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# Green molecularly imprinted polymer-based electrochemical sensors: Toward sustainable analytical applications

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ABSTRACT

The escalating global pollution crisis, driven by population growth, urbanization, industrialization, and over-consumption, poses significant risks to ecosystems, environmental sustainability, and human health. Green molecular recognition strategies, particularly molecularly imprinted polymer-based electrochemical sensors, offer highly selective and sensitive platforms for pollutant detection, mimicking natural biological recognition sites while providing stability, reusability, and cost-effectiveness. Plant-assisted MIP-based electrochemical sensors represent a sustainable approach that integrates renewable and biodegradable materials to reduce the environmental footprint of traditional analytical techniques. Various construction methods for green MIPs, including energy-efficient polymerization techniques and sustainable solvents, further enhance environmental compatibility without compromising analytical performance. Plant-based materials play a crucial role in MIP fabrication by enhancing biocompatibility, mechanical stability, and functional versatility. Electrochemical MIP sensor development benefits from plants by enabling portable, in situ detection platforms for real-world environmental sample analysis and pollutant tracking in industrial and agricultural settings. Analytical applications of green MIPs demonstrate high selectivity and sensitivity toward a wide range of contaminants, including pollutants, pharmaceuticals, and biomolecules, highlighting their potential as eco-friendly alternatives to conventional methods. Future developments in green MIP technology emphasize integrating sustainability, cost-efficiency, and high analytical performance, paving the way for broader adoption in field-deployable sensing systems. This review highlights recent advances (2021–2026) in plant-assisted, molecularly imprinted polymer-based electrochemical sensors from a green analytical chemistry perspective, critically evaluating sustainable design strategies, emerging functional materials, and the balance between analytical performance and environmental sustainability.

## 1. Introduction

The global pollution crisis has emerged as one of the most pressing environmental and public health challenges of the twenty-first century. Rapid population growth, heavy urbanization, industrialization, and unsustainable consumption patterns have all contributed to this problem [1,2]. Industrial effluents, agrochemicals, toxic heavy metals, pharmaceutical residues, and persistent plastic debris are increasingly being released into the air, water, soil, and surrounding ecosystems. This is a serious threat to both the environment and public health. Pollution not only harms human health right away but also exacerbates broader ecological and socioeconomic problems by threatening food production systems, depleting natural resources, accelerating biodiversity loss, and worsening climate change [3–6].

The global pollution crisis underscores the urgent need for reliable environmental monitoring systems. Various techniques, such as liquid chromatography-mass spectrometry (LC-MS/MS), inductively coupled plasma mass spectrometry (ICP-MS), high-performance liquid chromatography (HPLC), gas chromatography, UV–visible spectroscopy, fluorescence spectroscopy, electrochemical methods, and sensor technologies, can be used for monitoring and addressing emerging pollutants [7–14]. These analytical methods are essential for detecting

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contaminants; however, methods based on green chemistry principles should be used to minimize environmental pollution.

Integrating green chemistry principles minimizes these disadvantages, including the use of toxic solvents, non-biodegradable chemicals, high energy consumption, and lengthy sample-preparation steps [15]. Based on the 12 principles of green chemistry, safe, non-toxic, biodegradable, and ecologically benign reagents, green solvents (e.g., ionic liquids, deep eutectic solvents), and methods (microextraction and different types of biosensor detection) improve sensitivity, portability, and applicability in field settings, in addition to lowering hazardous waste [16]. In this regard, green analytical chemistry offers two advantages: it enables accurate identification of contaminants and aligns the monitoring procedure with the broader objectives of environmental preservation and sustainability.

A promising nexus between cutting-edge analytical technology and green chemistry is represented by molecularly imprinted polymer (MIP) sensors. Following the fundamental principles of green chemistry, MIP preparation can be optimized to reduce the use of hazardous solvents and toxic reagents, as well as energy-intensive procedures. MIP sensors utilize fewer reagents and are often incorporated into portable, in situ detection platforms [17]. In contrast, traditional analytical techniques frequently require time-consuming sample preparation and substantial amounts of organic solvents. This lowers the analysis's overall environmental impact by reducing chemical waste and facilitating quick monitoring at the contamination site. Therefore, by combining sustainability and high analytical performance, green analytical chemistry can enhance pollutant detection, as demonstrated by the development and application of MIP sensors.

MIPs are stable, reusable, and reasonably priced to produce. They are designed to resemble biological recognition sites, such as antibodies and enzymes, and offer high selectivity and sensitivity for target pollutants, pharmaceuticals, and biomolecules. Green chemistry concepts are increasingly being explored through energy-saving polymerization techniques (e.g., microwave- or UV-assisted synthesis), renewable monomers, natural polymers, plant-based materials, and green solvents (e.g., water, ionic liquids, deep eutectic solvents), as shown in Fig. 1 [18–20]. Green chemistry's growing framework thus offers a way to reduce MIPs' environmental impact while improving their efficacy, scalability, and integration into environmentally friendly sensing platforms for real-world monitoring.

This review addresses the growing environmental challenges and highlights the role of green molecular recognition strategies, particularly MIPs, as sustainable solutions for pollutant detection. This study explores MIPs in chemical sensing; the role of plant-based materials in environmentally friendly MIP design; sustainable green MIP synthesis strategies; and examples of composite materials used in electrochemical MIP sensor development for environmental monitoring; nanomaterial synthesis from plants; their use in electrochemical sensors; and food quality control. In this regard, the current study focuses on developments in molecularly imprinted polymer-based electrochemical sensors reported over the past 5 years (2021–2026), with a focus on plant-assisted and sustainable design approaches. In contrast to earlier studies, this work takes a green analytical chemistry stance, emphasizing energy-efficient techniques, renewable resources, and environmentally safe synthesis pathways. Additionally, it addresses the range of newly developed functional materials used in MIP-based sensing platforms and offers a critical assessment of the balance between analytical performance and environmental sustainability. This integrated perspective, combining sustainability, plant-assisted nanomaterial design, and electrochemical sensing performance, represents a distinct contribution to the current literature.

