Science of the Total Environment 697 (2019) 134200

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Can biotechnology strategies effectively manage environmental (micro) plastics?

Maocai Shen, Guangming Zeng*, Yaxin Zhang*, Xiaofeng Wen, Biao Song, Wangwang Tang

College of Environmental Science and Engineering, Hunan University and Key Laboratory of Environmental Biology and Pollution Control (Hunan University), Ministry of Education, Changsha 410082, PR China

ARTICLE INFO

Article history:
Received 19 July 2019
Received in revised form 27 August 2019
Accepted 29 August 2019
Available online 30 August 2019

Editor: Daqiang Yin

ABSTRACT

With the convenience of plastic products to daily life, the negative sides of the plastic-age have gradually emerged. Like other pollutants, complex environmental factors result in the ubiquitous presence of (micro)plastics worldwide, raising potential risks to the ecological systems. However, due to the limitation of traditional technologies in treating these materials, new strategies should be developed. More recently, researchers have showed that biotechnology strategies could be promising approaches to effectively manage and control (micro)plastics in the environment, because some microorganisms have been confirmed to be successfully capable of degrading (micro)plastics. Nevertheless, the biotechnology is still in its infancy, and most studies are carried out under laboratory conditions. The biodegradation process is affected by many factors: microorganism species, carbon sources, material types and sizes. Problematically, (micro)plastics are highly stable in the environment, which are difficult to be used as carbon sources for microorganisms. Biodegradation of (micro)plastics requires appropriate conditions, which are not always feasible in field conditions. As such, although biotechnology strategies might be a promising approach to remove environmental (micro)plastics, we believe it is not now at least.

1. Concerns of (micro)plastics

Plastics are inevitable reality in modern society due to their low manufacturing costs and resistance ability (Sharma and Chatterjee, 2017). It is reported that the global annual production of plastics has reached 348 million tons in 2017 and will continue to increase (PlasticsEurope, 2018). Massive production and widespread applications of plastics increase their chances of entering the environment. The ideal properties endow them with high flexibility, stability and resistance to degradation, resulting in continuous accumulation in the global environment (Barnes et al., 2009). Large plastic wastes can be decomposed into small fragments under ultraviolet irradiation, weathering and erosion. When the particle size decreases to less than 5 mm, they are called microplastics (Thompson et al., 2004). Many studies have reported the ubiquitous occurrence of microplastics in the environment (Dobaradaran et al., 2018; Eckert et al., 2017; Fang et al., 2018; Li et al., 2018; Slootmaekers et al., 2019; Su et al., 2016; Teng et al., 2019; Wen et al., 2018). The widespread presence of plastic wastes and microplastics not only causes direct landscape problems, but also poses potential environmental risks to living organisms, even humans (Diepens and Koelmans, 2018; Fossi et al., 2012; Miranda and Carvalho-Souza, 2016; Shen et al., 2019b). A research conducted by Chen et al. (2017) reported that polystyrene microplastic particles can reduce the growth rate and the larval migration behavior of zebrafish (*Danio rerio*). Kettner et al. (2017) showed that the presence of microplastics (polyethylene (PE) and polystyrene (PS)) in different environments had a certain influence on the composition and diversity of aquatic fungi community. In addition, microplastics can be transferred from lower trophic levels to higher-grade predators along the food chain (Setälä et al., 2014; Shen et al., 2019a).

The plastic pollution and potential risks of microplastics have attracted considerable concerns. Therefore, remediation strategies are

