, Hou J, Gao X, Lin D (2018) Effect and mechanism of TiO_2 nanoparticles on the photosynthesis of *Chlorella pyrenoidosa*. Ecotoxicol Environ Saf 161:497–506

Minguez L, Pedelucq J, Farcy E, Ballandonne C, Budzinski H, Halm-Lemeille M-P (2016) Toxicities of 48 pharmaceuticals and their freshwater and marine environmental assessment in northwestern France. Environ Sci Pollut Res 23(6):4992–5001

Minh-Ky N, Lin C, Nguyen H-L, Le V-G, Haddout S, Um M-J, Chang SW, Nguyen DD (2023) Ecotoxicity of micro- and nanoplastics on aquatic algae: facts, challenges, and future opportunities. J Environ Manage 346:118982. https://doi.org/10.1016/j.jenvman.2023.118982

Mofeed J, Mosleh YY (2013) Toxic responses and antioxidative enzymes activity of *Scenedesmus obliquus* exposed to fenhexamid and atrazine, alone and in mixture. Ecotoxicol Environ Saf 95:234–240

Natarajan L, Soupam D, Dey S, Chandrasekaran N, Kundu R, Paul S, Mukherjee A (2022) Toxicity of polystyrene microplastics in freshwater algae Scenedesmus obliquus: effects of particle size and surface charge. Toxicol Rep 9:1953–1961. https://doi.org/10.1016/j.toxrep.2022.10.013

Naveed S, Li C, Lu X, Chen S, Yin B, Zhang C, Ge Y (2019) Microalgal extracellular polymeric substances and their interactions with metal (loid) s: a review. Crit Rev Environ Sci Technol 49(19):1769–1802

Nguyen MK, Hadi M, Lin C, Nguyen H-L, Thai V-B, Hoang H-G, Vo D-VN, Tran H-T (2022a) Microplastics in sewage sludge: distribution, toxicity, identification methods, and engineered technologies. Chemosphere 308:136455. https://doi.org/10.1016/j.chemosphere.2022.136455

Nguyen MK, Lin C, Hung NTQ, Vo D-VN, Nguyen KN, Thuy BTP, Hoang HG, Tran HT (2022b) Occurrence and distribution of microplastics in peatland areas: a case study in Long An province of the Mekong Delta. Vietnam Sci Total Environ 844:157066. https://doi.org/10.1016/j.scitotenv.2022.157066

Nguyen M-K, Lin C, Nguyen H-L, Le V-R, Kl P, Singh J, Chang SW, Um M-J, Nguyen DD (2023a) Emergence of microplastics in the aquatic ecosystem and their potential effects on health risks: the insights into Vietnam. J Environ Manage 344:118499. https://doi.org/10.1016/j.jenvman.2023.118499

Nguyen MK, Lin C, Quang Hung NT, Hoang H-G, Vo D-VN, Tran H-T (2023b) Investigation of ecological risk of microplastics in peatland areas: a case study in Vietnam. Environ Res 220:115190. https://doi.org/10.1016/j.envres.2022.115190

Niu Z, Na J, Xu Wa WuN, Zhang Y (2019) The effect of environmentally relevant emerging per- and polyfluoroalkyl substances on the growth and antioxidant response in marine *Chlorella* sp. Environ Pollut 252:103–109. https://doi.org/10.1016/j.envpol.2019.05.103

Nizzetto L, Lohmann R, Gioia R, Jahnke A, Temme C, Dachs J, Herckes P, Guardo AD, Jones KC (2008) PAHs in air and seawater along a North-South Atlantic transect: trends, processes and possible sources. Environ Sci Technol 42(5):1580–1585

Othman HBP, Frances R, Asma SH, Leboulanger C (2023) Effects of polycyclic aromatic hydrocarbons on marine and freshwater microalgae—a review. J Hazard Mater 441:129869. https://doi.org/10.1016/j.jhazmat.2022.129869

Pastorino P, Broccoli A, Anselmi S, Bagolin E, Prearo M, Barceló D, Renzi M (2022) The microalgae *Chaetoceros tenuissimus* exposed to contaminants of emerging concern: a potential alternative to standardized species for marine quality assessment. Ecol Ind 141:109075. https://doi.org/10.1016/j.ecolind.2022.109075