## 2. Overview of molecularly imprinted polymers

MIPs are a synthetic approach, similar to antibody-antigen systems based on the key-lock relationship, that can mimic natural systems. MIPs are a great example of biomimetic recognition at the molecular level because they replicate the recognition phenomena found in natural biomolecules within synthetic polymeric matrices, earning them the moniker "plastic antibodies" [21,22]. Creating a prearranged system of a selected template molecule and its matching functional monomer, followed by cross-linking polymerization in the presence of an initiator and a suitable cross-linker, is a common step in molecular imprinting. Complementary cavities of the template molecule remain in the polymer matrix after it has been extracted using the appropriate solvents, and the resulting polymer composite is referred to as a molecularly imprinted polymer [22]. The polymer can selectively rebind the target analyte because cavities with "molecular memory" remain after the template is

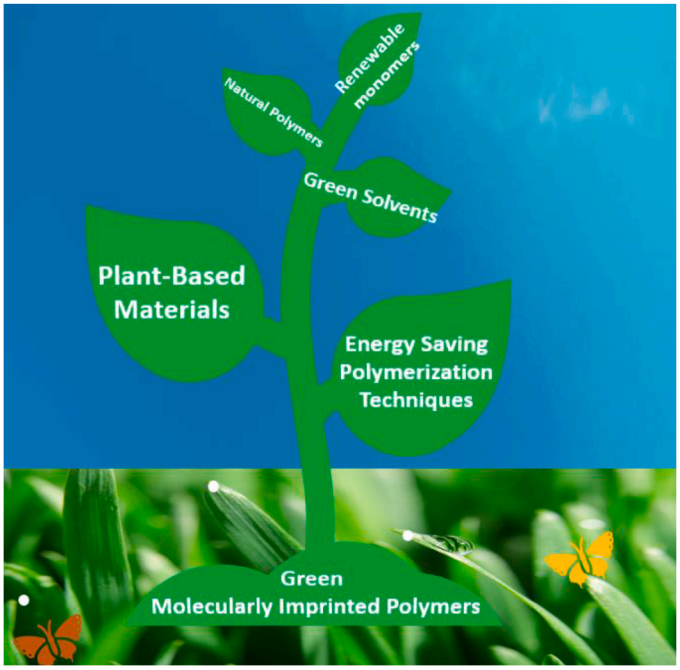



**Fig. 1.** Key requirements for the construction of green MIPs.

removed. The schematic representation of the formation of a conventional MIP process is shown in Fig. 2. The components of the polymeric complex are the target molecule, the functional monomer, the cross-linking monomers, the initiators, and the porogenic solvent [22].

The most crucial step in this formation process is the set of intermolecular interactions that occur during polymerization. The stronger the interactions within the polymeric complex, the more selective the molecular recognition becomes. The two primary methods for creating MIPs can be classified as covalent and non-covalent, depending on the interactions between the template molecule and the monomer functional groups during the pre-polymerization stage. Non-covalent interactions, such as van der Waals forces, hydrogen bonding, π-π interactions, dipole-dipole interactions, and ion-dipole interactions, facilitate the formation of a template and functional monomer complex through self-assembly [23]. On the other hand, in covalent interactions, molecular recognition occurs through chemical synthesis, allowing the creation of polymers with binding groups present only in the imprinted holes, thereby reducing the likelihood of non-specific interactions [22].

MIPs have evolved into multipurpose instruments over the last few decades, finding applications in pharmaceuticals, food safety, environmental monitoring, catalysis, and biomedical diagnostics [24]. They are ideal for detecting pollutants because they are flexible, stable under challenging physical and chemical conditions, and compatible with a range of transduction systems (electrochemical, optical, thermal, and mass-sensitive) [25]. Increasingly, electrochemical sensors are being combined with MIPs to create highly reliable and selective platforms for environmental pollutants, industrial and food safety targets, biomedical and clinical analytes, and biological macromolecules [26–28]. Integrating MIPs into electrochemical sensors results in a polymeric complex with specific binding cavities that complement the target compound. The electrode acts as a transduction interface, converting the binding event into a detectable electrical signal. Electrochemical signals, such as current, potential, and impedance, can be measured using electrochemical impedance spectroscopy, differential pulse voltammetry, and amperometry [29,30]. By adding selective recognition components to the electrode surface, such as enzymes, antibodies, aptamers, or MIPs, electrochemical sensors can detect everything from small ions to large biomolecules [31,32]. This collaboration combines the cost-effective, portable, and miniaturized nature of electrochemical detection with the molecular recognition powers of MIPs. It is particularly useful for on-site monitoring of pollutants, drugs, and biomarkers, where real-time, point-of-care measurements are essential. By directly immobilizing MIP films onto conductive electrode surfaces, such as screen-printed electrodes, glassy carbon, or gold, you obtain a sensor that is highly sensitive and chemically stable, enabling rapid, label-free detection of analytes. Innovations such as green-synthesized MIPs, conductive polymers, and nanostructured electrodes further enhance sensor performance while adhering to principles of sustainable chemistry. As a result, MIP-based electrochemical sensors offer a robust, environmentally friendly method for identifying analytes in complex matrices, such as environmental water samples and clinical specimens. Additionally, MIP electrochemical sensors provide a wide detection range, excellent sensitivity, a low detection limit, simple operation, high stability, and ease of miniaturization [30]. By adjusting the optimization parameters of the polymerization process, such as monomer ratio, temperature, polymerization type, removal-rebinding time, and solvent, it is possible to enhance MIP specificity and mitigate the impact of non-specific interactions.

### 2.1. *Historical overview and improvements*

The historical journey of MIP sensors spans nearly a century, evolving from early silica-gel chemistry into a nanotechnology-driven revolution that yields durable "plastic antibodies" to bypass the fragility and high cost of biological receptors. In 1931, Soviet chemist M. V. Polyakov conducted the first recorded imprinting experiments, observing that silica gels prepared alongside specific additive molecules demonstrated a distinct preference for re-adsorbing those exact compounds [33,34]. Building on these concepts in 1949, Linus Pauling presented research by his student, Frank H. Dickey, on silica gels designed to mimic biological antibodies; however, silica's structural instability and poor reproducibility stalled commercial progress for decades. The field was revitalized in 1972, when Günter Wulff and Ahmed Sarhan introduced organic MIPs, successfully synthesizing rigid, covalent molecular cavities within organic polymers and establishing the structural foundation for modern imprinted materials [33–35].