* Corresponding authors.
URL's: zgming@hnu.edu.cn (G. Zeng), zhang_yx@hnu.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.scitotenv.2019.134200

needed to manage (micro)plastics in the environment. Source control and clean up from the environment are two important strategies. At present, some countries and organizations, such as America, England, Canada and the United Nations, have already established national laws and regulations in order to reduce the release of (micro)plastics (Hu et al., 2019). These legislative methods aimed at raising the public awareness of the potential risks of (micro)plastics. Another strategy is to develop reliable technologies for direct removal of microplastics from the environment. Now, the removal of (micro)plastics in the environment is just from one phase to another, such as removing microplastics in wastewater treatment plants and drinking water treatment plants. So what and how can we do? Biotechnology strategy may be a promising approach to meet the demand. Under the action of microbes (plastic-degrading enzymes), the long chain of polymers can be gradually broken down to form short chain and fatty acids, eventually CO_2 and H_2O (Yoshida et al., 2016). Biotechnology strategy is environmentally friendly and can be alone or combined with other conventional treatment methods. Very recently, a review on the management of plastics documented that biotechnology-based tools will be pivotal approaches for the biodegradation of environmental plastics, leading from waste to wealth (Paço et al., 2019).

Although biodegradation of (micro)plastics is still in its infancy and most studies are performed under the lab conditions, the biodegradability of (micro)plastics is of great significance for the development in plastic industry and society. Biotechnology strategy requires further research and development at present and in the near future so as to make it reproducible and suitable for real environmental applications. As such, clearly, biotechnology strategies may be one of the most promising methods to control plastic pollution.

2. Biodegradation of microplastics

Global plastic waste has become one of the most serious solid waste pollution problems at present. How to deal with plastic waste has become an important issue. A number of studies have demonstrated that microorganisms have the ability to degrade microplastics, principally because they can produce plastic-degrading bioenzymes, such as laccase from *Staphylococcus epidermis* (Chatterjee et al., 2010), and PETase from *Ideonella sakaiensis* (Yoshida et al., 2016). Currently, dozens of strains, mainly fungi (mold), have been screened to degrade polyoleins and polyester plastics. Known microorganisms for microplastic biodegradation mainly include the bacterial species *Enterobacter asburiae*, *Bacillus sp.* (Jun et al., 2014; Yu et al., 2015a), *Exiguobacterium sp.* (Yu et al., 2015b), *Ideonella sakaiensis* (Yoshida et al., 2016), *Rhodococcus rhodochrous*, *Nocardia asteroids* (Bonhomme et al., 2003), *Streptomyces badius*, *Comamonas acidovorans*, *Rhodococcus ruber*, and *Clostridium thermocellum* (Paço et al., 2019), and fungal species *Phanerochaete chrysosporium*, *Engyodontium album* (Jeyakumar et al., 2013), *Cladosporium cladosporoides* (Bonhomme et al., 2003), *Pycnoporus cinnabarinusand* and *Mucor rouxii* (Pathak and Navneet, 2017). These species have been obtained and isolated from field-collected soil, landfill, dumping sites, etc. Microorganisms can utilize microplastics as an energy source and carbon source to decompose microplastics, thereby increasing the mineralization of microplastics and biomass (Weber et al., 2018). Taking the biodegradation of polyethylene terephthalate (PET) by *Ideonella sakaiensis* as an example, as described in Fig. 1, the biodegradation can be divided into four processes: 1) biosorption and erosion of plastic matrices; 2) the long chain being decomposed into short chain through biological oxidation or enzymatic hydrolysis; 3) the short chain being broken down to form fatty acids; and 4) microorganisms feeding on fatty acids and finally, and these products being transformed into CO_2 (or CH_4) and H_2O (Yoshida et al., 2016). Due to high molecular weight, strong hydrophobicity, low surface energy and other factors, the biodegradation process of PET is complex, and the degradation rate is low (approximately 6 weeks). Despite this, this may imply that it is realistic to improve the performance of enzymes to strengthen the biodegradability of microplastics. Biodegradation technology can be used alone or as a complement to the already existing traditional schemes for plastic waste treatment, thereby enhancing the management of plastic wastes. As