Pereira FF, Paris EC, Bresolin JD, Mitsuyuki MC, Ferreira MD, Corrêa DS (2020) The effect of ZnO nanoparticles morphology on the toxicity towards microalgae *Pseudokirchneriella subcapitata*. J Nanosci Nanotechnol 20(1):48–63

Pessôa LC, Deamici KM, Pontes LAM, Druzian JI, Assis DdJ (2021) Technological prospection of microalgae-based biorefinery approach for effluent treatment. Algal Res 60:102504. https://doi.org/10.1016/j.algal.2021.102504

Phan CC, Nguyen TQH, Nguyen MK, Park KH, Bae GN, Seung-bok L, Bach QV (2020) Aerosol mass and major composition characterization of ambient air in Ho Chi Minh City. Vietnam Int J Environ Sci Technol 17(6):3189–3198. https://doi.org/10.1007/s13762-020-02640-0

Pilatti FK, Ramlov F, Schmidt EC, Kreusch M, Pereira DT, Costa C, de Oliveira ER, Bauer CM, Rocha M, Bouzon ZL (2016) In vitro exposure of *Ulva lactuca* Linnaeus (Chlorophyta) to gasoline–Biochemical and morphological alterations. Chemosphere 156:428–437

Pradhan D, Sukla LB, Mishra BB, Devi N (2019) Biosorption for removal of hexavalent chromium using microalgae Scenedesmus sp. J Clean Prod 209:617–629

Priyadarshini E, Priyadarshini SS, Pradhan N (2019) Heavy metal resistance in algae and its application for metal nanoparticle synthesis. Appl Microbiol Biotechnol 103(8):3297–3316

Qian H, Li J, Pan X, Sun L, Lu T, Ran H, Fu Z (2011) Combined effect of copper and cadmium on heavy metal ion bioaccumulation and antioxidant enzymes induction in *Chlorella vulgaris*. Bull Environ Contam Toxicol 87(5):512–516

Qiu Y-W, Zeng EY, Qiu H, Yu K, Cai S (2017) Bioconcentration of polybrominated diphenyl ethers and organochlorine pesticides in algae is an important contaminant route to higher trophic levels. Sci Total Environ 579:1885–1893. https://doi.org/10.1016/j.scitotenv.2016.11.192

Quetglas-Llabrés MM, Tejada S, Capó X, Langley E, Sureda A, Box A (2020) Antioxidant response of the sea urchin Paracentrotus lividus to pollution and the invasive algae Lophocladia lallemandii. Chemosphere 261:127773. https://doi.org/10.1016/j.chemosphere.2020.127773

Rana S, Kumar A (2022) Toxicity of nanoparticles to algae-bacterial co-culture: knowns and unknowns. Algal Res 62:102641. https://doi.org/10.1016/j.algal.2022.102641

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol Rev 94(3):849–873

Rhee G, Thompson P-A (1992) Sorption of hydrophobic organic contaminants and trace metals on phytoplankton and implications for toxicity assessment. J Aquat Ecosyst Health 1(3):175–191

Rohr JR, Salice CJ, Nisbet RM (2016) The pros and cons of ecological risk assessment based on data from different levels of biological organization. Crit Rev Toxicol 46(9):756–784

Saleem M, Iqbal J, Shah MH (2019) Seasonal variations, risk assessment and multivariate analysis of trace metals in the freshwater reservoirs of Pakistan. Chemosphere 216:715–724

Salomão ALdS, Soroldoni S, Marques M, Hogland W, Bila DM (2014) Effects of single and mixed estrogens on single and combined cultures of D subspicatus and P subcapitata. Bull Environ. Contam. Toxicol. 93(2):215–221

Samanta SK, Singh OV, Jain RK (2002) Polycyclic aromatic hydrocarbons: environmental pollution and bioremediation. Trends Biotechnol 20(6):243–248

Schmitt-Jansen M, Veit U, Dudel G, Altenburger R (2008) An ecological perspective in aquatic ecotoxicology: approaches and challenges. Basic Appl Ecol 9(4):337–345. https://doi.org/10.1016/j.baae.2007.08.008

Schuijt LM, Peng F-J, van den Berg SJP, Dingemans MML, Van den Brink PJ (2021) (Eco)toxicological tests for assessing impacts of chemical stress to aquatic ecosystems: facts, challenges, and future. Sci Total Environ 795:148776. https://doi.org/10.1016/j.scitotenv.2021.148776

