Recent advances in impacts of microplastics on nitrogen cycling in the environment: A Review

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Abstract

Nitrogen cycling plays a decisive role in biogeochemistry, and largely depends on microbial driven nitrogen transformation. The environmental problems caused by microplastics are becoming more serious, and the analysis and control of its pollution in the environment have become a research hotspot in the field. The nitrogen transformation and nitrogen cycling in the environment are mainly driven by microorganisms in the environment, and the existence of microplastics can affect the microbial population, abundance and type, thus affecting the transformation of nitrogen. The effect of microplastics on microorganisms involved in nitrogen transformation is briefly described. This paper mainly reviews the research progress on the impacts of microplastics on nitrogen transformation and nitrogen cycling in water, soil, sediment and sewage sludge. Microplastic type, size and concentration can cause obvious difference in the impacts of microplastics on nitrogen transformation. Then, response and mechanism of microplastics to microorganism mediated nitrogen transformation and nitrogen cycling are introduced. Processes of nitrogen transformation are affected by interfering with microorganism diversity and structure, enzyme activities and related coding genes and oxygen flux. Additionally, additives released from microplastics can also affect the microbial activity. However, mechanisms of microplastics on environmental nitrogen transformation and nitrogen cycling are not fully understood due to the lack of relevant research. There are effective strategies to evaluate complex environmental systems, prolong action time, strengthen multi factor and multi-level research, and assist molecular biology and stable isotope technology. This review article can provide valuable insights into the impact of microplastics on microorganisms mediated nitrogen transformation processes and evaluate the impact on ecological and environmental health.

Keywords: Microplastics; Nitrogen transformation; Nitrogen cycling; Microorganisms; Coding gene; Environmental pollution

1. Introduction

The pollution of microplastics and its accumulation and harm in the environment have attracted more attention (Shen et al., 2019d). Due to the small particle size and large specific surface, microplastics can adsorb and enrich various environmental pollutants such as heavy metal, organic compounds and microorganisms from external environment (Hartmann et al., 2017). Microplastics can not only carry the adsorbed pollutants in different environmental media, but also can promote the migration or transportation of pollutants in organisms, tissues and organs through desorption, so as to alter the environmental behavior and ecological risks of microplastics themselves and their adsorbed pollutants (Shen et al., 2019c). Microplastics in the environment may threaten the growth, development and reproduction of microorganisms through their own physical effects, additives release and adsorption of coexisting pollutants (Shen et al., 2019b; Wang et al., 2020). As such, microplastic pollution has become one of the research hotspots and frontier issues in the field of environmental science (Hu et al., 2019).

The wide distribution of microplastics is closely related to its migration characteristics in the environment. The sources of microplastics in the water environment mainly include land-based input, shipping, tourism, and aquaculture and fishing (Kumar et al., 2021). The pandemic of COVID-19 unexpectedly increased the production of microplastics (Shen et al., 2021b). Microplastics in land environment mainly come from agricultural plastic film residue, compost, sludge application, wastewater irrigation, automobile tire debris (Bläsing and Amelung, 2017). In the atmosphere, synthetic fibers (such as clothes, curtains and soft carpets), coating materials, erosion of synthetic rubber tires and urban dust are the important sources of microplastics (Huang et al., 2020b; Petersen and Hubbart, 2020). Microplastics have a cyclic exchange process in the four environments of water, soil, sludge and air (Huang et al., 2020a). Microplastics in the ground environment are washed into the water environment by surface runoff, and the application of irrigation and sludge introduces microplastics in water into the soil environment.

Microplastics can not only adsorb nutrients and organic matters from the surrounding environment, provide an ideal niche for environmental microorganisms and promote microbial colonization and biofilm growth, but also help microorganisms resist environmental pressure and accelerate diffusion (Shen et al., 2019d). Microplastics can also change the community structure and function of microorganisms and finally affect the geochemical cycle process of biogenic substances such as carbon, nitrogen and phosphorus (Bank and Hansson, 2019). Nitrogen cycling plays a decisive role in biogeochemistry, and largely depends on microbial driven nitrogen transformation in the environment. Microbial action is the main factor controlling nitrogen transformation and can be recycled orderly through the following processes. Ammonia is assimilated into organic nitrogen, which is degraded and ammoniated to form ammonium salt, then oxidized to nitrate through nitrification, and converted to N_2O or N_2 through denitrification, or nitrate is reduced to ammonia or anaerobic ammonia oxidation to N_2. The key processes related to nitrogen cycling are driven by microorganisms, and the processes in which microorganisms paly a decisive role are enzymatic reactions by various key enzymes, encoded by corresponding functional genes. However, evidence showed that biofilm attached on the surface of microplastics can promote the oxidation and denitrification of ammonia nitrogen and nitrite, but may also inhibit the nitrogen removal by reducing the content of denitrifying bacteria (Chen et al., 2020a). In addition, the presence of microplastics can not only disturb the activity of nitrogen cycling related enzymes (Qin et al., 2020), but restrict the expression of functional genes encoding nitrogen cycling related enzymes (Seeley et al., 2020). This means that microplastics pollution can also affect the earth nitrogen cycling and then threaten the security of global ecosystem.

Recently, experimental studies on the impacts of microplastics on nitrogen transformation and nitrogen cycling in the environment have been reported. However, there is still a lack of timely review of this subject to provide basic understanding and guide further research. Although some studies have been done on the effect of microplastics on environmental nitrogen cycling, most of the research is carried out under laboratory conditions. The existing results show that microplastics in the environment have a significant impact on nitrogen cycling, unfortunately, the current research still focuses on the "phenomenon" and the mechanism is still not fully understood. The research focuses on the impact of a single microplastic on nitrogen transformation and nitrogen cycling in a single environment (sediment or soil), and do not take into account the impact of complex environment (different microplastics and particle size distribution and ecosystem). In the water environment, microplastics can affect the photosynthesis and growth of phytoplankton, inhibit the activities of zooplankton, and affect the biological pump and carbon storage (Shen et al., 2019a). Phytoplankton plays an important role in the process of carbon and nitrogen fixation. Its growth is inhibited by microplastics, which then could interfere with the process of nitrogen transformation. Microplastics can alter the physical and chemical properties of soil environment, and these changes would directly affect the functional and structure diversity of soil microbial community, resulting in more serious soil environmental problems. Compared with the surrounding soil particles, the uneven surface of microplastic particles and various substances attached to the surface will form a completely different microbial community form that in the soil (Chai et al., 2020). The interference of microplastics on nitrogen transformation in environmental media such as submerged zone or farmland using sludge as fertilizer is more complex. The interference effect of microplastics in complex system on nitrogen cycling and its related mechanisms still require to be clarified. Consequently, recent studies about the effect of microplastics on nitrogen cycling are thoroughly reviewed. The effects of microplastics on nitrogen transformation in water soil, sediment and sludge are focused, and the potential influence mode of microplastics on nitrogen cycling process is further revealed. This paper is expected to provide reference for the follow-up exploration of the influence of microplastics on global nitrogen cycling.

