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Can biotechnology tackle invisible risks of microplastics and PFAS?

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EDITORIAL

Microplastics (MPs) and per- and polyfluoroalkyl substances (PFAS) are integrated with human cycles and causing severe health and environmental challenges. Therefore, the need to tackle them together efficiently is still lacking and demands novel approaches, such as biotechnology, which can play a crucial role due to its capability to develop biomolecules (enzymes and microbiomes) for the efficient degradation of PFAS and MPs at a large scale and testing at the point of need. In addition, biomaterials such as algal biomass serve as efficient filter materials for the biosorption of PFAS and MPs. Synthetic cell-based biosensors emerge as highly sensitive analytical tools for detecting these pollutants in real time under various circumstances and conditions. Biotechnology-assisted handling of MPs and PFAS is a newly emerging approach and needs global attention for scaling up wide applications. The aspects, capabilities, and trends of this proposed field are discussed in this editorial.

1. BACKGROUND

To meet the everyday life demands of survival, society relies on synthetic materials, including microplastics (MPs) and per- and polyfluoroalkyl substances (PFAS). Given the increasing demand, the PFAS market is valued at $3.0 billion in 2026 and is estimated to reach $4.8 billion by 2033. At the same time, the plastic market is valued at approximately $533 billion in 2026 and is estimated to reach between $832 billion and $1.3 trillion in the coming decade. The other side of plastics is MPs, which are being produced at an industrial scale to meet the demand of several practical applications. The market for MP production is valued at $1.3 billion in 2026, and this is estimated to reach $2.5 billion in 2033. MPs, defined as small plastic particles, are generated from plastics under various operational conditions, such as temperature, heat, moisture, and other environmental conditions.

It has been evident that PFAS and MPs are constantly leaching from their respective materials and enter the human cycle, including water, air, and food. Once integrated, the MPs and PFAS can enter the human system and altering cellular function. In the current scenario, MPs and PFAS have also been investigated in water, air, food, and the human body, causing serious consequences, including polluted water and contaminated air along with contaminated food [1]. Adverse effects of MPs and PFAS have been investigated, and efforts are being made to explore chronic environmental and health issues. Additionally, PFAS and MPs stay together in nature, as the loading of PFAS on the surface of MPs has been investigated, which makes detection and management of both pollutants challenging [2]. This is more serious considering the long-term stability of MPs (approximately 1,600 years) and PFAS (thousands of years). Due to the extremely high thermal and chemical stability of C–F bonds, PFAS have been called forever chemicals.

Global environmental and health agencies are continuously increasing the demand for investigating novel and efficient approaches to tackle both PFAS and MPs' invisible threats [3]. Advanced materials have been investigated for the trapping and degradation of both MPs and PFAS in various settings. Very specific materials have been designed to develop highly sensitive sensors for MPs [4–6] and PFAS detection [2], but the selectivity of these systems is not yet well demonstrated. To date, materials investigated for tackling MPs and PFAS are synthesized using chemical routes, but sometimes these syntheses are not environmentally friendly. At the same time, there is considerable scope to improve their performance, and the focus is now more oriented towards biotechnology, where biomolecules can be designed to trap, detect, and degrade MPs and PFAS. Such proposed approaches are contributing significantly and align well with the goals of the United Nations related to green technology. State-of-the-art biotechnology-assisted frameworks for tackling PFAS and MPs efficiently are illustrated in Figure 1.

Integration of MPs and PFAS (A): biomolecules (enzymes, microbiomes, and cells) and biomaterials (bioplastics) to achieve the degradation testing of MPs and PFAS (B). For efficient management, showing the role of AI and IoT (C), for example: 1) investigating efficient biocatalysts and biomolecules, 2) efficient sensing for PoU AND PoL applications, 3) risk assessment based on careful data analytics, and 4) overall analysis of outcomes for projecting biotechnology-assisted approaches for surveillance applications. This image is self-designed and does not require any permission.