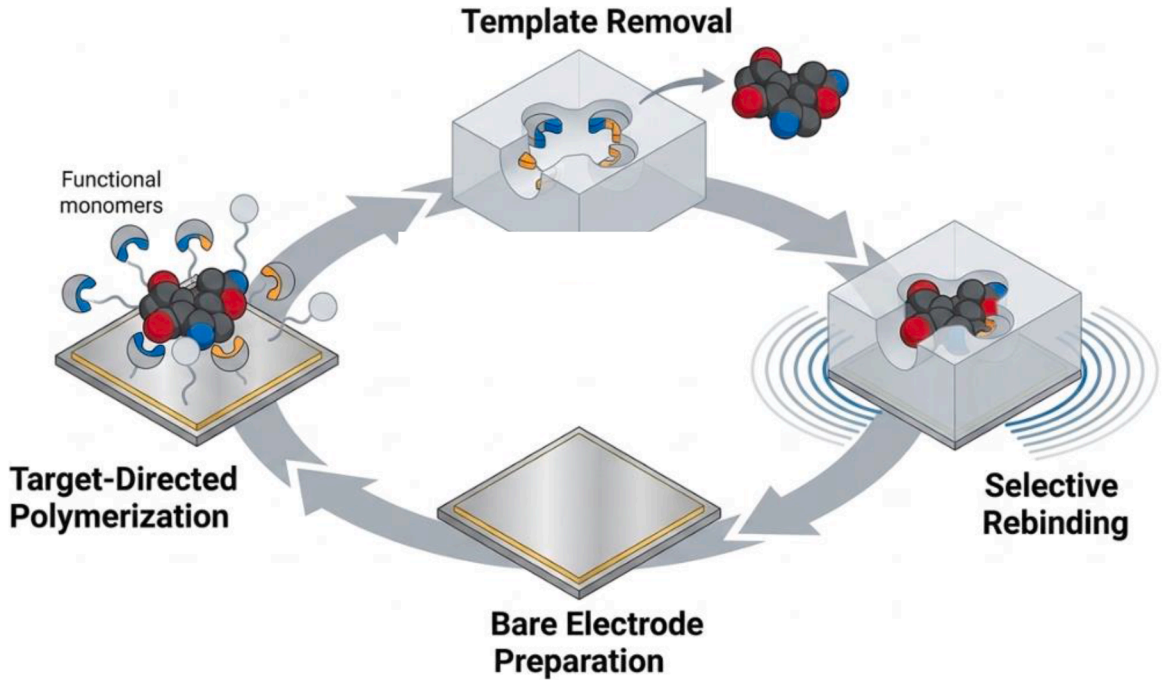



**Fig. 2.** Schematic representation of the MIP process.

Building on non-covalent imprinting advancements pioneered by Klaus Mosbach in 1981, MIP-based electrochemical sensors ultimately emerged from fusing these synthetic recognition elements directly with electrochemical transducers.

While early sensors relied on bulk polymers, in the late 1990s, conducting electropolymerized materials such as polyaniline, polypyrrole, and polythiophene were explored due to their superior electrical conductivity, environmental stability, and facile functionalization [36,37]. Initially constrained in the 1990s by bulky, ground-polymer coatings that suffered from slow mass transfer, the field transformed through in situ electropolymerization, allowing ultra-thin, highly controllable functional films to grow directly on electrode surfaces. The integration of high-surface-area nanomaterials such as carbon nanotubes, graphene, and gold nanoparticles during the 2000s dramatically accelerated electron transfer and sensitivity, ultimately enabling modern advancements, including epitope imprinting of large biomacromolecules (proteins, viruses) and their integration onto screen-printed electrodes for point-of-care medical diagnostics and environmental monitoring [38]. Afterward, different types of electrodes, such as gold, glassy carbon, platinum, and carbon paste, have been used in voltammetric and amperometric methods [39]. During the 2000s, nanomaterial-assisted MIPs, firstly carbon nanomaterials such as carbon nanotubes and graphene, and after that gold, magnetic, and hybrid nanoparticles and nanocomposites were incorporated, offering electrical conductivity, high surface-to-volume ratio, excellent mechanical stability, and abundant functional groups for MIP immobilization. Nanomaterials facilitate π-π interactions and improve electrical conductivity and surface area, thereby increasing sensor sensitivity and providing sub-nanomolar detection limits, ultimately enabling modern advancements such as epitope imprinting for large biomacromolecules (proteins, viruses) and integration onto screen-printed electrodes for point-of-care medical diagnostics and environmental monitoring [27,36]. MXenes, Metal-Organic Frameworks (MOFs), graphene composite materials, and quantum dots have emerged as promising materials applying a dual nanomaterial strategy to amplify electrochemical signals [40–42]. Over the past decade, MIP technology has evolved beyond conventional recognition materials toward smart sensing systems by integrating computationally assisted polymer design, nanostructured interfaces, flexible and wearable electrode platforms, miniaturized potentiometric devices, in situ and real-time monitoring, artificial intelligence-driven data analysis, and interconnected digital healthcare ecosystems [43–45].

Early electrochemical MIP sensors were hindered by several limitations, including heterogeneous distribution of binding sites, poor accessibility of imprinted sites, slow analyte diffusion, low signal intensity, incomplete template removal, and nonspecific binding [30]. Over the past decade, these challenges have been progressively addressed through advances in materials engineering, polymer chemistry, and sensor technology. The incorporation of conductive nanomaterials, electropolymerization of thin MIP films, computational designs, wearable devices, point-of-care approaches, miniaturized solid-contact potentiometric devices, and wireless data transmission have transformed MIP-based electrochemical sensors from proof-of-concept laboratory systems into intelligent analytical platforms capable of rapid, real-time, and in situ measurements [46–48]. Early limitations and modern solutions are summarized in Fig. 3. Seconds-to-minutes response times, picomolar detection limits, strong molecular recognition, excellent stability, selectivity, and reproducibility, portable, flexible, and miniaturized devices, in situ monitoring, and AI-connected systems are general breakthrough outcomes. These breakthroughs constitute meaningful technological advancements by combining the robustness and chemical stability of synthetic receptors with the enhanced analytical performance, portability, and digital connectivity required for next-generation point-of-care diagnostics.