Schwab F, Bucheli TD, Lukhele LP, Magrez A, Nowack B, Sigg L, Knauer K (2011) Are carbon nanotube effects on green algae caused by shading and agglomeration? Environ Sci Technol 45(14):6136–6144

Sharifi S, Behzadi S, Laurent S, Forrest ML, Stroeve P, Mahmoudi M (2012) Toxicity of nanomaterials. Chem Soc Rev 41(6):2323–2343

Sjollema SB, Redondo-Hasselerharm P, Leslie HA, Kraak MHS, Vethaak AD (2016) Do plastic particles affect microalgal photosynthesis and growth? Aquat Toxicol 170:259–261

Softcheck KA (2021) Marine algal sensitivity to source and weathered oils. Environ Toxicol Chem 40(10):2742–2754

Suman TY, Radhika Rajasree SR, Kirubagaran R (2015) Evaluation of zinc oxide nanoparticles toxicity on marine algae chlorella vulgaris through flow cytometric, cytotoxicity and oxidative stress analysis. Ecotoxicol Environ Saf 113:23–30. https://doi.org/10.1016/j.ecoenv.2014.11.015

Tato T, Beiras R (2019) The use of the marine microalga *Tisochrysis lutea* (T-iso) in standard toxicity tests; comparative sensitivity with other test species. Front Mar Sci 6:488

Tišler T, Krel A, Gerželj U, Erjavec B, Dolenc MS, Pintar A (2016) Hazard identification and risk characterization of bisphenols A, F and AF to aquatic organisms. Environ Pollut 212:472–479

Tomar RS, Jajoo A (2021) Enzymatic pathway involved in the degradation of fluoranthene by microalgae *Chlorella vulgaris*. Ecotoxicology 30(2):268–276

Tomar RS, Rai-Kalal P, Jajoo A (2022) Impact of polycyclic aromatic hydrocarbons on photosynthetic and biochemical functions and its bioremediation by *Chlorella vulgaris*. Algal Res 67:102815. https://doi.org/10.1016/j.algal.2022.102815

Torres MA, Barros MP, Campos SCG, Pinto E, Rajamani S, Sayre RT, 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

Tran H-T, Dang B-T, Thuy LTT, Hoang H-G, Bui X-T, Le V-G, Lin C, Nguyen M-K, Nguyen K-Q, Nguyen P-T, Binh QA, Bui T-PT (2022a) Advanced treatment technologies for the removal of organic chemical sunscreens from wastewater: a review. Curr Pollut Rep 8(3):288–302. https://doi.org/10.1007/s40726-022-00221-y

Tran HT, Lesage G, Lin C, Nguyen TB, Bui X-T, Nguyen MK, Nguyen DH, Hoang HG, Nguyen DD (2022) Chapter 3—Activated sludge processes and recent advances. In: Bui X-T, Nguyen DD, Nguyen P-D, Ngo HH, Pandey A (eds) Current developments in biotechnology and bioengineering. Elsevier, Amsterdam, pp 49–79

Tsygankov VY (2019) Organochlorine pesticides in marine ecosystems of the Far Eastern Seas of Russia (2000–2017). Water Res 161:43–53

Tuan Tran H, Lin C, Bui X-T, Ky Nguyen M, Dan Thanh Cao N, Mukhtar H, Giang Hoang H, Varjani S, Hao Ngo H, Nghiem LD (2022) Phthalates in the environment: characteristics, fate and transport, and advanced wastewater treatment technologies. Biores Technol 344:126249. https://doi.org/10.1016/j.biortech.2021.126249

Van der Oost R, Beyer J, Vermeulen NPE (2003) Fish bioaccumulation and biomarkers in environmental risk assessment: a review. Environ Toxicol Pharmacol 13(2):57–149

Vardhan KH, Kumar PS, Panda RC (2019) A review on heavy metal pollution, toxicity and remedial measures: current trends and future perspectives. J Mol Liq 290:111197

Vieira LR, Guilhermino L (2012) Multiple stress effects on marine planktonic organisms: influence of temperature on the toxicity of polycyclic aromatic hydrocarbons to *Tetraselmis chuii*. J Sea Res 72:94–98

