AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 03, Issue: 08 (August, 2026)
Available online at http://www.agrimagazine.in

Sustainable Molecularly Imprinted Polymers: Green Synthesis Strategies

*Amandeep and Arunima M.U.
Research Scholar, Division of Agricultural Chemicals, ICAR-Indian Agricultural Research Institute, New Delhi, India
*Corresponding Author's email: amandeep87082@gmail.com

Molecularly imprinted polymers (MIPs) are the emerging technique offering versatile tool which possess high selectivity and strong binding affinity toward specific target molecules, even in complex environmental sample matrices. Conventional MIP synthesis frequently involves the use of hazardous solvents and chemicals, which causes rise in environmental and sustainability concerns. To overcome these limitations, environmentally benign synthetic strategies guided by the principles of green chemistry and sustainable engineering are being increasingly adopted. This article highlights the use of microwave-assisted methods, supercritical fluid technology, biomass-based material and environmentally friendly green solvents for the synthesis of MIPs. These approaches require only small amounts of solvent and produce less hazardous waste, making them safer for both human health and the environment.

Keywords: Molecularly Imprinted Polymers (MIP), Waste water treatment, Green chemistry, Deep eutectic solvents (DES)

Introduction

Molecularly imprinted polymers (MIPs) have developed into an important class of functional materials with applications in sensing, analytical separations, drug delivery, catalysis, and materials science (Amandeep *et al*.,2026). Their major advantage lies in the presence of highly selective recognition sites that are tailored for a specific target molecule. During synthesis, the template molecule interacts with functional monomers through covalent or non-covalent interactions, and subsequent polymerization with suitable cross-linkers fixes these interactions within a rigid polymeric network. After removal of the template, complementary cavities remain in the polymer matrix that match the target analyte in size, shape, and chemical functionality, thereby enabling selective rebinding. Owing to these characteristics, MIPs are often considered synthetic analogues of biological recognition systems and have attracted considerable attention for selective extraction, sensing, and controlled drug delivery applications (Ali *et al*.,2023).

Considerable research has been devoted to improving the recognition performance and binding capacity of MIPs. Optimization of porogenic solvents, initiation methods, polymerization conditions, functional monomers, and cross-linkers has been widely explored to obtain polymers with higher affinity, faster binding kinetics, and improved selectivity. In drug delivery applications, the fabrication of MIPs under well-defined synthesis conditions has also shown potential for achieving controlled and sustained release behaviour. Recent advances further emphasize the development of MIPs with uniform binding sites, improved morphology, and enhanced mass-transfer properties.

Despite these advances, conventional MIP synthesis frequently relies on organic solvents and synthetic reagents that raise environmental and sustainability concerns. Exposure to such solvents may cause respiratory irritation, skin disorders, and neurological effects, while occupational exposure during industrial handling can increase the risk of inhalation toxicity, dermal contact, and fire-related accidents. Many organic solvents are highly flammable, creating hazards during storage and processing. Their volatility also contributes to the release of volatile organic compounds (VOCs), which participate in photochemical smog formation and deteriorate air quality. Inappropriate disposal or accidental leakage can contaminate soil and groundwater, whereas discharge into aquatic environments may adversely affect aquatic organisms and ecosystem health (Bedwal and M.U., 2026). In addition, solvent-intensive processes generate substantial hazardous waste, leading to disposal challenges and increased environmental burden. Consequently, industries using large quantities of organic solvents are subject to stringent regulations concerning emissions, waste management, and worker safety.

To overcome these limitations, increasing attention is being directed toward green synthesis strategies for MIPs based on the principles of green chemistry and sustainable engineering. These approaches aim to reduce or eliminate hazardous solvents, minimize waste generation, lower energy consumption, and employ safer raw materials.