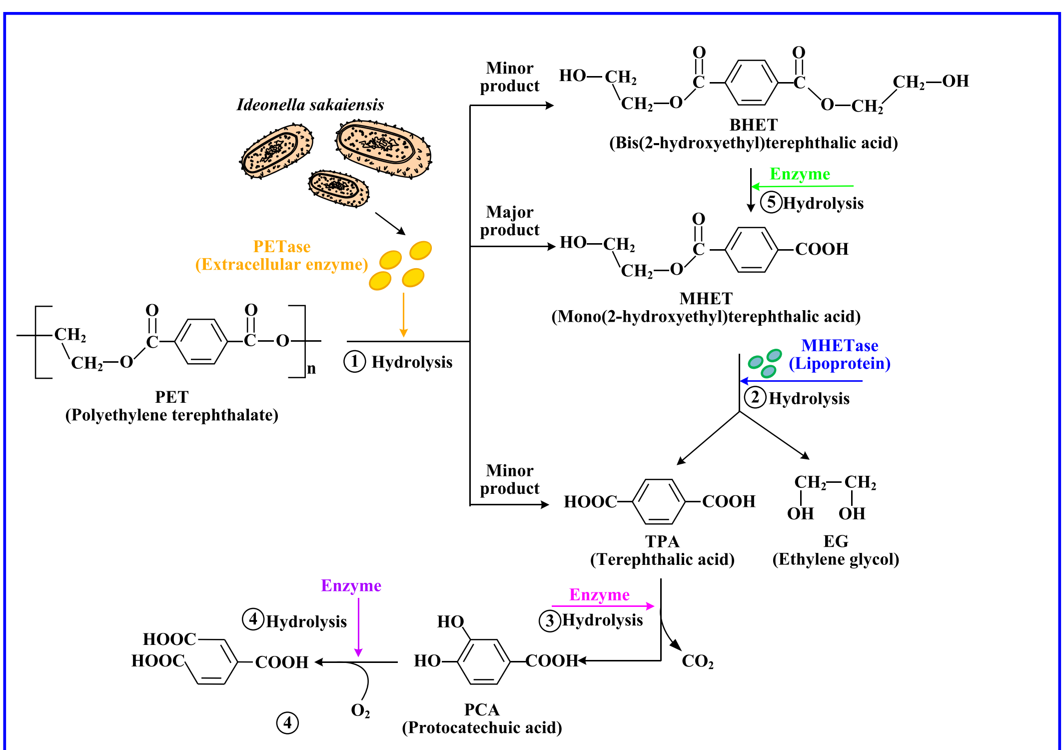

Fig. 1. Predicted PET degradation pathway by *I. sakaiensis*. Firstly, extracellular enzyme (PETase) secreted by *I. sakaiensis* hydrolyzes PET to form the major products, MHET. Secondly, MHET is degraded to TPA and EG under the action of MHETase. Intermediate products are further decomposed. Adapted from Yoshida et al. (2016).