2. Impacts of microplastics on microorganisms

Microplastics can adsorb organic matter and inorganic nutrients in the environment, so as to attract microorganisms such as bacteria and viruses to adhere to them. On the other hand, microplastic particles can help microorganisms resist environmental pressure, provide relatively stable habitat, and enhance microbial diffusion ability (Shen et al., 2019d). The material circulation and energy flow in the environment are mainly driven by microorganisms, which are closely related to community composition and metabolic function. The accumulation of microplastics can significantly affect the enzyme activity and microbial community structure (Chen et al., 2020a). The effect of microplastics on bacterial community structure can be changed by changing the physical and chemical characteristics or nutritional conditions. A study carried out by Fei et al. (2020) has found that the presence of PE and PVC microplastics in acid cropped soil significantly inhibited the activity of fluorescein diacetate hydrolase, stimulated the activities of acid phosphorus and urease, and reduced the diversity and richness of microbial community, and the effects of PE microplastic on soil was more serious than that of PVC microplastic. Huang et al. (2019) found that LDPE microplastic addition can affect microbial community composition and activity of urease in soil, thus disturbing the hydrolysis of organic nitrogen, and pointed out that microplastics in soil can be used as a unique habitat, potentially altering the ecological function of soil ecosystem. Moreover, a recent study done by

Rong et al. (2021) also reported that existence of LDPE microplastics in soil affected niche and nutrient competition and the correlation of soil bacteria, thus altering the nitrogen cycling driven by soil microorganisms. Qian et al. (2018) showed that plastic film residual in agricultural soil could reduce the content of soil inorganic nitrogen and the activity of functional enzymes, and inhibit the expression of functional genes related to nitrogen cycling. Awet et al. (2018) evaluated the effects of PS nanoplastics on soil microbial activity and biomass, as well as the functional enzyme diversity, and the results showed that the presence of nanoplastics significantly decreased the activity of N-(leucine aminopeptidase) and limited the potential utilization ability of nitrogen in soil. Since the main component of microplastics is carbon, it may affect the storage and conversion of carbon in the environment (Ho et al., 2017).

Microplastics can improve the functions of cell membrane transporters and movement, and reduce some essential metabolic pathways. As a protein system, membrane transporters play an extremely important role in regulating adverse changes in the bacterial environment (Langille et al., 2013). Microplastics can stimulate the function of bacterial membrane transporters, so as to regulate the mechanism of maintaining the stability of intracellular environment (Fei et al., 2020). The existence of micro plastics makes bacteria have higher cell mobility, which may help to speed up the movement of bacteria to nutrients and avoid toxic substances to adapt to the changeable environment (Kisand et al., 2012). The metabolic pathways of amino acids, cofactors and vitamins in the biofilm of micro plastic matrix are significantly enhanced, which also shows that micro plastic, as a unique microbial habitat, can not only change the community structure, but also affect the microbial function, and potentially affect the ecological function of the microbial community in the ecosystem (Miao et al., 2019b). Additionally, biofilms attached to microplastics are very complex and contain many genes, which may lead to gene exchange between biofilm communities or between biofilm communities and surrounding communities. A variety of bacteria are attached to organic particles. Due to the strong variability of bacterial genes, gene exchange occurs among communities through horizontal gene transfer, such as absorption and utilization of DNA in the environment, gene transformation between cells, transduction through phage. Therefore, microplastics may become a hot area of bacterial gene exchange, which has affected the energy flow of ecosystem and the circulation of nitrogen, phosphorus and other substances (Rong et al., 2021).

3. Interference ways of microplastics on environmental nitrogen transformation and nitrogen cycling

Microorganisms are the engine of nitrogen and other nutrient elements circulation. Ammoniation, nitrogen fixation, nitrification and denitrification constitute the main links of nitrogen transformation and nitrogen cycling, and each process requires the participation of corresponding microorganisms. Microbial community structure controls nitrogen cycles in different ecosystem, and then regulates the function and stability of ecosystems. The number, activity, and flora structure of microorganisms involved in nitrogen cycles control the direction and process of nutrient mineralization and fixation, and then affect the process and products of nitrogen cycles (**Fig. 1**). Dai et al. (2020) found that the presence of PVC microplastics aerobic sewage sludge obviously reduced the content of denitrifying bacteria, thereby affecting the relative removal of total nitrogen in the reaction system. Huang et al. (2021) reported that PE microplastics in sediments could promote the growth of denitrifying bacteria and anaerobic ammonia oxidizing bacteria, and at the same time, the health and activity of benthos in sediments is also affected by microplastics.

Environmental media, polymer type, particle size and concentration of microplastics can also affect the functional bacteria related to nitrogen cycling, which may be related to the fact that microplastics can act as organic substrates and release of additives in microplastics (Seeley et al., 2020). As an organic substance, microplastics can be utilized by microorganisms with the participation of oxygen. It can not only promote the growth of related functional bacteria, but also form an oxygen concentration gradient conducive to nitrogen transformation on its inner surface (Huang et al., 2021). Li et al. (2020) have revealed that PP microplastics produce additional anaerobic atmosphere on its inner surface, which contributes to the growth and denitrification activity of denitrifying bacteria. Additionally, plastics used in daily life often add a variety of plasticizers to improve the performance of plastics. Evidence showed that the additives released by microplastics can affect microbial activities by directly destroying microbial cells (Mohammad Mirsoleimani Azizi et al., 2021; Shen et al., 2019c). For example, bisphenol A released from PVC is the key inhibition mechanism to promote the cell wall rupture of anaerobic digestion microorganisms (Wei et al., 2019). Antibacterial PE microbeads used in cosmetic scrub also inhibit the process of sediment bacteria transforming nutrient into bioavailable forms, resulting in changes in nutrient cycling (Cluzard et al., 2015). PVC plastic products used in the medical field have antibacterial properties because they contain plasticizers, which are selective to specific types of microorganisms such as Gram-negative bacteria and sulfate reducing bacteria, and are resistant to nitrifying bacteria. Furthermore, microplastics in the environment can be further degraded into nanoplastics (Shen et al., 2019c). nanoplastics can catalyze the production of reactive oxygen species such as hydroxyl radical (·OH), which can directly destroy microbial cells and inhibit metabolic function (Azizi et al., 2021). PS-NH_2 nanoplastics could bind to lipid bilayers on the cell membrane with high affinity and show the highest toxicity to its surface biofilm, resulting in excessive reactive oxygen species, destroying the basic ecological function of microorganisms and affecting the process of nitrogen cycles (Miao et al., 2019a).