Green chemistry focuses on the design of chemical products and manufacturing processes that reduce or avoid the use and formation of hazardous substances. Its primary goal is to promote sustainable and environmentally responsible approaches for producing chemicals and materials. In practice, green chemistry encourages the adoption of innovative techniques that lessen environmental impacts across the entire life cycle of chemical products, from synthesis to disposal. The concept is guided by the twelve principles of green chemistry introduced by Paul Anastas and John Warner in 1998.Green Chemistry in Molecular Imprinting: (Madikizela *et al*.,2019)

- Minimize waste by efficiently using monomers and avoiding excess reagents.
- Environmentally benign solvents in the synthesis of MIPs
- Microwave-assisted synthesis or ambient temperature polymerization are employed to reduce energy consumption in molecular imprinting.
- Use of bio-based or renewable monomers
- Employ catalysis in the polymerization steps
- Minimize the production of unwanted by-products

Green Synthesis Strategies for MIP

- **Microwave-Induced Polymerization:** Microwave-assisted synthesis is regarded as an efficient and environmentally friendly approach because it enables rapid and uniform heating of the reaction system. This enhanced heat transfer accelerates the polymerization process, thereby reducing reaction time and facilitating the formation of polymers with improved yields. This approach ensures uniform heating of the reaction mixture to reduce thermal gradients in the reaction solution. This phenomenon is the source of a stable nucleation and growth environment, leading to the preparation of MIPs with a regular size distribution. Xu *et al*. (2013) synthesized monolithic molecularly imprinted polymer (MIP) fibers through a microwave-assisted polymerization method. The prepared material was successfully applied for the preconcentration of bisphenol A (BPA) and its analogues, including diethylstilbestrol and hexestrol.
- **Supercritical fluid technology approach:** Supercritical carbon dioxide ($scCO_2$) has emerged as a promising and environmentally friendly medium for the synthesis of molecularly imprinted polymers (MIPs). Its use offers several advantages, including the production of high-purity materials, elimination of harmful organic solvents, simplified synthesis procedures, and the formation of free-flowing polymer particles with controllable morphology and porosity (R. Viveiros *et al*., 2017). Affinity polymers prepared in $scCO_2$ are particularly attractive because they are free from residual organic solvents, easy to process, and can be tailored to achieve specific functional properties. Moreover, $scCO_2$ offers several advantages, including low toxicity, non-flammability, chemical stability, and the absence of odor. It can also be readily separated from the final product, requires relatively little energy for removal, and can be recovered and reused,

making it a cost-effective and environmentally favorable alternative. The first MIP synthesized using $scCO_2$ was reported by Duarte *et al*. in 2006 for potential drug delivery applications.

- **Biomass-Derived Material Approach:** Several sustainable and nanostructured materials have been incorporated into molecularly imprinted polymer (MIP) systems to improve their environmental compatibility and functional performance. Chitosan is a biodegradable biopolymer obtained from chitin, a naturally occurring polysaccharide present in the exoskeletons of crustaceans and insects. Because it is renewable, biocompatible, and environmentally benign, chitosan has become an attractive material for the preparation of green MIP composites. Activated carbon is widely used as a support material in molecular imprinting because its high surface area and porous structure enhance adsorption capacity, binding efficiency, and overall MIP performance. In addition, cellulose-based nanocomposites offer biodegradability, mechanical stability, and abundant surface functional groups that facilitate imprinting. Carbon nanotube-based nanocomposites improve electrical conductivity, surface area, and mass transfer properties, making them valuable in sensing and separation applications. Quantum dot-based nanocomposites provide unique optical characteristics that are useful for fluorescence sensing, while graphene quantum dot-based nanocomposites combine excellent fluorescence behaviour with high surface activity and chemical stability, thereby improving sensitivity and selectivity in analytical applications. Together, these materials contribute to the development of efficient, sustainable, and high-performance MIP systems.
- **Green solvents**: Conventional MIPs, which often depend on petrochemical-derived monomers, hazardous organic solvents such as chloroform, acetonitrile, benzene, and methanol, and poorly biodegradable crosslinking agents, green MIPs aim to incorporate renewable compounds, environmentally friendly solvents, and biodegradable constituents (Maki *et al*.,2025). Deep eutectic solvents (DESs) have attracted considerable attention as greener alternatives to conventional organic solvents and ionic liquids. DESs are composed of a mixture of two or more constituents with melting points lower than those of their components. One component act as a hydrogen-bond donor (HBD), whereas the other acts as a hydrogen-bond acceptor (HBA) (Shah *et al*.,2023). Their unique physicochemical properties, including easy preparation, low viscosity, negligible toxicity, and simple composition, make DESs promising green materials for environmental pollutant removal. Their ability to interact with contaminants through hydrogen bonding, van der Waals forces, electrostatic attraction, and charge-transfer interactions facilitates the solubilization, selective capture, and efficient extraction of diverse pollutants from complex environmental matrices. DESs offer considerable versatility in MIP technology, as they can function as template-removal eluents as well as functional monomers, crosslinking agents, porogens, or even template components during polymer preparation (Cheng *et al*.,2026). Owing to these properties, DESs can enhance the removal of emerging contaminants, dyes, pesticides, pharmaceuticals, and other organic pollutants from aqueous systems. Furthermore, their structural tunability allows DESs to be designed for specific pollutant–solvent interactions, thereby improving removal efficiency and selectivity while reducing the environmental impacts associated with conventional solvent-based remediation processes.