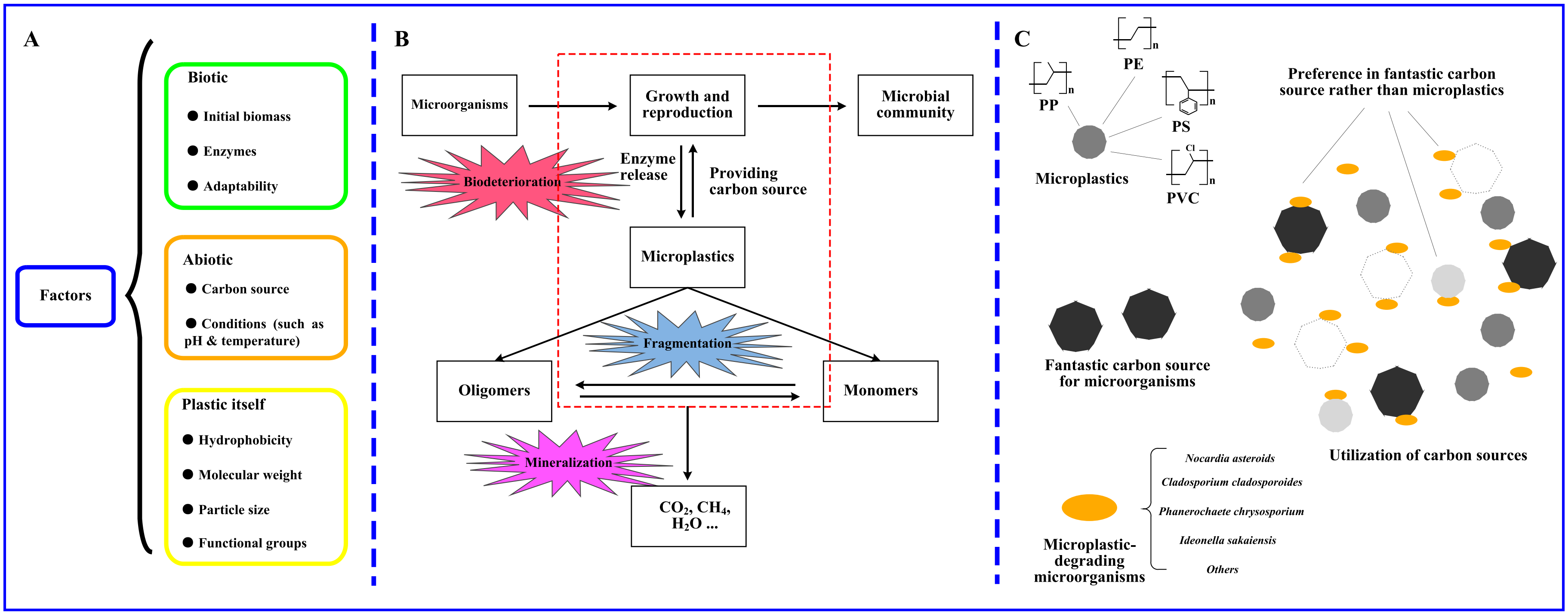

Fig. 2. Factors influencing the biodegradation process by microorganisms. Through enzymatic action, microorganisms degrade polymers into oligomers and monomers. The development and reproduction leads to the production of H_2O, CO_2, and others, thereby causing the complete mineralization of polymers. However, microplastics are not a good carbon source for microorganisms since their backbone consists entirely of C—C bonds without other reactive functional groups. Microplastics mainly include PP, PE, PS, PVC, PET, etc. Microorganisms prefer fantastic carbon sources to microplastics in the environment. Evidence showed that only a minority of microplastics has been degraded by microorganisms.

such, many scientists and researchers believe that biodegradation may be a feasible alternative for bioremediation strategies to solve the increasingly serious plastic waste problem in the future, as described by Yoshida et al. (2016) and Paço et al. (2017).