1.1. Emergence of Biotechnology-Assisted Tackling of MPs and PFAS

MPs and PFAS remediation remain a challenge associated with strong thermal and chemical stability because 1) the C–F bond in PFAS is

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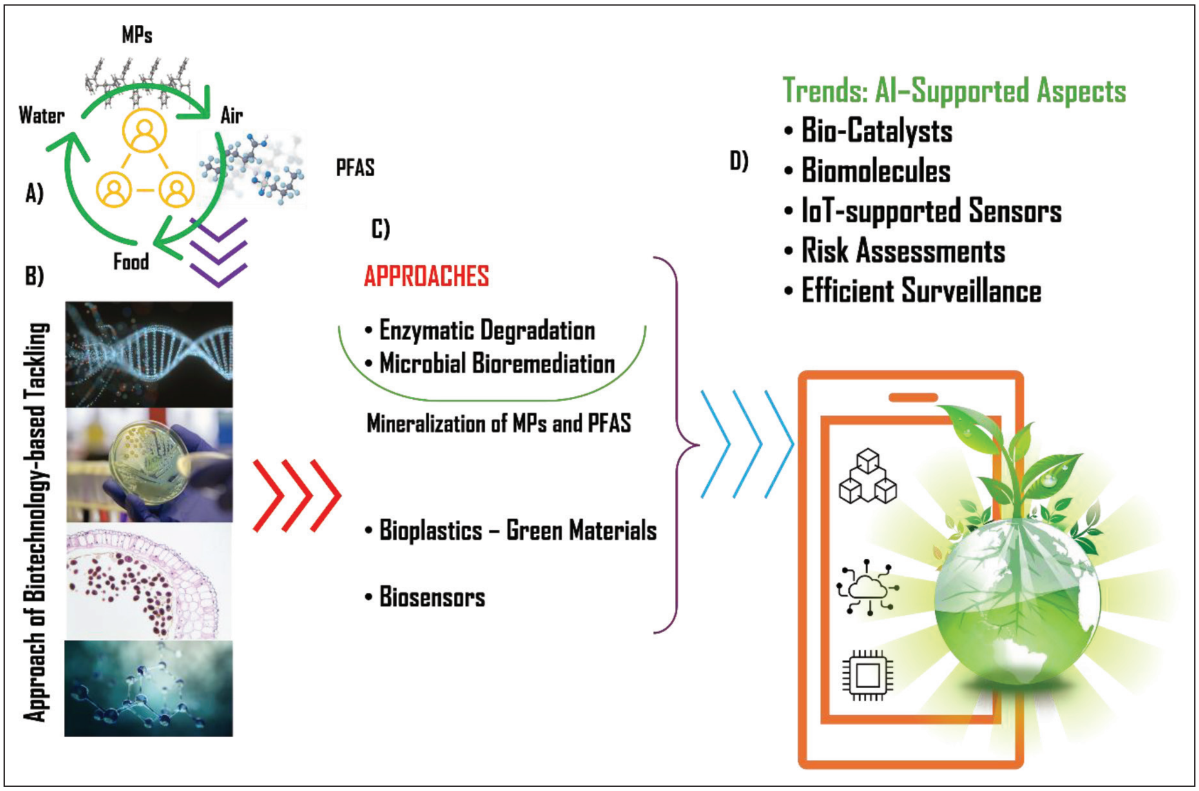

Figure 1. Biotechnology-assisted frameworks for tackling PFAS and MPs.

the strongest in organic molecules, and 2) the tightly bonded structure (repeating C–C chain) of MPs does not break down easily. The key approach to tackling MPs and PFAS is to investigate efficient materials that can break down C–F and C–C bonds. Materials developed using bio-routes are emerging as a potential solution to handle MPs and PFAS [7–9]. In this approach, designing and developing engineered proteins and microbial enzymes are getting attention and have demonstrated plastic-eating ability. For example, PETase has emerged as an efficient catalyst for a wide range of MPs under diverse environmental conditions. On the other hand, specialized bacterial strains have been isolated that can break down PFAS in soil and wastewater treatment. There is scope to explore various synthetic biology routes to assemble metabolic pathways in microbial consortia for sequential degradative steps that cannot be demonstrated by any single organism.