## 3. Ways to construct green MIPs

Conventional MIP synthesis typically relies on synthetic chemicals, hazardous organic solvents, and energy-intensive preparatory techniques, all of which present significant environmental and sustainability issues. Polymerization and template removal often involve solvents such as methanol, acetonitrile, toluene, and chloroform; these substances can be hazardous to human health and the environment. Long-term chemical waste is also increased because many conventional monomers and cross-linkers are not biodegradable. In addition to requiring large amounts of solvent, long reaction times, and numerous purification steps, conventional synthesis processes often result in excessive energy consumption and waste. These disadvantages have prompted researchers to focus more on developing environmentally friendly MIP synthesis methods that use safer solvents, bio-based ingredients, and more sustainable polymerization processes.

Guided by Green Analytical Chemistry (GAC) principles, green MIP synthesis rethinks traditional methods to prioritize sustainability. Instead of relying on the usual monomers, toxic organic solvents, and energy-intensive polymerization, this eco-friendly approach replaces them with bio-based materials and safer solvents, such as ionic or deep eutectic solvents. It also reduces waste by using computational design tools, harmless templates, and energy-efficient, sometimes entirely solvent-free techniques [49]. Ultimately, by incorporating biodegradable polymers and smart recycling strategies, green MIPs minimize

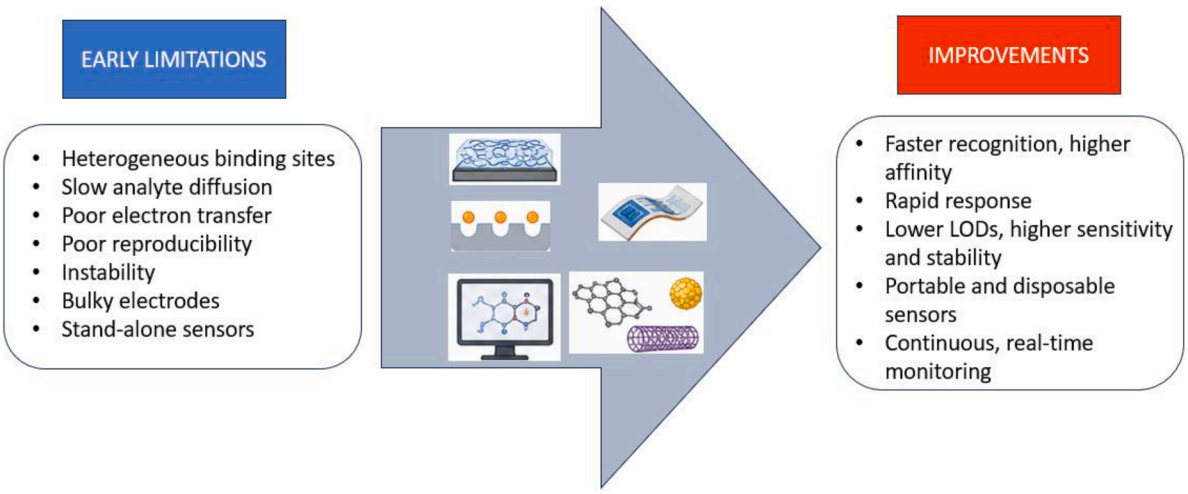



**Fig. 3.** Evolution and breakthrough of MIP-based electrochemical sensor.

environmental harm without sacrificing their analytical performance or selectivity. The comparison of the traditional MIP and green MIP synthesis prospects is presented in Table 1.

Protecting human health, preserving ecosystems, strengthening the economy, and promoting climate resilience and sustainable development depend on greenification. Methods to make MIP synthesis more sustainable are highlighted in the GAC guide framework. It requires combining sustainable ingredients, natural biomaterials, environmentally friendly solvents, energy-efficient polymerization techniques, and computational design tools, which is a fundamental strategy for creating green MIPs, as shown in Fig. 4.

### 3.1. Bio-based renewable ingredients

Many natural biomaterials (e.g., chitosan, alginate, cellulose, pectin, lignin, silk fibroin, hyaluronic acid) are derived from renewable resources and are often biodegradable, thereby reducing environmental impact. Their remarkable structural characteristics, widespread accessibility, nontoxicity, adaptability, and biocompatibility help align MIP fabrication with green principles [50]. Many natural polymers possess functional groups, such as hydroxyl and amino groups, that enable them to interact with template molecules through dipole-dipole, electrostatic, and hydrogen-bonding interactions. These groups contribute to stronger interactions and enhanced selectivity.

Cheng et al. present a sensitive molecularly imprinted electrochemical sensor for chloramphenicol (CAP) detection, which is a widely used antibiotic with the highest dosage because of its broad-spectrum antibacterial qualities and affordability, developed using a chitosan-derived carbon material that serves as a precursor for the conductive carbon framework integrated with hollow spherical hydroxylated poly (3,4-propylenedioxythiophene) (PProDOT-2$CH_2OH$) [51]. Chitosan synergistically improved the surface functionality, electrical conductivity, interfacial stability, and robustness. This dual system demonstrates outstanding selectivity and long-term stability with a wide linear detection range (0.0001–125 μM) and an ultralow detection limit of 6.6 pM. Another important environmental contaminant, the pesticide atrazine, causes long-term contamination of groundwater and agricultural soils due to its widespread use, high stability, and mobility. Hidalgo et al. developed a MIP sensor with a poly(3,4-ethylenedioxythiophene) (PEDOT)/chitosan/$TiO_2$ nanocomposite, achieving excellent sensitivity, a low detection limit (0.57 nM), and high recovery (98.72%) in spiked environmental water samples [52]. Natural chitosan-based biomaterials can simultaneously improve sensor sustainability and performance, enabling more environmentally friendly electrochemical monitoring of persistent pesticides in environmental systems. Reproducibility, repeatability, and stability were studied. The MIP sensor showed good repeatability (RSD = 1.49% over 10 consecutive measurements), good reproducibility (RSD = 1.52% across 9 sensors), and satisfactory stability, maintaining >90% of its initial response after 1000 electrochemical cycles and 91% after 30 days of room-temperature storage.