3. Factors of microplastic biodegradation by microorganisms

Evidence from biodegradation studies of microplastics shows that microorganisms can lead to the degradation of microplastics, which is of great significance to combat microplastic pollution. However, unfortunately, there are still many challenges to eliminate microplastics by microorganisms in practical application. Fig. 2 illustrates the different factors that directly affect the biodegradation of microplastics. Microbial species, initial biomass, hydrophobicity of plastic, and plastic particle size influence the biodegradation process (Fig. 2A). For instance, the basidiomycete *Zalerion maritimum* has shown high removal efficiencies of PE microplastics; however, other basidiomycetes, such as *Nia vibrissa* shows lower biodegradation efficiencies under the same conditions (Paço et al., 2019). Another example is a research done by Hadad et al. (2005), which described the degradation of PE by *Brevibacillus borstelensis* in detail. The authors reported that approximately 11% weight loss of PE films was observed in a month, however, the PE films with low density have previously been exposed to ultraviolet radiation. Additionally, microplastics are unsavory carbon source for microorganisms (Fig. 2C). For PE, polypropylene (PP), polyvinyl chloride (PVC), these synthetic materials possess a main chain composed of C—C bonds and have no other active functional groups. The carbons from these polymers are highly stable. Above mentioned tests were performed under laboratory conditions. There is a quite big difference between laboratory conditions and those of field environment. More fantastic carbon sources for microorganisms are existed under real environmental conditions. Microorganisms prefer various available carbon sources to microplastics (Fig. 2C). As a matter of fact, microplastics are difficult to be biodegraded under field conditions. For instance, a research reported that the weights of LDPE, HDPE, PP and polycarbonate submerged in the ocean waters got loss in approximately 1.9%, 1.6%, 0.69% and 0.65%, respectively, within a 12 month period (Artham et al., 2009). The increase of biomass and mineralization of organic compounds are key steps for biodegradation of microplastics by microorganisms (Weber et al., 2018). The main chain of microplastics breaks and the molecular weight gradually deceases, thereby finally becoming a utilized monomer via enzymolysis, hydrolysis or synergistic effect by microorganisms (Fig. 2B). Consequently, considering the different microorganisms, characteristics and types of microplastics and available nutrients, it is necessary to improve microbial populations and increase contacts with each other. For example, Syranidou et al. (2017) reported that the biodegradation degree of PS was improved from 0.19%–2.3% within a period of 6 months via successive inoculations of the indigenous marine community. But, such degradation efficiency is still considerably low. Tribedi and Alok (2013) showed that the degradation of microplastics can also be enhanced by promoting the interaction between polymers and microplastic-degrading microbes. The authors reported that the presence of mineral oil promoted the hydrophobicity and strengthened adhesion of polymer surface, thereby improving the biodegradation efficiency of PE. Evidence has been demonstrated that the formation of biofilms plays a vital role on the biodegradation of microplastics, in part, reasonably, the use of biotechnology strategies enhanced biofilm formation could ameliorate biodegradation status of microplastics (Pathak and Navneet, 2017). In addition, the development and reproduction of microorganisms are related to their specific natural environment (Fig. 2). Microorganisms screened to degrade microplastics may be not necessarily dominant species in real environment. Enhancement of the adaptability of microorganisms to the specific environment is conducive to their survival and speeding up the utilization and degradation of microplastics.

4. Ways forward

(Micro)plastics are everywhere. The ubiquitous presence of microplastics needs removal strategies after they are released into the environment due to its potential toxic effects and bioaccumulation on many organisms, even humans. As such, their disposal has become a matter of great concern, especially in view of the growing evidence that they are harmful to the environment. Although microplastics are difficult to be degraded, from the aforementioned descriptions, they are still degradable. Although the biodegradation efficiency of microplastics is low, the degrading ability of microorganisms can be further enhanced. Microorganisms and surrounding conditions are most crucial during biodegradation. Therefore, screening suitable microorganisms and adapting to environmental conditions are the challenges for biodegradable plastics in the current and the future. Efficient strains with high performance of degrading plastics may be screened by high strength and mixed cultures. In addition, bioengineering can also be used to enhance the biodegradable ability though cultivation of new microorganisms or enzymes. The in-situ biodegradation for (micro)plastics may be achieved adding microbes or extracellular enzymes or utilizing natural microbial communities through related bioengineering. Therefore, biotechnology strategies are expected to become an effective way to control microplastic pollution in view of many constraints, such as poor utilization of microplastics as carbon source, limited number of known degradation microorganisms, etc. Recent advances in biotechnology strategies have demonstrated great potential possibilities not only in designing new approaches to effectively degrade conventional plastics, but also of the synthesis of existing polymers, as well as new biodegradable materials. The one way is to understand potential biochemical degradation mechanisms, which may help to design plastics that are easily decomposed when exposed to specific environmental conditions, such as high temperature, humidity and salinity. A thorough understanding of the degradation mechanism of plastics may lead to the development of new materials that can easily be converted into useful materials. Another way is to convert non-biodegradable plastics into raw materials for sustainable supply chains. A variety of pure organic acids can be produced in waste plastics after a series of biochemical treatments. These degradation products can be used as raw materials for the production of new degradable plastics. Consequently, plastic wastes, to some extent, may become a valuable resource. It is necessary to adopt more sustainable biotechnology strategies to solve the most promising environmental concerns of our time. However, the challenges of biotechnology strategies to manage (micro)plastics still exist: potential risks and investment cost. There is potential risk on biotechnology strategies for the rapid removal of (micro) plastics. The plastic-eating bugs made through biotechnology strategies might change the community structure of the area and might also destroy the useful items containing plastics, which subsequently cause inevitable great loss. Additionally, specific selected microorganisms (enzymes) and limited biodegradation conditions invisibly increase the investment and operating costs in biotechnology strategy to manage (micro)plastics. Thus, biotechnology strategies are still needed to be furtherly studied to make it reproducible, inexpensive and suitable for large-scale applications. A circular plastic economy is required in the current and the future, and biotechnology strategies are interesting and will help us move towards a more sustainable and closed-loop development of plastics economy.