Moreover, microplastics can inhibit the activity of enzymes related to nitrogen transformation, and then affect the nitrogen cycling (**Fig. 1**). The enzymes involved in nitrogen cycling mainly include nitrate reductase, nitrite reductase, nitrite oxidoreductase, nitric oxide reductase, and nitrous oxide reductase. Evidence showed that the presence of PS microplastics significantly decreased the activity of N-(leucine aminopeptidase), a key enzyme of nitrogen cycling, which disturbed the nitrogen cycling in freshwater (Miao et al., 2019a) and soils (Awet et al., 2018). Gao et al. (2021) found that LDPE microplastics could enhance the activity of urease in soil environment and improve the utilization potential of nitrogen, and Huang et al. (2019) reported that microplastic addition had little impact on soil nitrite reductase and nitrous oxide reductase. The participation of enzymes in a series of redox reaction is the key to the nitrogen cycling. Influencing the activity and quantity of related enzymes would inevitably interfere with the nitrogen transformation processes.

Furthermore, the functional genes encoding enzymes related to nitrogen cycling are also affected by microplastics (**Fig. 1**). Nitrification is a series of oxidation processes from NH_3 or NH_4^+ to NO_3^- under aerobic conditions, mainly involving three nitrogen transformation stages ($NH_3/NH_4^+ \rightarrow NH_2OH \rightarrow NO_2^- \rightarrow NO_3^-$). The transformation of NH_3/NH_4^+ to hydroxylamine (NH_2OH) is mainly catalyzed by ammonia monooxygenase, encoded by *amo*A gene, produced by ammonia oxidizing bacteria and Archaea (Pjevac et al., 2017), and the transformation of NH_2OH to NO_2^- is controlled by hydroxylamine reductase, encoded by *hao* gene, metabolized by ammonia oxidizing bacteria (Simon and Klotz, 2013). Most ammonifying bacteria belong to β- and γ- *Proteus*, which are chemoautotrophs that can oxidize NH_4^+ to NO_2^-. The transformation from NO_2^- to NO_3^- is completed by nitrite oxidizing bacteria, light energy utilization bacteria and nitrite oxidoreductase metabolized by anaerobic ammonia oxidizing bacteria, and its coding gene is *nxr*AB (Schweiger, 2016). Nitrite oxidoreductase can be produced by aerobic nitrous oxidizing bacteria (such as *Curvularia*, *Spirochetes*, α-*Proteus*, β-*Proteus*, and γ-*Proteus*) (Daims et al., 2016), anaerobic light energy utilization bacteria (*Rhodopseudomonas*) (Griffin et al., 2007), and anaerobic ammonia oxidizing bacteria (Strous et al., 2006). Denitrification is a series of reduction reaction in which NO_3^- is reduced to N_2O/N_2 under anoxic conditions, mainly including four nitrogen transformation stages ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$). The transformation from NO_3^- to NO_2^- is mainly catalyzed by cytoplasmic membrane bound nitrate reductase (encoded by *nar*G gene) or extracellular peripheral nitrate reductase (encoded by *nap*A gene) (Butala and Falkinham, 2018), which generally occurs in an anoxic environment rich in NO_3^- and most microorganisms contain both enzymes (Philippot et al., 2007). The transformation of NO_2^- to NO is catalyzed by two unrelated nitrite reductase (NIRS) in peripheral stromal cells, including cd1-NIR encoded by *nir*S gene and Cu-NIR encoded by *nir*K gene, which are common in bacteria and Archaea (Graf et al., 2014). The transformation of NO to N_2 is catalyzed by nitric oxide reductase, encoded by *nar*B gene, which widely exists in various environments (Yang et al., 2014), and the transformation of N_2O to N_2 is catalyzed by nitrous oxide reductase, encoded by *nos*Z gene, which is found in a variety of bacteria (*Proteus*, *Bacteroidea* and *Chloromycetes*) and Archaea (*Halophilia*) (Zumft and Kroneck, 2006). Ammoniation is a process of transformation of organic nitrogen into NH_4^+ (organic N $\rightarrow NH_4^+$), which is catalyzed by keratinase (encoded by *cyn*S gene) and urease (encoded by *ure*ABC gene) (Kuypers et al., 2018). A series of nitrogen redox reactions catalyzed by enzymes secreted by microorganism are the main drivers of nitrogen transformation and nitrogen cycling, and the genes encoding enzymes are the key to control microbial processes. Qian et al. (2018) have revealed that agricultural residual plastic films increased the abundance of nitrogen fixation related functional gene (*nif*H), N_2O reduction related gene (*nos*Z) and denitrification related functional gene (*nir*S), but decreased denitrification gene (*nir*K). Seeley et al. (2020) reported that PLA microplastics also increased the abundance of *amo*A gene and *nir*S gene, and decreased the abundance of *nir*K gene in sediments, while PVC microplastics decreased the abundance of all of them (*amo*A, *nir*S and *nir*K gene). Rong et al. (2021) showed that microorganisms containing AOA*amo*A and *nir*S genes were more vulnerable to the presence of LDPE microplastics, and LDPE addition increased the abundance of *nif*H, AOB*amo*A and *nir*K genes involved in nitrogen cycle at different culture stages. According to the changes of functional gene abundance, combined with the changes of enzymes, functional microbes and nitrogen concentration in certain ecosystem, the influence mode of microplastics on nitrogen transformation and nitrogen cycling can be evaluated.

Finally, oxygen content is also a key in the process of nitrogen transformation and nitrogen cycling (**Fig. 1**). Nitrification mainly occurs under aerobic conditions, while denitrification, anaerobic ammonia oxidation and dissimilatory reduction of nitrate to ammonium are more common under anaerobic conditions. Kojima et al. (2012) found that the functional genes of anaerobic bacteria were detected in deep lake sediments, but they were difficult to detect in shallow lake sediments. The microplastics in the environment have the characteristics of small particle size, easy to migrate vertically to the deep layer of the sediment, and may remain in the sediment due to the change on the surface (Dong et al., 2018). When microplastics settle into sediments, it would affect the porosity of sediments (Seeley et al., 2020), and the increase of porosity not only promotes the rate of sediment nutrient flux, but also increases the diffusion of oxygen (Cluzard et al., 2015). However, limited information can be available on the effect of oxygen content on nitrogen transformation, and whether it would affect the process and its potential mechanism needs to be further explored.