Alginate, extracted from brown algae (Phaeophyceae) and composed of beta-D-mannuronic acid and alpha-L-guluronic acid units, is a naturally occurring marine-derived biomaterial that offers biodegradability, a high density of carboxylate groups, and facile $Ca^{2+}$-mediated cross-linking, enabling the formation of a stable, selective polymeric network that enhances target rebinding efficiency and the development of imprint cavities [53]. Cetinkaya et al. developed a green MIP electrochemical sensor for vancomycin detection using an alginate-$TiO_2$ modified glassy carbon electrode, achieving an ultralow detection limit (2.808 pM) and excellent performance in serum and tap water samples. The greenness of the developed sensor stems from the use of calcium chloride-alginate as a cross-linker and biodegradable polymeric matrix. The method's greenness profile was assessed using the Analytical Greenness Metric Approach and Software (AGREE), yielding a score of 0.75 [54]. While this study used AGREE for a general evaluation of greenness, AGREEMIP offers a specialized framework for assessing the sustainability of molecularly imprinted polymer-based analytical techniques.

The chitosan-alginate combination offers notable advantages in sensor design by providing complementary amino and carboxyl functionalities, superior natural biodegradability, and a robust, electrostatically stabilized sensing surface. Budak and collaborators reported a green method using alginate, chitosan, and $TiO_2$ nanoparticles that involves selective imprinting, enhanced conductivity, and improved signal

**Table 1**
The comparison between traditional and green MIP aspects.

| ASPECT | TRADITIONAL MIP | GREEN MIP |
|---|---|---|
| Monomers | Synthetic monomers | Bio-based monomers, renewable biomaterials |
| Solvents | Toxic organic solvents | DESs, ILs, supercritical $CO_2$ |
| Polymerization process | High energy consumption | Energy efficient, short reaction times |
| Optimization | Trial and error | Computational tools |
| Reusability and Stability | Limited reusability and stability | Highly stable, recovery, recycling |
| Waste management | Discarded without recovery | Lower waste production |
| Environmental impact | Higher toxicity, waste generation, and carbon footprint. | Reduced toxicity, lower waste production, improved recyclability, and environmentally friendly synthesis. |
| Overall | Focus mainly on analytical performance and selectivity. | Achieve high analytical performance while integrating sustainability and green chemistry principles. |



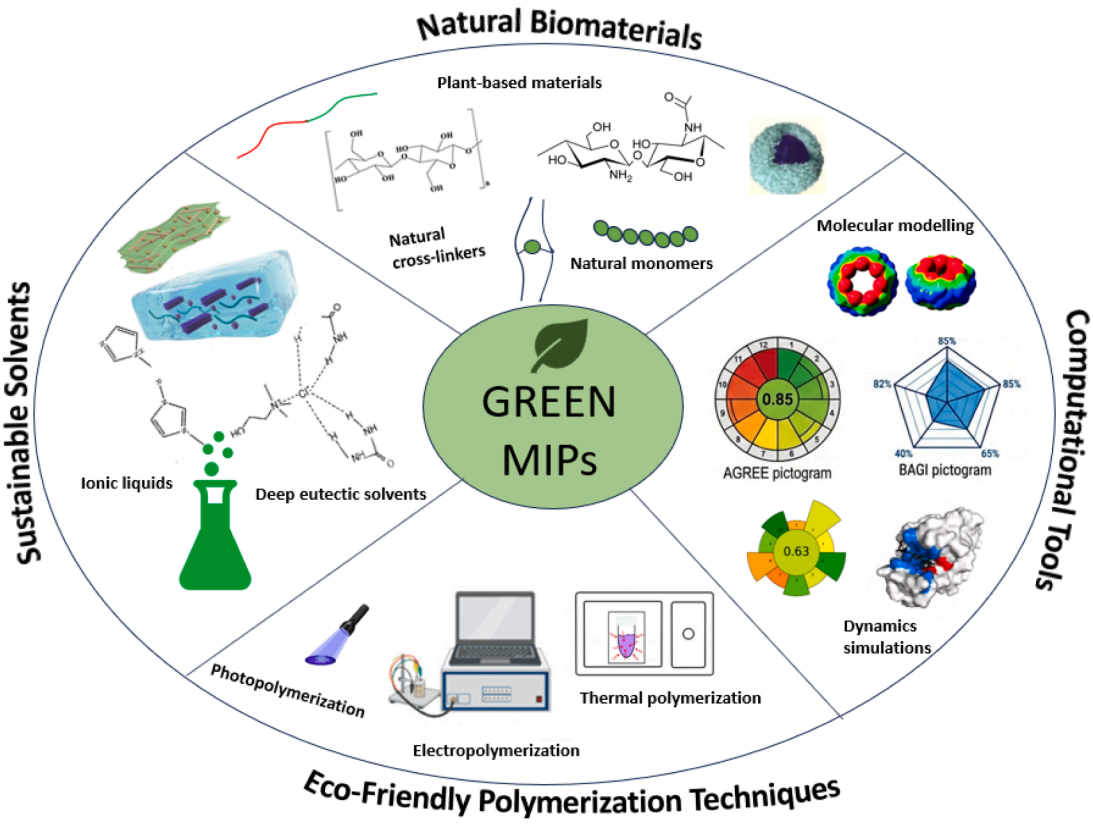



**Fig. 4.** The construction of the green MIPs.

stability. This study exhibits ultrahigh sensitivity and excellent stability, successfully detecting roxithromycin in food samples with an LOD of $1.31 \times 10^{-14}$ M. By assessing the approach using four distinct green analytical metrics, the study supports its sustainability claim. It demonstrated that good analytical performance can be achieved through an eco-friendly sensor production process [55]. The use of four complementary green analytical metrics to assess the environmental profile of the analytical process was a significant improvement over previous green MIP sensors. However, the platform's practical sustainability and scalability may be limited by its extremely narrow calibration range, reliance on a traditional glassy carbon electrode, use of $TiO_2$ nanoparticles, and optimization-intensive template-removal technique.

