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Molecularly Imprinted Polymers As A Remediation Technique For Emerging Contaminants

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Clean water, healthy soil and a safe environment are essential for human well-being. However, alongside well-known pollutants such as heavy metals and pesticides, researchers are becoming increasingly concerned about a newer group of chemicals known as emerging contaminants. These substances are not new; many have been used for decades in medicines, personal care products, industries and agriculture. Nevertheless, a long-term and sustainable approach requires improving existing water and wastewater treatment systems and integrating them into a circular water management framework that supports efficient resource utilization and environmental sustainability. In this context, Molecularly Imprinted Polymers (MIPs) have gained considerable attention because of their high selectivity and ability to recognize and capture specific target molecules. These synthetic polymers are engineered with tailor made binding sites that match the size, shape and chemicals properties of the contaminant of interest, enabling efficient removal even from complex environmental complexes.

Keywords: Emerging contaminants, Molecularly Imprinted Polymers (MIP), Wastewater treatment, Environmental complex, Endocrine-disrupting chemicals (EDCs).

Introduction

The emerging contaminants are synthetic or naturally occurring chemicals or biological agents that are detected in environment and potentially hazardous to humans and ecosystem. Various studies have reported the presence of emerging chemical pollutants at trace concentrations (ranging from ng L^{-1} to µg L^{-1}) in different environmental compartments (Surana *et al.*, 2022). These pollutants, commonly called "emerging micro-pollutants" or emerging contaminants, currently lack legislative regulations (Sarkar *et al.*, 2022). As of 2000, the European Union (EU) has identified 33 chemical compounds in surface waters, both freshwater and marine, as priority pollutants to be eliminated within two decades to protect the aquatic environment's ecological status. In 2007, additional compounds, including pharmaceuticals and personal care products (PPCPs) such as phthalates, iopamidol, diclofenac, carbamazepine, triclosan, clofibric acid and ibuprofen were added to the priority pollutant list. Many of these toxic substances are known to be endocrine-disrupting chemicals (EDCs) or even carcinogens (Priya *et al.*, 2022). These anthropogenic micropollutants primarily include industrial chemicals, pesticides and PPCPs. A range of conventional treatment technologies, including adsorption, membrane filtration, and ozonolysis, are available for the removal of emerging contaminants. Despite their effectiveness, their widespread application is constrained by high costs, limited recovery, and operational challenges. Molecular Imprinting Technology (MIT) is a versatile approach for fabricating synthetic receptors with high molecular recognition capability. Molecularly Imprinted Polymers (MIPs) are prepared by polymerizing functional monomers and crosslinkers in the presence of a template molecule. Subsequent template removal generates recognition cavities that are complementary in shape, size, and functional groups to the target, enabling selective rebinding even in complex matrices. Based on the template–monomer interactions, MIPs are classified as covalent, semi-covalent, or non-covalent (BelBruno *et al*., 2018). Covalent MIPs provide high structural stability through covalent template binding, semi-covalent MIPs combine covalent imprinting with non-covalent recognition, whereas non-covalent MIPs rely on reversible interactions such as hydrogen bonding, electrostatic forces, hydrophobic interactions, van der Waals forces, and π–π stacking. The choice of imprinting strategy depends on the required selectivity, binding affinity, stability, and intended application.

Synthesis of MIP

The fabrication of molecularly imprinted polymers (MIPs) generally involves a multistep synthesis procedure. Initially, functional monomer(s) are mixed with a chosen template molecule in a suitable porogenic solvent system to form a self-assembled pre-polymerization complex through specific intermolecular interactions (Fig.1). Subsequently, the polymerization process is carried out in the presence of cross-linking agents to generate a rigid polymeric network. Following polymer formation, the embedded template molecules are extracted from the polymer matrix, thereby creating well-defined recognition cavities complementary in shape, size, and functional groups to the target analyte. After template removal, the synthesized MIP becomes capable of highly selective recognition and rebinding of the target molecule.

