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Editorial

The mitigation and remediation of micro(nano)plastics to improve environmental and public health

Micro(nano)plastics (MNPs) pollution with its extensive environmental accumulation is a pressing environmental and public health problem. Plastic waste is ubiquitously present in different environmental matrices such as atmosphere, water bodies, sediment, marine systems, even remote places like Antarctica, mountain tops including the summit of Mt. Fuji, and the deep sea (Luo et al., 2024; Y. Wang et al., 2023). The detection of MNPs in several remote regions has implicated atmospheric transport via currents as an important pathway for global dissemination, increasing the associated health risks. In their life cycle, plastic waste can break down into MNPs by a variety of processes, such as mechanical (erosion and wear), chemical (photo-oxidation and corrosion), and biological (biotransformation), leading to new interactions with the environment and organisms. MNPs have unique properties such as larger specific surface area, easier entry into organisms, ability to adsorb and carry other pollutants (surface adsorbed co-pollutants such as hormones, heavy metals including arsenic, persistent organic pollutants (POPs) and plasticizers) and even pathogens and antibiotics resistance genes (H. Wang et al., 2023; Ma et al., 2023; Wang et al., 2020; Lu et al., 2021; Tang et al., 2020). MNPs also serve as breeding ground for antimicrobial resistant-microorganisms, and they effect primary producers in various ecosystems (and ultimately the food chain) (Gaur et al., 2023; Stungaru et al., 2019; H-P. Wang et al., 2023). Furthermore, they can modulate the toxicity of pharmaceuticals and pesticides in various environmental compartments (Barreto et al., 2023). At the molecular level, MNPs can induce a broad range of cellular responses in animal cells, including pyroptosis, a pro-inflammatory cell death mechanism, resulting in immune responses (Berkel and Cacan, 2023). MNPs can negatively impact the behavior and reproductive health of aquatic organisms (Gao et al., 2022). They also cause detrimental ecotoxicological impact on the rhizosphere (disturbs community structures of soil microbiota), impacts plants (causing plant biomass reduction; intracellular oxidative stress burst; photosynthesis inhibition; water and nutrient absorption reduction; genotoxicity; reprogramming of transcriptome, proteome and metabolome; and seed germination retardation, etc.), thereby negatively influencing agro-ecosystems, food safety and security in addition to the others (Hu et al., 2024). Therefore, there is an urgent need to provide sustainable and cost-effective solutions for the mitigation / remediation of micro(nano) plastics.

A plethora of mitigation / remediation strategies for MNPs have been developed, and they include (direct or multi-stage) filtration with membrane technology and nanosheets, phytoremediation, biodegradation, adsorption (for instance, using carbon-based adsorbents such as bichar), sedimentation, use of coagulants, magnetic extraction, reverse osmosis, photocatalysis and micro/nanorobots (V. Kumar et al., 2023; R. Kumar et al., 2023; Li et al., 2023). All these methodologies for the decontamination/removal of MNPs currently have certain limitations, cost and efficiency problems which should be considered in future research. The challenges faced include effectively removing ultrasmall particles, achieving high removal efficiency for low MNPs concentrations, and treating significant amounts of environmental contamination at a low cost. Some removal methods can even lead to secondary pollution. Plastic-degrading enzymes (for instance, those from certain microorganisms incl. bacteria and fungi) can be utilized as green catalytic tools since they can specifically target the complex polymer structure for their further degradation by breaking down long carbon chains into simpler monomers through enzymatic degradation and even into benign end products such as carbon dioxide and water (Cárdenas-Alcaide et al., 2022; Tang et al., 2022). For MNP degradation by microorganisms in the environment, the problem of biodegradation efficiency has to be overcome, for instance, through protein engineering, since microbial degradation is influenced by multiple biotic and abiotic factors, such as temperature and pH (Silva et al., 2018). The major drawback associated with bioremediation of MNPs is that microorganisms are able to degrade only certain plastics. There is also the requirement of optimum environmental conditions and of enough nutrient supply for microorganismal growth; therefore, it has a slow removal rate. In order to maximize the depolymerization efficiency of MNP-degrading enzymes, novel approaches to enhance the performance and stability of natural enzymes including immobilization methods onto different materials and nanomaterials, and the protocols to strengthen the binding of the substrate to the active site of the enzyme have been developed in recent years and must be further improved (Cárdenas-Alcaide et al., 2022). Other technologies to address these challenges have also particular disadvantages. For instance, filtration methods might provide a high decontamination efficiencies; however, their energy consumption and nanoplastic filtering loss impede treatment at large scale. Therefore, an optimal solution is needed to balance the trade-off between removal efficiency, cost, and environmental impact in MNPs remediation / decontamination.

For the proper and sustainable mitigation of MNPs from different environmental matrices, effective and robust analytical-based

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detection/identification/characterization methods are also of high interest. The optimization of current techniques with an interdisciplinary approach is necessary to achieve enhanced MNP removal efficiency at large-scale to generate innovations with realistic applicability. Furthermore, although experimental conditions used in previous studies are important to understand MNP mitigation abilities of the developed methods by creating an interference-free environment, some critical aspects of the processes have been overlooked. Hence, further research using more complex systems are required for a more realistic determination and comparison of MNP removal efficiency of different methodologies. Besides, more frequent use of computational tools such as computer-aided modeling and simulation in the mitigation and remediation of MNPs will be of critical importance in the coming years. Special emphasis should also be laid upon the upcycling approaches such as the valorization of MNPs into chemicals, fuels or new materials as a way forward for circular bioeconomy and to attain the sustainable development goals considering the fact that they can even provide opportunity for producing profit (for instance, through the generation of high calorific fuel via the pyrolysis process) in polluted and resource-limited areas, considering the fact that the largest increases in plastic waste generation are expected in regions where waste management is poor.

Declaration of competing interest

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

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Caglar Berkel, Oguz Özbek*

Tokat Gaziosmanpasa University, Faculty of Science and Arts, Department of Molecular Biology and Genetics, 60250, Tokat, Turkey

* Corresponding author.

E-mail address: oguz.ozbek@gop.edu.tr (O. Özbek).