One of the most significant renewable, biodegradable biomaterials is cellulose-derived carboxymethyl cellulose (CMC), which offers improved surface functionality, a stable, hydrophilic platform, and efficient analyte binding [56]. The introduction of carboxymethyl groups (-$CH_2COOH$) onto the cellulose backbone imparts high water solubility, excellent film-forming properties, and a high density of anionic coordination sites, thereby maximizing analyte binding efficiency within imprinted polymer cavities. Liu et al. reported a MIP sensor for perfluorooctanoic acid based on a carboxymethyl cellulose (CMC)/MWCNT-modified glassy carbon electrode, delivering a wide linear range (0.1–2000 ng $mL^{-1}$), a low detection limit (0.1287 ng $mL^{-1}$), and successful application in food and river samples with excellent recoveries. This work demonstrates how cellulose-based natural materials can enhance the analytical performance and environmental sustainability of electrochemical MIP sensors, making them extremely attractive for real-time monitoring of persistent pollutants in complex matrices [57]. The MIP/CMC-MWCNTs@GCE demonstrated good reproducibility (RSD = 1.06% across five independently fabricated electrodes), good repeatability (RSD = 0.5% for five consecutive measurements), and satisfactory short-term stability, maintaining 90.54% of its initial response after about two weeks of storage at room temperature.

Even though the environmental profile of MIP production is significantly improved by renewable biopolymers such as chitosan, alginate, and cellulose, several obstacles still prevent their widespread use. Many natural biopolymers have relatively low electrical conductivity. Despite their advantages, they may exhibit variability in naturally sourced materials, such as harvesting season, cultivation conditions, and origin of plant species, as well as potential challenges related to large-scale production and plant species, which can influence the polymerization process, imprinting effect, and analytical reproducibility. Additionally, biodegradable polymers may gradually deteriorate over time, particularly in humid or microbiologically active environments, thereby reducing sensor shelf life and scalability [58,59]. These factors may impact polymerization kinetics, cavity imprinting efficiency, and overall analytical reproducibility.

### 3.2. *Sustainable solvents and cross-linkers*

Researchers are turning to less toxic or bio-derived cross-linkers, ionic liquids (ILs), and deep eutectic solvents (DESs) to improve sustainability [60,61]. ILs are organic salts with low melting points, and DESs are mixtures with eutectic points below those of the components, providing excellent tunability, customized physicochemical properties, and less hazardous application profiles [62]. Green solvents focus on water, DESs, ILs, supercritical fluids, bio-based solvents, and mixtures of natural molecules to reduce solvent use in MIP reactions and minimize toxicity [19].

Liu et al. developed a dual-mode molecularly imprinted sensor that combines electrochemiluminescence (ECL) with differential pulse voltammetry (DPV) to detect enrofloxacin (ENR) in eggs, achieving extremely low detection limits of 0.13 nM. They synthesized bismuth sulfide quantum dots ($Bi_2S_3$ QDs) as an ECL luminophore and carbazole-functionalized ILs as a functional monomer, both of which exhibit high

ionic conductivity and excellent electrochemical stability [63]. While independently prepared sensors demonstrated greater variability (RSD = 7.78% for DPV and 10.39% for ECL), indicating acceptable but relatively limited inter-sensor reproducibility, the $Bi_2S_3$ QDs/MIP/GCE sensor demonstrated good short-term reproducibility and storage stability over 72 h (RSD = 1.39% for DPV and 5.62% for ECL). Nevertheless, thorough batch-to-batch repeatability of MIP synthesis, manufacturing scalability, long-term storage stability, and regeneration/reuse capacity were not methodically verified.

ILs are especially significant because they serve as both functional monomers and cross-linking agents. Chen et al. used this synergetic energy to detect oxytetracycline in real water samples, achieving a wide linear range (0.02–20 μM) and a low detection limit (5 nM) [64]. The developed MIP-IL@Au-CNS composite prepared gold nanoparticle-modified carbon nanospheres (Au-CNS) as a support, and ILs [methyl 2-(3-vinylimidazolidin-1-yl) acetate bromide and 1,6-di (3-vinylimidazolium) hexane bromide] as a functional monomer and a cross-linking agent, respectively. When combined with Au-carbon nanospheres, N-doped graphene, and MWCNTs, strong ionic contacts with OTC are produced, mass transfer is accelerated, imprint cavity fidelity is improved, and conductivity is significantly increased. Overall, this research demonstrates that ionic liquids enhance signal amplification, enable fast regeneration, and enable selective recognition, making IL-based MIPs extremely attractive for pollution monitoring and removal. The MIP-IL@Au-CNS/IL@N-rGO-MWCNT sensor demonstrated good repeatability (RSD = 5.4% for five consecutive measurements), moderate reproducibility (RSD = 6.6% across five independently fabricated sensors), and satisfactory long-term stability, maintaining 96.8% and 92.7% of its initial response after two and four weeks of refrigerated storage, respectively.

Ionic gel formation is a green strategy that yields a conductive, stable polymer network, thereby improving template recognition and electrode durability in electrochemical MIP sensors. Wang et al. developed an innovative ionic gel, produced by sulfuric acid cross-linking of carboxymethyl chitosan, for ciprofloxacin detection, achieving a broad linear range and an ultralow detection limit of 43 pM [65]. They generated a stable, conductive polymeric network comprising carboxymethyl chitosan, $Ti_3C_2T_x$ titanium carbide, and sulfuric acid, which improves film integrity, electron transfer, and the selective rebinding of ciprofloxacin within the imprinted cavities. The sensor showed good repeatability (RSD = 1.0% for eight consecutive measurements), good reproducibility (RSD = 0.6% across six independently prepared sensors), and acceptable short-term storage stability (RSD = 1.0% after 14 days at room temperature). Its operational stability was moderate, with 85.24% current retention after 50 CV cycles.