Acknowledgements

The study is financially supported by the Program for the National Natural Science Foundation of China (51521006) and the Program for Changjiang Scholars and Innovative Research Team in University (IRT-13R17).

Declaration of competing interest

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

References

Artham, T., Sudhakar, M., Venkatesan, R., Nair, C.M., Murty, K.V.G.K., Doble, M., 2009. Biofouling and stability of synthetic polymers in sea water. Int. Biodeterior. Biodegradation 63, 884–890.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364, 1985–1998.

Bonhomme, S., Cuer, A., Delort, A.M., Lemaire, J., Sancelme, M., Scott, G., 2003. Environmental biodegradation of polyethylene. Polym. Degrad. Stabil. 81, 441–452.

Chatterjee, S., Roy, B., Roy, D., Banerjee, R., 2010. Enzyme-mediated biodegradation of heat treated commercial polyethylene by Staphylococcal species. Polym. Degrad. Stabil. 95, 195–200.

Chen, Q., Gundlach, M., Yang, S., Jiang, J., Velki, M., Yin, D., 2017. Quantitative investigation of the mechanisms of microplastics and nanoplastics toward zebrafish larvae locomotor activity. Sci. Total Environ. s584–585, 1022–1031.

Diepens, N.J., Koelmans, A.A., 2018. Accumulation of plastic debris and associated contaminants in aquatic food webs. Environ. Sci. Technol. 52, 8510–8520.

Dobaradaran, S., Schmidt, T.C., Nabipour, I., Khajeahmadi, N., Tajbakhsh, S., Saeedi, R., 2018. Characterization of plastic debris and association of metals with microplastics in coastline sediment along the Persian Gulf. Waste Manag. 78, 649–658.

Eckert, E.M., Di, A.C., Kettner, M.T., Ariasandres, M., Fontaneto, D., Grossart, H.P., 2017. Microplastics increase impact of treated wastewater on freshwater microbial community. Environ. Pollut. 234, 495–502.

Fang, C., Zheng, R., Zhang, Y., Hong, F., Mu, J., Chen, M., 2018. Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions. Chemosphere 209, 298–306.

Fossi, M.C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., 2012. Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (Balaenoptera physalus). Mar. Pollut. Bull. 64, 2374–2379.

Hadad, D., Geresh, S., Sivan, A., 2005. Biodegradation of polyethylene by the thermophilic bacterium Brevibacillus borstelensis. J.Appl.Microbiol. 98, 1093–1100.

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

Jeyakumar, D., Chirsteen, J., Doble, M., 2013. Synergistic effects of pretreatment and blending on fungi mediated biodegradation of polypropylenes. Bioresour. Technol. 148, 78–85.

Jun, Y., Yu, Y., Wei-Min, W., Jiao, Z., Lei, J., 2014. Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environ. Sci. Technol. 48, 13776–13784.

Kettner, M.T., Rojas-Jimenez, K., Oberbeckmann, S., Labrenz, M., Grossart, H.P., 2017. Microplastics alter composition of fungal communities in aquatic ecosystems. Environ. Microbiol. 19, 4447–4459.

Li, J., Green, C., Reynolds, A., Shi, H., Rotchell, J.M., 2018. Microplastics in mussels sampled from coastal waters and supermarkets in the United Kingdom. Environ. Pollut. 241, 35–44.