Conclusion

In conventional techniques limitation arises due to the reliance on organic chemical solvents and elevated temperatures, under these rigorous conditions, proteins, bacterial cells, and viruses undergo denaturation. Thus, the green MIP synthesis routes could be a suitable solution to make this hybrid material more selective and adaptable for sorptive extraction and sensing approaches for such targets. Innovative approaches, including deep eutectic solvents (DESs) and biomass-based composites, offer sustainable alternatives to conventional synthesis methods by minimizing the use of organic solvents and hazardous chemicals while reducing chemical waste and the associated environmental impact. Microwave and supercritical CO_2 techniques facilitate fast, solvent-free polymer reactions, however, their application necessitates specialized equipment, signifying a shift towards more sustainable practices. The mentioned approaches present unique benefits by providing cost-effective and non-toxic alternatives to traditional synthesis techniques.

References

1. Ali, Y. A. E. H., Hejji, L., Lahcen, A. A., Pérez-Villarejo, L., Azzouz, A., & Kim, K. H. (2023). Progress and prospects in the green synthesis of molecularly imprinted polymers for sorptive extraction and sensing applications toward emerging contaminants in various sample matrices. *Trends in Analytical Chemistry*, 117466.
2. Amandeep., M.U. A., Narayanan, N., Kaushik, P., & Gupta, S. (2026). Molecularly imprinted polymers as a remediation technique for emerging contaminants. *Agri Articles*, *6*(4), 301.
3. Bedwal, A., & M.U.A. (2026). Aquatic and marine pollution: sources, impacts, and remediation. *Advances in Environmental Science and Sustainable Development* (1st ed., pp. 87–98). Agri root publication house.
4. Maki, M. A. A., Tan, K. F., Yee, M. T. S., Mishra, D. K., Venkatesh, M. P., Abduljaleel, O. W., ... & Palanirajan, V. K. (2025). Green solvents as a sustainable strategy to reduce the impact of hazardous waste on human health. *Discover Chemistry*, *2*(1), 342.
5. Cheng, D., Wang, X., Li, J., Dai, Y., Jin, P., Li, Y., Lu, L., Luo, X., Lin, J., Wang, Z. & Feng, S. (2026). Deep eutectic solvents in molecularly imprinted materials: a comprehensive review of functional roles and recent advances. *Analyst*, *151*(6), 1549-1566.
6. Duarte, A. R. C., Casimiro, T., Aguiar-Ricardo, A., Simplício, A. L., & Duarte, C. M. (2006). Supercritical fluid polymerisation and impregnation of molecularly imprinted polymers for drug delivery. *The Journal of supercritical fluids*, 39(1), 102-106
7. Madikizela, L. M., Ncube, S., & Chimuka, L. (2019). Green chemistry features in molecularly imprinted polymers preparation process. *In Comprehensive Analytical Chemistry (*Vol. 86, pp. 337-364).
8. Shah, S. A. H., Ramachandran, M. R., Mansur, S. A., Saleh, N. M., & Asman, S. (2023). Selective recognition of bisphenol a using molecularly imprinted polymer based on choline chloride-methacrylic acid deep eutectic solvent monomer: Synthesis characterization and adsorption study. *Polymer*, 283, 126279.
9. Viveiros, R., Pinto, J. J., Costa, N., Heggie, W., & Casimiro, T. (2023). Development of affinity polymeric particles for the removal of 4-dimethylaminopyridine (DMAP) from active pharmaceutical ingredient crude streams using a green technology. *The Journal of Supercritical Fluids*, 194, 105853.
10. Xu, S., Zhang, X., Sun, Y., & Yu, D. (2013). Microwave-assisted preparation of monolithic molecularly imprinted polymeric fibers for solid phase microextraction. *Analyst*, 138(10), 2982-2987.