4. Impacts of microplastics on nitrogen transformation and nitrogen cycling in different environments

4.1 Water

Freshwater is not only an important source and sink of microplastics, but also an important channel and bridge of microplastics from the land to the ocean. In general, the process of water nitrogen transformation is mediated by microorganisms, and the formation of biofilms on the surface of mciroplastics may affect the process of water nitrogen cycling. A research performed by Chen et al. (2020b) has revealed that the formation of biofilm on polypropylene (PP) microplastic surface can promote the oxidation and denitrification of ammonia (NH_4^+-N) and nitrite (NO_2^--N), thus affecting the nitrogen cycling in the freshwater system (**Table 1**). The study also pointed out that when the biofilm was mature and disintegrated, the nitrogen and phosphorus elements constituting microorganisms would also be released back to the freshwater environment. Additionally, the release of chemical additives, such as bisphenol A and phthalate, in the microplastics may further harm the microbial community, thereby disturbing the nitrogen cycles in the environment. Miao et al. (2019a) have studied that acute effect of microplastic and nanoplastic polystyrene (PS) with particle size range of 100 nm - 9 mm on five biological endpoints in biofilms. The finding showed that PS with large particle size (500 nm, 1 mm and 9 mm) had little effect on the biological endpoints determined in the biofilms, while high concentration nanoplastic PS significantly reduced the content of chlorophyll a and the functional enzyme activities of b-glucosidase and N-(leucine aminopeptidase), demonstrating a negative impact on the carbon and nitrogen cycles of freshwater biofilm.

The marine nitrogen cycling is mainly driven by a variety of nitrogen transformation processes mediated by microorganisms, including nitrogen sequestration and retention processes, and denitrification processes (Pajares and Ramos, 2019). Microplastics can affect the photosynthesis and growth of phytoplankton, inhibit zooplankton activities, disturb the marine biological pump and global carbon storage in the ocean (Shen et al., 2019a). Phytoplankton plays a key role in the process of global carbon and nitrogen sequestration, and the inhibition of phytoplankton growth by microplastics may interfere with the marine nitrogen cycles. Furthermore, microplastics can also alter the feeding selectivity of copepods, and interfere with the important links of marine food chain/web and nutrient cycles (Shen et al., 2019d). Cluzard et al. (2015) applied laboratory micro-research to control of microplastic concentration, organic matter content and bivalves to determine the impact of sediment microplastics on the ammonium cycles in intertidal zone, and the research showed that microplastic amended made the ammonium concentration in overlying water significantly higher compared with the treatment without microplastics. This preliminary study indicated that high concentration of microplastics may alter key deposition processes of ammonium flux, having significant consequences such as eutrophication events and res tides because of the increase of ammonium content in the water column. The mechanism of marine nitrogen fixation is relatively complex, but limited information is available on the direct impact of microplastics on marine nitrogen cycles. Most of these conclusions are derived from indirect evidence and analysis, that is, they are expounded by evaluating the impact of microplastics on global marine organisms, and its direct impact on global marine nitrogen cycles is still not fully understood. Consequently, it is urgent to further strengthen the exploration and research on the influence of microplastics on nitrogen cycles in water environment.

4.2 Soil

Microplastic in soil environment mainly comes from agricultural film mulching, sludge utilization, wastewater/river irrigation and composting (Bläsing and Amelung, 2017). Microplastics could significantly reduce the physical and key ecological functions of soil, such as nutrient cycling and soil microbial activity, after entering the soil (Fei et al., 2020; Iqbal et al., 2020). Although some studies on the impact of microplastics and nanoplastics on nitrogen transformation and nitrogen cycling have been done, there are still many limitations, such as the type and single particle size of microplastics and nanoplastics (**Table 1**). Limited by the differences of microplastic concentrations and polymer types, the effects of microplastics on soil nitrogen cycling are not consistent. Awet et al. (2018) investigated the short-term effects (28 d) of PS nanoplastics on soil microbial activity and biomass, as well as the functional diversity of soil enzymes at low levels related to the environment, and the findings demonstrated that nanoplastic addition obviously decreased the activity of N-(leucine aminopeptidase), a key nitrogen cycling enzyme, and affected the potential utilization ability of nitrogen in soil environment. Although nanoplastics have a significant effect on the activity of leucine aminopeptidase, microplastics account for the main type in the environment, and they affect the soil nitrogen transformation by affecting the microbial activity in the soil in a short time. Gao et al. (2021) evaluated the effects of LDPE microplastic pollution on soil microbial community structure and soil nutrient cycling, and the results suggested that microplastic addition had little impact on soil nitrous oxide (N_2O) emission, but significantly promoted carbon dioxide (CO_2) emission. The presence of LDPE microplastics had little effect on soil functional genes of ammonia oxidizing archaea, nitrous oxide reductase and nitrite reductase, while the abundance of ammonia oxidizing bacteria and nitrous oxide reductase was reduced. The addition of microplastics affects the growth of tolerant microorganisms in soil, and indirectly affects nitrogen transformation by affecting the abundance of some important bacteria.

Rong et al. (2021) found that presence of LDPE microplastics in soil environment affected niche and nutrient competition and the response of microbial community driven by resistance and resilience to interference was also limited, thereby influencing the correlation of soil bacteria and changing nitrogen cycling driven by soil microorganisms. Microplastic exposure had little effect on soil bacterial diversity even at high concentrations (7%), but it changed the process of soil nitrogen cycling by affecting the structure of soil bacterial network. Additionally, LDPE microplastics can interfere with the hydrolysis of organic nitrogen by affecting microbial community composition and activity of urease in soil environment (Huang et al., 2019). The long-term residual plastic film in agricultural production activities can also reduce the content of soil inorganic nitrogen, down regulate microbial genes related to nitrogen transformation and nitrogen cycling and reduce the activity of related enzymes (Qian et al., 2018).

Moreover, the existence of biodegradable plastics could also have different effects on nitrogen transformation and nitrogen cycling in soil. Despite considered as a promising alternative to conventional plastics, biodegradable plastics may produce more microplastics, thereby bringing greater microplastic pollution (Shen et al., 2020a). A study carried out by Chen et al. (2020a) has revealed that PLA microplastics had no obvious effect on the overall diversity and composition of bacterial community and related ecosystem functions and processes, but could promote the transformation rate of ammonia in soil, resulting in faster reduction of NH_4^+ concentration. Therefore, the gradual application of biodegradable plastics in agriculture requires the improvement of test methods to ensure its environmental safety. Furthermore, the additives released by microplastics may also accelerate soil pollution and destroy nutrient circulation by limiting the activity of key enzymes such as nitrite reductase and nitrous oxide reductase. In addition to nitrification and denitrification, whether microplastics will affect the nitrogen cycling processes such as anaerobic ammonia oxidation and nitrate dissimilatory reduction to ammonium and its potential mechanism in soil environment still remains to be explored.