Miranda, D.D.A., Carvalho-Souza, G.F.D., 2016. Are we eating plastic-ingesting fish? Mar. Pollut. Bull. 103, 109–114.

Paço, A., Duarte, K., Costa, J.P.D., Santos, P.S.M., Pereira, R., Pereira, M.E., 2017. Biodegradation of polyethylene microplastics by the marine fungus *Zalerion maritimum*. Sci. Total Environ. 586, 10–15.

Paço, A., Jacinto, J., Costa, J.P.D., Santos, P.S.M., Vitorino, R., Duarte, A.C., 2019. Biotechnological tools for the effective management of plastics in the environment. Crit. Rev. Env. Sci. Tec. 49, 410–441.

Pathak, V.M., Navneet, 2017. Review on the current status of polymer degradation: a microbial approach. Bioresour. Bioproces. 4, 15–46.

PlasticsEurope, 2018. Plastics-the Facts 2018.

Setälä, O., Fleming-Lehtinen, V., Lehtiniemi, M., 2014. Ingestion and transfer of microplastics in the planktonic food web. Environ. Pollut. 185, 77–83.

Sharma, S., Chatterjee, S., 2017. Microplastic pollution, a threat to marine ecosystem and human health: a short review. Environ. Sci. Pollut. R. 24, 21530–21547.

Shen, M., Zhang, Y., Zhu, Y., Song, B., Zeng, G., Hu, D., 2019a. 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., 2019b. Micro(nano)plastics: Unignorable vectors for organisms. Mar. Pollut. Bull. 139, 328–331.

Slootmaekers, B., Catarci-Carteny, C., Belpaire, C., Saverwyns, S., Fremout, W., Blust, R., 2019. Microplastic contamination in gudgeons (Gobio gobio) from Flemish rivers (Belgium). Environ. Pollut. (Barking, Essex: 1987) 244, 675–684.

Su, L., Xue, Y., Li, L., Yang, D., Kolandhasamy, P., Li, D., 2016. Microplastics in Taihu Lake, China. Environ. Pollut. 216, 711–719.

Syranidou, E., Karkanorachaki, K., Amorotti, F., Franchini, M., Repouskou, E., Kaliva, M., 2017. Biodegradation of weathered polystyrene films in seawater microcosms. Sci. Rep. 7, 17991–18003.

Teng, J., Wang, Q., Ran, W., Wu, D., Liu, Y., Sun, S., 2019. Microplastic in cultured oysters from different coastal areas of China. Sci. Total Environ. 653, 1282–1292.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., 2004. Lost at sea: where is all the plastic? Science 304, 838.

Tribedi, P., Alok, K., 2013. Low-density polyethylene degradation by Pseudomonas sp AKS2 biofilm. Environ. Sci. Pollut. R. 20, 4146–4153.

Weber, M., Makarow, D., Unger, B., Mortier, N., Wilde, B.D., Eekert, M.V., 2018. Assessing marine biodegradability of plastic—Towards an environmentally relevant international standard test scheme. Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea.

Wen, X., Du, C., Xu, P., Zeng, G., Huang, D., Yin, L., 2018. Microplastic pollution in surface sediments of urban water areas in Changsha, China: abundance, composition, surface textures. Mar. Pollut. Bull. 136, 414–423.

Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., 2016. A bacterium that degrades and assimilates poly(ethylene terephthalate). Science 351, 1196–1199.

Yu, Y., Jun, Y., Wei-Min, W., Jiao, Z., Yiling, S., Longcheng, G., 2015a. Biodegradation and mineralization of polystyrene by plastic-eating mealworms: part 1. Chemical and physical characterization and isotopic tests. Environ. Sci. Technol. 49, 12080–12086.

Yu, Y., Jun, Y., Wei-Min, W., Jiao, Z., Yiling, S., Longcheng, G., 2015b. Biodegradation and mineralization of polystyrene by plastic-eating mealworms: part 2. Role of gut microorganisms. Environ. Sci. Technol. 49, 12087–12093.