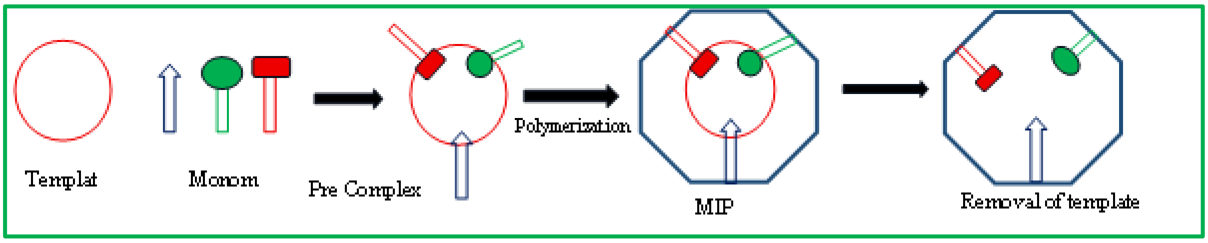

Fig.1: Schematic illustration of the molecular imprinting process. Adapted from Ayivi *et al.*, 2023)

Applications of MIP

Molecularly imprinted polymers (MIPs) have attracted considerable attention because of their wide-ranging applications across various areas of science and technology (Sajini and Mathew, 2021). These benefits have led to their application in various areas, including electrochemical sensing (Lahcen and Amine, 2018), chiral molecule separation (Wu *et al*., 2018), solid phase extraction catalysis and adsorptive removal of contaminants.

Separation- Separation science is a rapidly advancing field with major applications in the pharmaceutical, chemical, wastewater treatment, and water purification sectors. Molecularly imprinted polymers (MIPs) are widely employed as selective sorbent materials in various extraction and separation techniques, including solid-phase extraction (SPE), dispersive SPE, solid-phase microextraction (SPME), magnetic SPE, and as stationary phases in high-performance liquid chromatography (HPLC). In addition, MIPs have been utilized for the adsorption and removal of environmental contaminants and hazardous compounds. These imprinted materials also demonstrate excellent performance in the selective extraction and purification of drugs, nucleic acids such as DNA and RNA, peptides, and amino acids.

Sensors- MIPs have emerged as robust alternatives to biological receptors in sensor technology owing to their high selectivity, excellent chemical and thermal stability, and low cost (Rinaldi *et al*., 2025). MIP-based sensors, typically fabricated by electro polymerization or immobilization on transducer surfaces, have been widely applied for the selective detection of sugars, herbicides, nucleic acids, toxins, drugs, and other analytes. Their integration into electrochemical, fluorescence, surface plasmon resonance, conductivity, and mass-sensitive sensing platforms further demonstrates their broad analytical potential.

Drug Delivery- MIPs have demonstrated considerable potential in controlled drug delivery owing to their high selectivity, molecular recognition, and rebinding capabilities. They have been extensively investigated for sustained and targeted drug release, with applications including theophylline-imprinted beads, propranolol–cyclodextrin delivery systems, and MIP-based soft contact lenses and composite membranes. These advances highlight the promise of MIPs as efficient platforms for targeted drug delivery in pharmaceutical and biomedical applications.

Catalyst- MIPs have emerged as promising materials for catalysis, with applications in zeolite design, stereoselective catalysis, and enzyme-mimicking systems. By imprinting acid–base catalysts, metal complexes, or reaction intermediates, MIPs function as artificial enzyme-like catalysts with high selectivity. Advances in polymeric and sol–gel imprinting, including beads, monoliths, ultrathin films, and dendrimer-based imprinting, have further enhanced their molecular recognition and catalytic efficiency.

Conclusion

Molecularly imprinted polymers (MIPs) have become an important class of synthetic materials owing to their exceptional molecular recognition capability and broad applicability in separation, sensing, catalysis, controlled drug delivery and the removal of emerging contaminants. Their excellent molecular recognition, stability, reusability, and cost-effectiveness make them promising alternatives to conventional materials. Although challenges such as template leakage and complex synthesis remain, continued advances in sustainable fabrication and multifunctional MIP design are expected to overcome these limitations. Consequently, MIPs are poised to play n increasingly important role in future analytical, environmental, and biomedical technologies.

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