4.3 Sediment

Sediment plays a dual role of source and sink in aquatic ecosystem. In addition to being absorbed and utilized by ascending water organisms, the nitrogen input from external sources will also settle at the bottom of the water body through physical, chemical and biological effects. The nitrogen enriched in sediment will release to the overlying water under certain conditions, which will affect the water environment quality. Meanwhile, sediment is also the natural carrier of microorganisms. The single cycle driven by microorganisms in sediment plays a vital role in maintaining the ecological balance of water body. Single cycle microorganisms are involved in ecological processes such as ammoniation, nitrification and denitrification. The microplastics entering the water body can settle in the sediment through colonizing biofilms in the natural environment, which will affect the structure and function of sediment microbial community, thus interfering with the process of nitrogen cycling. Seeley et al. (2020) have revealed that microplastics could change the microbial community composition and nitrogen cycling processes in sediments, and they could be used as organic carbon matrix of microbial community (**Table 1**). The findings indicated that the addition of PLA and PUF microplastics in sediments promoted nitrification and denitrification, while PVC microplastics significantly inhibited both processes. The author furtherly demonstrated that considering increasing global microplastic pollution and this powerful evidence, it is worth critically studying the impact of microplastics on ecosystems and nitrogen cycling. Huang et al. (2021) studied the effect of microplastics on nitrogen removal in freshwater sediments with the coexist of microorganisms and benthic invertebrate, and the results showed that microplastic addition can accelerate the growth of denitrifying and anaerobic ammonia oxidizing bacteria, so as to improve the total nitrogen removal rate, implying that the increase of microplastics concentration in freshwater ecosystem is related to the nitrogen cycling mediated by benthic invertebrates. In addition to microbial mediation, benthos in sediments also plays a vital role in the process of nitrogen transformation and nitrogen cycling. Microplastics can also interfere with the nitrogen cycling of sediments by affecting benthos in sedimentary habitats, the findings showed that 1% PE microplastics could have an adverse effect on the biological denitrification mediated by macroinvertebrates (Huang et al., 2021). Green et al. (2016) have assessed the effects of PLA, HDPE and PVC microplastic pollution on the health and biological activity of *Arenicola marina* as well as the nitrogen cycling and primary productivity of the sediments, and the results indicated that the metabolic rate of *Arenicola marina* increased and its burrowing behavior was also disturbed, having an adverse effect on the health and biological activity of benthos and the nitrogen cycling processes dominated by them. Additionally, Hope et al. (2020) have also reported that the increase of microplastic fiber concentration would affect the multiple ecological functions mediated by benthos in offshore sediments, and then further disturb the nitrogen transformation and nitrogen cycles.

Microplastics of different types mostly promote the nitrification and denitrification processes in sediments. In the aspect of mechanism research, microplastics indirectly interfere with the nitrogen cycling in the sediment environment through adverse effects on the metabolic behavior and biological activity of benthos. Unfortunately, however, relevant studies mainly focus on the short-term impact of microplastics, and it is still unknown whether the nitrogen transformation process in sediments would continue to deteriorate or recover under the long-term effect. Moreover, most microplastics in the actual environment have different degrees of aging and biofilm adhesion, whether these phenomena would change their impact on nitrogen transformation requires to be further considered. In addition, follow-up studies should pay more attention to the direct impact and path of microplastics in sediments on nitrogen transformation and nitrogen cycling.

4.4 Sewage sludge

Sewage treatment plants are an important collecting and distributing center of microplastics in the environment. The primary treatment and secondary treatment in municipal sewage treatment plant can remove more than 90% of microplastics in the sewage, but if excessive sewage is discharged into the environment, a large number of microplastics will still enter the water environment (Shen et al., 2020b; Sun et al., 2019). Although the microplastics in sewage can be treated three times to achieve a certain effect, these processes are not specially designed to remove microplastics. At present, the removal rate of microplastics in sewage plants is generally calculated by the concentration of microplastics in inlet and outlet water (Shen et al., 2021a). Without the establishment of a special technology to remove microplastics, more microplastics removed in sewage treatment plants are retained in sewage sludge. Denitrification is an important part of sewage treatment process, and due to the influence of microplastics, the denitrification capacity of activated sludge and aerobic granular sludge is disturbed (**Table 1**). A research performed by Li et al. (2020) has revealed that five microplastics (PE, PES, PP, PS, and PVC) with different concentrations (1000, 5000, and 10000 particles/L) have similar effects on activated sludge nitrification and denitrification. These microplastics have an adverse effect on ammonia oxidation rate in activated sludge nitrification process, while have little effect on nitrite oxidation rate, and promote the denitrification process. In addition, high concentration of PVC microplastics significantly increased the emission of N_2O in the denitrification process, and the findings showed that the N_2O emission with addition of PVC microplastics 10000 particles/L was about 4.6 times than that of the control group. Dai et al. (2020) also found that PVC microplastics could promote the release and absorption of phosphorous by phosphorous accumulating bacteria, and inhibit the removal of total inorganic nitrogen by reducing the content of denitrifying bacteria. Qin et al. (2020) reported that PES microplastics had little inhibitory effect on ammonia nitrogen removal in aerobic granular sludge, while the total nitrogen removal increased by 5.6% with addition of PES. Moreover, PES microplastics inhibited the activity of nitrite oxidase in the nitrification process of aerobic granular sludge and promoted the growth of nitrate reductase, thus resulting in the accumulation of nitrite and disturbing the process of nitrogen metabolism. Cui et al. (2021) reported that PA microplastics had little short-term and long-term effect on activated sludge partial nitrification system, but the ammonia oxidation rate decreased slowly with the increase concentration of PA microplastics. The microplastic amended could also reduce microbial activity and change the microbial community structure and reproduction of the system. Song et al. (2020) investigated the effect of PVC microplastics on partial nitrification process with different concentration range of 0 – 10000 particles/L, and the findings showed that with the increase of PVC concentration, the mobility rate of nitrite in the system was significantly reduced, and the ammonia oxidation rates and average emission of dissolved N_2O were also decreased in carrying degree compared with the control group because of the limitation on the activities of ammonia oxidation bacteria and nitrite oxidizing bacteria.

At present, the research on the effect of microplastics on nitrogen transformation of sewage sludge is still in its infancy, and there is no consistent conclusion. The impacts of microplastics on sewage sludge nitrogen transformation and nitrogen cycling mainly affect the process of nitrification and denitrification. The nitrification process of sewage sludge may be inhibited because the ammonia oxidation process or nitrite oxidation process is limited by the presence of microplastics, and the denitrification rate is usually improved accordingly. In addition, microplastics not only can act as an important microbial carrier, but also hinder the absorption of dissolved oxygen by sewage sludge, from anaerobic atmosphere, and promote the denitrification process to a certain extent. The existence of microplastics will interfere with the denitrification performance of sewage sludge in sewage treatment system, mainly resulting in the accumulation of nitrite and the increase of greenhouse gas N2O emission. In addition, the monomers and additives released from microplastics could affect the nitrogen transformation process of sewage sludge, but the relevant mechanism needs to be further explored.