Food security depends on efficient pollution monitoring, as prompt identification of pollutants in water, soil, and food products promotes ecosystem health, agricultural sustainability, and human health. Ochratoxin A, citrinin, and patulin are among the most important mycotoxins, as they are frequently found in cereals, fruits, and processed foods and pose serious toxicological concerns for human health [66]. For the first time, Zahra et al. prepared a magnetic nanoparticles/graphene oxide ($Fe_3O_4$/GO) nanocomposite for electrode modification, then developed a MIP sensor with IL (1-ethyl-3-methylimidazolium tetrafluoroborate ([EMIM][$BF_4$]) as the monomer and patulin as the template. They found the detection limit to be $3.33 \times 10^{-4}$ nM and tested the developed sensor in the apple juice [67]. The MIP/$Fe_3O_4$/GO/GCE sensor showed good long-term stability, maintaining 99.0% of its initial response after one month of storage at 4 °C; good operational stability, with <10% signal deviation after 80 CV cycles; and excellent reproducibility (RSD = 0.98% across six independently prepared sensors). Hu et al. used ionic liquid-decorated boron- and nitrogen-codoped hierarchical porous carbon (BN—HPC) as a surface modifier, thereby increasing adsorption capacity and enabling highly selective detection of citrinin. Because IL improved surface functionalization, enhanced probe immobilization, stabilized the sensing interface for improved repeatability and signal reliability, and controlled the anchoring of thionine onto the boron/nitrogen-doped hierarchical porous carbon. Using poly(thionine) as both the molecularly imprinted recognition layer and reference probe, together with $[Fe(CN)_6]^{3-/4-}$ as the signaling probe, the sensor achieved a wide linear range ($1 \times 10^{-3}$–10 ng $mL^{-1}$), an ultralow detection limit ($1 \times 10^{-4}$ ng $mL^{-1}$), and excellent recovery in real samples, demonstrating strong potential for citrinin detection [68]. Hu et al. used a gold nanoparticle/poly(ionic liquid)-FMN/CNT-$MoS_2$ composite as a signal-amplifying substrate to develop a ratiometric molecularly imprinted electrochemical sensor for ochratoxin A with high selectivity and a low detection limit of 14 nM [69]. Because it enhances conductivity, stabilizes the nanocomposite architecture, and provides a highly functional interface for effective MIP loading and electron transfer, the poly(ionic liquid) is particularly significant. Overall, this work demonstrates how ionic liquid-based polymers can improve identification efficiency, interfacial stability, and signal amplification, making them extremely useful for sensitive mycotoxin monitoring in food systems. Although adding an ionic liquid and nanoparticles enhances sensor performance, the analytical method's environmental sustainability is not automatically established.

Bai et al. developed a portable, eco-friendly molecularly imprinted SPCE sensor for sulfadimidine detection using v-COF@SWCNTs-COOH carriers [70]. An important green innovation is the 55 °C thermal steam elution method, which replaces conventional organic solvent washing with a rapid, solvent-free, and environmentally safer regeneration step, achieving complete template removal in only 4 min. As a whole, the study shows that thermal steam elution, which combines portability, affordability, reusability, and reduced chemical waste, provides a practical and sustainable method for monitoring antibiotics at the home and farm levels. The MIP/V-COF@SWCNTs-COOH/SPCE showed good inter-sensor reproducibility (RSD = 3.7%), good repeatability and reusability (RSD = 0.4%), and satisfactory long-term stability, retaining 94.5% and 82.4% of its initial response after 15 and 30 days of storage at 4 °C, respectively.

### 3.3. Eco-friendly techniques and computational evaluations

Eco-friendly green polymerization techniques reduce energy demand, reaction time, and the need for high temperatures or high pressures. Energy-efficient methods, such as electrochemical polymerization, microwave-assisted polymerization, and photopolymerization, offer several advantages, including easy control of film thickness, homogeneous film surface, specific interactions, and low toxicity [71]. In addition to these advantages, they lead to higher yields, shorter polymerization times, and faster reaction rates. Low solvent usage and non-toxic initiator usage, rapid and uniform heating, reduced reaction time, and enhanced diffusion, penetration, and movement of species in the media, as well as the solubility of the template and monomers [72]. Computational design strategies, molecular dynamics simulations, and theoretical calculations are among the most essential technological approaches for enhancing the impact of greenification, as they reduce the need for experiments and ensure safe use by researchers. Before experimental synthesis, screening template-monomer interactions, modeling the dynamic behavior of complexes, and calculating binding energies and interactions can reduce laboratory work, save time, and conserve resources [73–75]. Therefore, higher selectivity, specificity, and imprinting efficiency can be achieved, and rationally designed highly selective MIPs can be enabled by reducing unsuccessful trials, thereby supporting greenification [76]. Determining binding strengths, electronic structures, and molecular mechanisms identifies the most stable and energetically favorable interactions [77]. It predicts the stability of the polymer complex, aiding in the prediction of electrochemical characteristics. These computational techniques, which connect research and theory, are now recognized as crucial tools for designing MIP sensors that are efficient, environmentally friendly, and logical [78,79]. AGREE (Analytical GREEnness), AGREEprep,

AGREEMIP, and BAGI (Blue Applicability Grade Index) are complementary assessment tools for evaluating the quality and sustainability of analytical techniques [80]. AGREE employs a circular pictogram with 12 segments, each representing one of the 12 GAC principles, to highlight the environmental impacts of these principles. BAGI assesses a method's "blueness" or practical utility. It evaluates five important factors related to the method's applicability, including sample throughput, required equipment, and ease of use, using a radar chart (pentagram) [81].