Wang XH, Yu Y, Fu L, Tai HW, Qin WC, Su LM, Zhao YH (2016) Comparison of chemical toxicity to different algal species based on interspecies correlation, species sensitivity, and excess toxicity. CLEAN Soil Air Water 44(7):803–808

Wang H, Jin M, Mao W, Chen C, Fu L, Li Z, Du S, Liu H (2020) Photosynthetic toxicity of non-steroidal anti-inflammatory drugs (NSAIDs) on green algae *Scenedesmus obliquus*. Sci Total Environ 707:136176

Wang T, Xu F, Song L, Li J, Wang Q (2021) Bisphenol A exposure prenatally delays bone development and bone mass accumulation in female rat offspring via the ERβ/HDAC5/TGFβ signaling pathway. Toxicology 458:152830

Xiao X, Li W, Jin M, Zhang L, Qin L, Geng W (2023) Responses and tolerance mechanisms of microalgae to heavy metal stress: a review. Mar Environ Res 183:105805. https://doi.org/10.1016/j.marenvres.2022.105805

Xin X, Huang G, An C, Lu C, Xiong W (2020) Exploring the biophysicochemical alteration of green alga *Asterococcus* superbus interactively affected by nanoparticles, triclosan and illumination. J Hazard Mater 398:122855. https://doi.org/10.1016/j.jhazmat.2020.122855

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

Xu L, Xu X, Li C, Li J, Sun M, Zhang L (2022) Is mulch film itself the primary source of meso-and microplastics in the mulching cultivated soil? A preliminary field study with econometric methods. Environ Pollut 299:118915

Yang Y-j, Hong Y-p (2012) Combination effects of bisphenol A and isobutylparaben on the green macroalga Ulva pertusa. Toxicol Environ Heal Sci 4(1):37–41

Yap JK, Sankaran R, Chew KW, Halimatul Munawaroh HS, Ho S-H, Rajesh Banu J, Show PL (2021) Advancement of green technologies: a comprehensive review on the potential application of microalgae biomass. Chemosphere 281:130886. https://doi.org/10.1016/j.chemosphere.2021.130886

Zamani-Ahmadmahmoodi R, Malekabadi MB, Rahimi R, Johari SA (2020) Aquatic pollution caused by mercury, lead, and cadmium affects cell growth and pigment content of marine microalga, Nannochloropsis Oculata. Environ Monit Assess 192(6):1–11

Zhang A, Xu T, Zou H, Pang Q (2015) Comparative proteomic analysis provides insight into cadmium stress responses in brown algae Sargassum fusiforme. Aquat Toxicol 163:1–15. https://doi.org/10.1016/j.aquatox.2015.03.018

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

Zhang C, Wang X, Ma Z, Luan Z, Wang Y, Wang Z, Wang L (2020) Removal of phenolic substances from wastewater by algae. Rev Environ Chem Lett 18(2):377–392. https://doi.org/10.1007/s10311-019-00953-2

Zhang X, Zhang Z-F, Zhang X, Yang P-F, Li Y-F, Cai M, Kallenborn R (2021) Dissolved polycyclic aromatic hydrocarbons from the Northwestern Pacific to the Southern Ocean: surface seawater distribution, source apportionment, and air-seawater exchange. Water Res 207:117780

Zhang L, Zheng X, Liu X, Li J, Li Y, Wang Z, Zheng N, Wang X, Fan Z (2023) Toxic effects of three perfluorinated or polyfluorinated compounds (PFCs) on two strains of freshwater algae: implications for ecological risk assessments. J Environ Sci 131:48–58. https://doi.org/10.1016/j.jes.2022.10.042

Zhao J, Cao X, Wang Z, Dai Y, Xing B (2017) Mechanistic understanding toward the toxicity of graphene-family materials to freshwater algae. Water Res 111:18–27

Zheng B, Zhao X, Ni X, Ben Y, Guo R, An L (2016) Bioaccumulation characteristics of polybrominated diphenyl ethers in the marine food web of Bohai Bay. Chemosphere 150:424–430

Zhu X, Zou D, Du H (2011) Physiological responses of Hizikia fusiformis to copper and cadmium exposure. Bot Mar 54:431–439

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

Zounkova R, Kovalova L, Blaha L, Dott W (2010) Ecotoxicity and genotoxicity assessment of cytotoxic antineoplastic drugs and their metabolites. Chemosphere 81(2):253–260