5. Perspectives and challenges

Microplastics can directly affect the nitrogen cycling by disturbing the microbial community structure and productivity, changing the quality and quantity of organic matter input and the decomposition rate of organic matter, and indirectly affect the nitrogen cycling processes by altering biological activity. Although some studies have proved the impact of microplastics on the key processes of environmental nitrogen cycling, and the current research still focuses on the “phenomenon” and the mechanism is still not fully understood. Therefore, it is necessary to observe and study the response characteristics and mechanisms of microplastics to the change of global nitrogen cycling at different scales in the future.

5.1 Evaluating complex environmental systems

The research on the influence of nitrogen transformation in microplastics is mainly focuses on soil and sewage sludge, while it is still in its infancy in other environmental media. This limits the accurate evaluation of the change trend of nitrogen cycling caused by microplastic pollution under global change to a certain extent. The overall environment is relatively single, and the interference effect of microplastics in complex system, such as intertidal zone, mangrove area and other key zones, on nitrogen cycling and its related mechanisms still require to be clarified, especially the influence process and mechanism of horizontal and vertical distribution of microplastics on nitrogen cycling. It should be to explore the effects of physical, chemical, environmental and biological factors involved in the whole cycle process, to develop and construct nitrogen cycling models, to master the dynamic changes of nitrogen cycling in each reaction system, to realize the effective monitoring and provide scientific basis regulation and management.

5.2 Exploring impact of long-term effects

The inference about the effect of microplastics on nitrogen transformation and nitrogen cycling in environmental media is mainly based on short-term theoretical experiments. In the short term, microplastics addition would affect the nitrogen transformation processes, but it is still unknown whether the nitrogen transformation process would continue to deteriorate or recover in the long term. The short-term experiment is an accelerated experiment, and the difference between the experimental conditions and the real conditions will increase, which is not conductive to the conclusion of real phenomena and results. As such, the research on the impact of microplastics on nitrogen transformation process under long-term action is more helpful to deeply understand the impact of microplastic pollution on global nitrogen transformation and nitrogen cycling.

5.3 Strengthening exploration of potential mechanism

Nitrogen cycling processes mainly include nitrogen fixation, nitrification, denitrification, anaerobic ammonia oxidation and dissimilatory reduction of nitrate to ammonium. Microplastics could affect the nitrogen transformation processes by disturbing microbial colonization, releasing additives, broken into nanoplastics and inducing reactive oxygen species. Nevertheless, at present, the existing studies mainly focused on the impact of microplastics on nitrification and denitrification processes, and have achieved remarked results, while limited information is available on whether microplastics would affect other nitrogen transformation processes, especially on related functional microorganism, enzymes activities and functional genes. The coupling mechanism of nitrogen fixation, nitrification, denitrification, anaerobic ammonium oxidation and dissimilatory reduction of nitrate to ammonium in the same reaction system should be strengthened. Enzymes produced by microbial metabolism are the key to control the transformation process, and the gene encoding enzymes is the driver of the whole process. The interaction between microplastics and microorganisms and its impact on nutrient cycles involves metabonomics, microbiology, transcriptomics and biochemistry, which requires the joint efforts of multiple disciplines.

5.4 Carrying out multi-factor and multi-level research

The rise of temperature, the increased of atmospheric CO_2 concentration and nitrogen deposition and the change of precipitation pattern are important characteristics of global climate change. Climate change has s significant impact on biogeochemical cycle, ecosystem and aboveground and underground biological interaction. These changes can alter microbial species distribution, population dynamics and habitat, resulting in the loss of biodiversity on a global scale. Warming can affect the decomposition of organic matter, respiration and element mineralization, so as to affect the stability of carbon pool and nitrogen pool. Therefore, in order to reveal the response process and mechanism f microplastics to nitrogen transformation and nitrogen cycling under global change, it is necessary to comprehensively study the interaction of microplastics with other driving factors such as temperature, climate, moisture and nitrogen deposition.

5.5 Comprehensive applying isotope and molecular biology combined with indoor simulation and field test

At present, the main research of microplastics on nitrogen cycling is indoor simulation test. However, unfortunately, in terms of controlling experimental conditions, indoor culture is quite different from the actual situation in the field, and there are many uncontrollable factors. Accordingly, in the future research, the experimental scheme combing field in situ and indoor culture should be added, so as to improve the scientificity of the results and deeply and comprehensively reveal the regulation mechanism of microplastics on the key ecological processes of nitrogen cycling. To fully understand how microplastics and microorganisms affect the nitrogen cycling, systematic research needs to be carried out in a variety of ecosystems, such as farmland, grassland, wetland and forest ecosystem, to clarify the feedback mechanism of animals and microorganisms on environmental changes. Additionally, multi-factors and multi-level long-term tracking control test will help to ensure the accuracy and integrity of the test results. Stable isotope analysis provides a powerful research tool for revealing and quantifying the nutritional relationship in the food chain/web, while molecular technology can further understand the interaction and functional significance between microplastics and microorganisms. In the mechanism research, the means and methods of the combination of molecular biological and macrogenomics should be full used to explore the diversity of functional flora and enzymes in the ley process of nitrogen cycling. Exploring the effects of functional genes and nitrogen transformation processes has important guiding significance for studying the microbial driving mechanism of various nitrogen cycling processes in the future.

6. Conclusions

In summary, as a new environmental pollutant, microplastics can not only threaten the health of organisms, but also affect the normal nitrogen cycling through disturbing colonized microorganisms on microplastics. This paper reviews the potential effects of microplastics in four environmental media (water, soil, sediment and sewage sludge) on nitrogen transformation and nitrogen cycling and the corresponding mechanisms. Microplastics mainly affect nitrogen transformation via influencing microorganism diversity and structure, enzyme activities, related functional genes and oxygen flux of the system. Due to the lack of relevant research, the more mechanisms of microplastics on environmental nitrogen transformation and nitrogen cycling are not very clear. It is an effective strategy to further explore the impact of microplastics on environmental nitrogen cycling by evaluating complex environmental systems, prolonging the action time and assisting multi-factor and multi-level research. In addition, molecular biology and stable isotope technology have been used to explore the role of microorganisms in nitrogen transformation. The isotopic effect analysis of microbial functional genes and transformation processes would further clarity the driving mechanism of microplastics in the nitrogen cycling, which can provide support for the comprehensive evaluation of the impact of microplastics on ecological environmental health, and have important guiding significance in exploring the nitrogen cycling processes of global biogeochemistry.

Acknowledgement

The study is financially supported by the Program for Shanghai Tongji Gaotingyao Environmental Science & Technology Development Foundation, the National Natural Science Foundation of China (82003363, 82073449, U20A20323, 51521006) and the Natural Science Foundation of Changsha (kq2007059).

Declaration of interest

The authors have no conflict of interest to declare regarding this article.

Reference

Awet, T., Kohl, Y., Meier, F., Straskraba, S., Grün, A.L., Ruf, T., et al., 2018. Effects of polystyrene nanoparticles on the microbiota and functional diversity of enzymes in soil. Environ. Sci. Eur. 30, 1-10.