As a state-of-the-art approach, biotechnology-assisted approaches are highly effective at capturing MPs, but it still struggles to achieve rapid destruction of both PFAS and MPs. For example, biological systems, including algae-based bio-coagulants and membrane bioreactors, demonstrate 80% to 99%+ MPs removal by trapping, filtration, and concentrating them out of wastewater streams [10,11]. However, the degradation of isolated MPs is still a remaining challenge. In this situation, fungi and engineered microbes have demonstrated only a 0% to 15% mass reduction in MPs (over several months) [12]. In the case of PFAS, specifically designed bacterial consortia degraded 43% to 90% (specific to long-chain compounds) [13]. However, the destruction, i.e., mineralization, of these PFAS has yet to be achieved. Another concern is that bio-assisted processes, generally, leave short-chain and highly mobile PFAS and MPs by-products behind, and tackling these short-chain by-products requires secondary thermal or chemical treatment to achieve complete degradation.

Besides trapping and degradation, bio-assisted approaches are also evolving to develop efficient sensing systems for the detection of MPs and PFAS. Synthetic biology-driven molecules have been investigated to develop biosensors to detect MPs and PFAS selectively. Specific whole-cell and cell-free approaches have been adopted for the fabrication of electrochemical and fluorescence biosensing systems. For example, PFAS have been detected using fluorescence-based biosensors employing engineered whole-cell bacterial strains [14,15]. These biosensing systems demonstrated PFAS detection in the ng/l to ppb concentration range [14,15]. To detect PFAS, a human liver fatty acid binding protein (hLFABP)-based optical biosensor was fabricated to detect one of the PFAS-related pollutants at 236 ppb. While current benchtop mass spectrometry still holds the ultimate advantage in ultra-trace detection limits (reaching into parts-per-quadrillion levels), biosensors minimize sample preparation steps, eliminate heavy background noise from complex matrix interferences, and offer scalable architectures for real-time environmental monitoring. Lubricin (proteoglycan 4) and hLFABP [engineered with a methylene blue redox tag (FABP1-MB)] were utilized to fabricate a point-of-care (POC) electrochemical sensor to detect PFAS at 0.41 ng/l in real water and whole-blood samples [16]. According to the 6th-generation sensing technology, the above-reported sensing prototypes can be interfaced with Internet of Things (IoT)-based tools, including microelectronics, to achieve sensing for point of need (PoN) applications. Furthermore, artificial intelligence (AI) can be introduced to explore better sensing materials and analyze sensing outcomes. Such a collective approach helps to achieve PoN sensing of MPs and PFAS with a lot of benefits, including risk assessment, decision-making, management, and surveillance [6].

2. CONCLUSION AND VIEWPOINT

MPs, NPs, and PFAS are creating their own ecosystem and causing a serious, combined toxicity in the human and environmental systems. The natural defense system is not capable enough to degrade these pollutants fast; therefore, human involvement is a must by exploring engineered biotechnology, which can support remediation approaches and replacement of conventional materials. To date, the outcomes of the proposed biotechnology-assisted approaches to tackle MPs and PFAS are promising. However, more systematic research is required to adopt these approaches for real-world applications. With this view, first, there is a need to develop highly stable bacteria and laboratory-evolved enzymes that can maintain functional capabilities in harsh conditions and successfully break down C–F and polymeric chain bonds. Second, there could be ways to customize synthetic metabolic pathways in organisms (*Escherichia coli* or *Pseudomonas putida*) where plastic can be adopted as the source of carbon. Third, awareness of the adoptability bioplastic can be an efficient way to replace plastics; for example, algae-based polymeric systems. Fourth, developing more efficient and novel biomolecules for the fabrication of sensors that can selectively detect MPs and PFAS separately and simultaneously at very low concentrations, including ppt, in the setting of PoU, PoL, and POC. Fifth, introduction of AI, specifically machine learning, in the planning of systematic research, including design, optimization, execution, outcomes analysis, risk assessment, and decision-making. The above-discussed approaches are significant but require multidisciplinary actions when timely outcomes are the key focus. Therefore, this editorial is a call to the global community to explore multidisciplinary and collaborative research to develop scaled-up and adoptable biotechnology-assisted approaches for the efficient tackling of MPs and PFAS, as illustrated in Figure 1.

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4. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

5. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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