Azizi, S.M.M., Hai, F.I., Lu, W., Al-Mamun, A., Dhar, B.R., 2021. A review of mechanisms underlying the impacts of (nano)microplastics on anaerobic digestion. Bioresour. Technol. 329, 124894.

Bank, M.S., Hansson, S.V., 2019. The plastic cycle: a novel and holistic paradigm for the Anthropocene. Environ. Sci. Technol. 53, 7177–7179

Bläsing, M., Amelung, W., 2017. Plastics in soil: analytical methods and possible sources. Sci. Total Environ. 612, 422-435.

Butala, N.S., Falkinham, J.O., 2018. Nitrate and nitrite reductase activities of *Mycobacterium avium*. Int. J. Mycobact. 7, 328-331.

Chai B., Li X., Liu H., Lu G., Dang Z., Yin H., 2020. Bacterial communities on soil microplastic at Guiyu, an E-Waste dismantling zone of China. Ecotox. Environ. Safe. 195, 110521.

Chen, H., Wang, Y., Sun, X., Peng, Y., Xiao, L., 2020a. Mixing effect of polylactic acid microplastic and straw residue on soil property and ecological function. Chemosphere 243, 125271.

Chen, X., Chen, X., Zhao, Y., Zhou, H., Xiong, X., Wu, C., 2020b. Effects of microplastic biofilms on nutrient cycling in simulated freshwater systems. Sci. Total Environ. 719, 137276.

Cluzard, M., Kazmiruk, T.N., Kazmiruk, V.D., Bendell, L., 2015. Intertidal concentrations of microplastics and their influence on ammonium cycling as related to the shellfish industry. Arch. Environ. Con. Toxicol. 69, 310-319.

Cui, Y., Gao, J., Zhang, D., Li, D., Dai, H., Wang, Z., et al., 2021. Responses of performance, antibiotic resistance genes and bacterial communities of partial nitrification system to polyamide microplastics. Bioresour. Technol. 341, 125767.

Dai, H.H., Gao, J.F., Wang, Z.Q., Zhao, Y.F., Zhang, D., 2020. Behavior of nitrogen, phosphorus and antibiotic resistance genes under polyvinyl chloride microplastics pressures in an aerobic granular sludge system. J. Clean. Prod. 256, 120402.

Daims, H., Lücker, S., Wagner, M., 2016. A new perspective on microbes formerly known as nitrite-oxidizing bacteria. Trends Microbiol. 24, 699-712.

Dong, Z., Qiu, Y., Zhang, W., Yang, Z., Wei, L., 2018. Size-dependent transport and retention of micron-sized plastic spheres in natural sand saturated with seawater. Water Res. 143, 518-526.

Fei, Y., Huang, S., Zhang, H., Tong, Y., Wen, D., Xia, X., et al., 2020. Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil. Sci. Total Environ. 707, 135634.

Gao, B., Yao, H., Li, Y., Zhu, Y., 2021. Microplastic addition alters the microbial community structure and stimulates soil carbon dioxide emissions in vegetable-growing soil. Environ. Toxicol. Chem. 40, 352-365.

Graf, D.R., Jones, C.M., Hallin, S., 2014. Intergenomic comparisons highlight modularity of the denitrification pathway and underpin the importance of community structure for N_2O emissions. Plos One 9, e114118.

Green, D.S., Boots, B., Sigwart, J., Jiang, S., Rocha, C., 2016. Effects of conventional and biodegradable microplastics on a marine ecosystem engineer (*Arenicola marina*) and sediment nutrient cycling. Environ. Pollut. 208, 426-434.

Griffin, B.M., Schott, J., Schink, B., 2007. Nitrite, an electron donor for anoxygenic photosynthesis. Science 316, 1870-1870.

Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H., Schmidt, S.N., Mayer, P., et al., 2017. Microplastics as vectors for environmental contaminants: exploring sorption, desorption, and transfer to biota. Integr. Environ. Asses. Manag. 13, 488-493.

Ho, A., Di Lonardo, D.P., Bodelier, P.L., 2017. Revisiting life strategy concepts in environmental microbial ecology. Fems Microbiol. Ecol. 93, fix006.

Hope, J.A., Coco, G., Thrush, S.F., 2020. Effects of polyester microfibers on microphytobenthos and sediment-dwelling infauna. Environ. Sci. Technol. 54, 7970-7982.

Hu, D., Shen, M., Zhang, Y., Li, H., Zeng, G., 2019. Microplastics and nanoplastics: would they affect global biodiversity change? Environ. Sci. Pollut. Res. 26, 19997–20002.

Huang, D., Tao, J., Cheng, M., Deng, R., Chen, S., Yin, L., et al., 2020a. Microplastics and nanoplastics in the environment: macroscopic transport and effects on creatures. J. Hazard. Mater. 407, 124399.

Huang, Y., Li, W., Gao, J., Wang, F., Yang, W., Han, L., et al., 2021. Effect of microplastics on ecosystem functioning: Microbial nitrogen removal mediated by benthic invertebrates. Sci. Total Environ. 754, 142133.

Huang, Y., Qing, X., Wang, W., Han, G., Wang, J., 2020b. Mini-review on current studies of airborne microplastics: Analytical methods, occurrence, sources, fate and potential risk to human beings. TrAC Trend. Anal. Chem. 125,115821.

Huang, Y., Zhao, Y., Wang, J., Zhang, M., Jia, W., Qin, X., 2019. LDPE microplastic films alter microbial community composition and enzymatic activities in soil. Environ. Pollut. 254, 112983.

Iqbal, S., Xu, J., Allen, S.D., Khan, S., Nadir, S., Arif, M.S., et al., 2020. Unraveling consequences of soil micro- and nano-plastic pollution on soil-plant system: implications for nitrogen (N) cycling and soil microbial activity. Chemosphere 260, 127578.

Kisand, V., Valente, A., Lahm, A., Tanet, G., Lettieri, T., 2012. Phylogenetic and functional metagenomic profiling for assessing microbial biodiversity in environmental monitoring. Plos One 7, e43630

Kojima, H., Tsutsumi, M., Ishikawa, K., Iwata, T., Mußmann, M., Fukui, M., 2012. Distribution of putative denitrifying methane oxidizing bacteria in sediment of a freshwater lake, Lake Biwa. Syst. Appl. Microbiol. 35, 233-238.

Kumar, R., Sharma, P., Manna, C., Jain, M., 2021. Abundance, interaction, ingestion, ecological concerns, and mitigation policies of microplastic pollution in riverine ecosystem: a review. Sci. Total Environ. 782, 146695.

Kuypers, M.M., Marchant, H.K., Kartal, B., 2018. The microbial nitrogen-cycling network. Nat. Rev. Microbiol. 16, 263-276.

Langille, M.G., Zaneveld, J., Caporaso, J.G., McDonald, D., Knights, D., Reyes, J.A., et al., 2013. Predictive functional profiling of microbial communities using 16S rRNA marker gene sequences. Nat.biotechnol. 31, 814-821.

Li, L., Song, K., Yeerken, S., Geng, S., Liu, D., Dai, Z., et al., 2020. Effect evaluation of microplastics on activated sludge nitrification and denitrification. Sci. Total Environ. 707, 135953.

Miao, L., Hou, J., You, G., Liu, Z., Liu, S., Li, T., et al., 2019a. Acute effects of nanoplastics and microplastics on periphytic biofilms depending on particle size, concentration and surface modification. Environ. Pollut. 255, 113300.

Miao, L.Z., Wang, P.F., Hou, J., Yao, Y., Liu, Z.L., Liu, S.Q., et al., 2019b. Distinct community structure and microbial functions of biofilms colonizing microplastics. Sci. Total Environ. 650, 2395-2402.

Mohammad Mirsoleimani Azizi, S., Hai, F.I., Lu, W., Al-Mamun, A., Ranjan Dhar, B., 2021. A review of mechanisms underlying the impacts of (nano)microplastics on anaerobic digestion. Bioresour.Technol. 329, 124894.

Pajares, S., Ramos, R., 2019. Processes and microorganisms involved in the marine nitrogen cycle: knowledge and gaps. Front. Marin. Sci. 6, 739.

Petersen, F., Hubbart, J.A., 2020. The occurrence and transport of microplastics: the state of the science. Sci. Total Environ. 758, 143936.

Philippot, L., Hallin, S., Schloter, M., 2007. Ecology of denitrifying prokaryotes in agricultural soil. Adv. Agron. 96, 249-305.

Pjevac, P., Schauberger, C., Poghosyan, L., Herbold, C.W., van Kessel, M.A., Daebeler, A., et al., 2017. AmoA-targeted polymerase chain reaction primers for the specific detection and quantification of comammox Nitrospira in the environment. Front. Microbiol. 8, 1508.

Qian, H., Zhang, M., Liu, G., Lu, T., Qu, Q., Du, B., et al., 2018. Effects of soil residual plastic film on soil microbial community structure and fertility. Water Air Soil Pollut. 229, 1-11.

Qin, R., Su, C., Liu, W., Tang, L., Li, X., Deng, X., et al., 2020. Effects of exposure to polyether sulfone microplastic on the nitrifying process and microbial community structure in aerobic granular sludge. Bioresour. Technol. 302: 122827.

Rong, L., Zhao, L., Zhao, L., Cheng, Z., Yao, Y., Yuan, C., et al., 2021. LDPE microplastics affect soil microbial communities and nitrogen cycling. Sci. Total Environ. 773, 145640.

Schweiger, P,F., 2016. Nitrogen isotope fractionation during N uptake via arbuscular mycorrhizal and ectomycorrhizal fungi into grey alder. J. Plant physiol. 205, 84-92.

Seeley, M.E., Song, B., Passie, R., Hale, R.C., 2020. Microplastics affect sedimentary microbial communities and nitrogen cycling. Nat. Commun. 11, 1-10.

Shen, M., Hu, T., Huang, W., Song, B., Zeng, G., Zhang, Y., 2021a. Removal of microplastics from wastewater with aluminosilicate filter media and their surfactant-modified products: Performance, mechanism and utilization. Chem. Eng. J. 421, 129918.

Shen, M., Song, B., Zeng, G., Zhang, Y., Huang, W., Wen, X., et al., 2020a. Are biodegradable plastics a promising solution to solve the global plastic pollution? Environ. Pollut. 263, 114469.

Shen, M., Ye, S., Zeng, G., Zhang, Y., Xing, L., Tang, W., et al., 2019a. Can microplastics pose a threat to ocean carbon sequestration? Mar. Pollut. Bull. 150, 110712.

Shen, M., Zeng, G., Zhang, Y., Wen, X., Song, B., Tang, W., 2019b. Can biotechnology strategies effectively manage environmental (micro)plastics? Sci. Total Environ. 697, 134200.

Shen, M., Zeng, Z., Song, B., Yi, H., Hu, T., Zhang, Y., et al., 2021b. Neglected microplastics pollution in global COVID-19: disposable surgical masks. Sci. Total Environ. 790, 148130.

Shen, M., Zhang, Y., Zhu, Y., Song, B., Zeng, G., Hu, D., et al., 2019c. Recent advances in toxicological research of nanoplastics in the environment: a review. Environ. Pollut. 252, 511-521.

Shen, M., Zhu, Y., Zhang, Y., Zeng, G., Wen, X., Yi, H., et al., 2019d. Micro(nano)plastics: unignorable vectors for organisms. Mar. Pollut. Bull. 139, 328-331.

Shen, M., Song, B., Zhu, Y., Zeng, G., Zhang, Y., Yang, Y., et al., 2020b. Removal of microplastics via drinking water treatment: Current knowledge and future directions. Chemosphere 251, 126612.

Simon, J., Klotz, M.G., 2013. Diversity and evolution of bioenergetic systems involved in microbial nitrogen compound transformations. BBA-Bioenergetics 1827, 114-135.

Song, K., Li, Z., Liu, D., Li, L., 2020. Analysis of the partial nitrification process affected by polyvinylchloride microplastics in treating high-ammonia anaerobic digestates. ACS Omega 5, 23836-23842.

Strous, M., Pelletier, E., Mangenot, S., Rattei, T., Lehner, A., Taylor, M.W., et al., 2006. Deciphering the evolution and metabolism of an anammox bacterium from a community genome. Nature 440, 790-794.

Sun, J., Dai, X., Wang, Q., van Loosdrecht, M.C.M., Ni, B.J., 2019. Microplastics in wastewater treatment plants: Detection, occurrence and removal. Water Res. 152, 21-37.

Wang, W., Ge, J., Yu, X., 2020. Bioavailability and toxicity of microplastics to fish species: a review. Ecotox. Environ. Safe. 189, 109913.

Wei, W., Huang, Q.S., Sun, J., Wang, J.Y., Wu, S.L., Ni, B.J., 2019. Polyvinyl chloride microplastics affect methane production from the anaerobic digestion of waste activated sludge through leaching toxic bisphenol-A. Environ. Sci. Technol. 53, 2509-2517.

Yang, H., Gandhi, H., Ostrom, N.E., Hegg, E.L., 2014. Isotopic fractionation by a fungal P450 nitric oxide reductase during the production of N_2O. Environ. Sci. Technol. 48, 10707-10715.

Zumft, W.G., Kroneck, P.M., Respiratory transformation of nitrous oxide (N_2O) to dinitrogen by Bacteria and Archaea. Adv. Microb. Physiol. 52, 107-227.