Although AGREE assesses the entire analytical process, it may not identify the environmental impact of specific steps such as electrochemical detection, polymer synthesis, or sensor construction. AGREEprep focuses on pretreatment processes, including waste generation, energy use, solvent consumption, and operational complexity. AGREEMIP was created especially for MIP technologies and incorporates factors directly linked to MIP synthesis, such as template selection, polymerization method, template removal, solvent consumption, and material sustainability. BAGI evaluates the practical applicability of analytical techniques in terms of portability, cost, automation, and operational simplicity. GAPI offers a qualitative, step-by-step picture of the environmental impact of the complete analytical workflow. EcoScale focuses on renewable materials, life-cycle impacts, and sensor recyclability. AGREEMIP shows the highest relevance since it is specifically designed for MIPs, but it is still relatively new and has limited validation. Some research articles only provide the numerical score of the AGREEMIP, not a full explanation of what each number means. The scores should be compared and areas for improvement identified. They may not report exact solvent volumes, energy consumption, and waste amounts, resulting in an uncertain calculated score and incomplete reporting. In addition, greener MIP syntheses do not guarantee an overall greenness of the analytical method. AGREEMIP based on the MIP synthesis, but only one single assessment tool will not cover every parameter of the MIP synthesis, which may limit the evaluation of the greenness of the method [20,82]. There is a possible risk of "greenwashing" if the method could use very small amounts of reagents, generate little waste, require low energy, allow in situ measurement, miniaturization, and direct sampling techniques, which lead to labeling a method as green MIP without considering the materials' intrinsic toxicity, persistence, and environmental impact. Therefore, greenness measures should be viewed as supplementary screening and comparison tools and, when necessary, complemented by material-specific hazard assessments and assessments of analytical performance and application.

The other tools generally measure practical applicability and evaluate sample preparation, but they don't isolate sensor fabrication [82,83]. Recent studies on green MIP-based electrochemical sensors, evaluated using various greenness assessment tools, are summarized in Table 2.

Samancı et al. developed a low-cost, sensitive platform for ultralow femtomolar detection of abacavir in serum and tablet samples [84]. Photopolymerization and amine-functionalized MWCNTs were combined to build a green MIP sensor. The sensor's economical use of materials, straightforward manufacturing process, minimal sample preparation, and dependable performance in actual matrices, which minimize analytical waste while preserving superior selectivity and repeatability, highlight its environmental friendliness. Crucially, several green assessment techniques (AGREE, AGREEprep, BAGI, and AGREEMIP) were used to rigorously assess the platform's sustainability, confirming that the developed MIP sensor met green performance standards.

Mahmoud et al. developed a potentiometric sensor for trazodone hydrochloride using silica nanoparticles as the core and an MIP shell embedded in a PVC membrane [85]. Within its limited therapeutic window, the sensor's wide linear range ($1.0 \times 10^{-6}$ –$1.0 \times 10^{-2}$ M), low detection limit ($6.0 \times 10^{-7}$ M), and reliable recovery in tablet (103.08%) make it suitable for maximizing trazodone doses and enhancing patient safety. Importantly, the method's green and white analytical performance was validated through Analytical EcoScale (88), AGREE (0.78), and RGB assessments (95.7), confirming its strong alignment with green analytical chemistry principles. They also align with the worldwide movement toward environmentally friendly, sustainable methods for drug analysis.

**Table 2**
Recent studies of green MIP electrochemical sensors using greenness assessment tools.

| Analyte | Sensor | Green Strategy | Greenness Assessment Tools | Score | Ref |
|---|---|---|---|---|---|
| Abacavir | MWCNT-$NH_2$@MIP/GCE | Eco-friendly photopolymerization, less hazardous material, reduced reagent consumption | AGREE<br>AGREEprep<br>BAGI<br>AGREEMIP | 0.66<br>0.63<br>67.5<br>0.75 | [84] |
| Trazodone hydrochloride | Core-shell MIP potentiometric sensor | Bio-based reagents<br>Direct Analysis<br>Waste: 0 *g* | Analytical EcoScale<br>Analytical GREEnness<br>Red-Green-Blue | 88<br>0.78<br>95.7 | [85] |
| Abiraterone acetate | PP-MIP(AA)/GCE | Less energy<br>Fewer hazardous chemicals<br>Reusability | BAGI,<br>AGREEprep, AGREE,<br>AGREEMIP | 77.5<br>0.66<br>0.68<br>0.87 | [88] |
| *N*-Nitrosodiethylamine | NDEA/ZnONPs@APTES/CHT/3-TBA@MIP/GCE | Eco-friendly electrochemical approach<br>Less sample throughput<br>Less hazardous material | AGREE | 0.99 | [86] |
| Ivermectin | MAA-IVM@MIP/GCE | Eco-friendly materials, Energy-efficient manufacturing, Minimal waste | BAGI, AGREE AGREEMIP | 75<br>0.64<br>0.86 | [89] |
| Apalutamide | APA-imprinted poly(*o*-phenylenediamine)/SPGE | Low energy, Minimal reagent consumption<br>Green synthesis | AGREEMIP | 0.75 | [90] |
| Ethylene glycol | EG@oPD/MIP/SPGE | Minimal volume of solvent<br>Eco-friendly fabrication | AGREEMIP | 0.76 | [91] |
| Zanamivir | 4-ABA/ZAN@MIP-GCE | Avoidance of toxic reagents, Energy-efficient synthesis<br>Waste reduction | AGREE AGREEMIP | 0.56<br>0.84 | [87] |

MWCNT-$NH_2$@MIP/GCE: Amine-functionalized multi-walled carbon nanotubes@Molecularly Imprınted Polymer/Glassy Carbon Electrode, PP-MIP(AA)/GCE: Photopolymerization-molecularly imprinted polymer (Abiraterone acetate)/Glassy carbon electrode, NDEA/ZnONPs@APTES/CHT/3-TBA@MIP/GCE: *N*—Nitrosodiethylamine/ZnO nanoparticles@3-aminopropyl triethoxysilane/chitosan/3-thienyl boronic acid@molecularly imprinted polymer/glassy carbon electrode, MAA-IVM@MIP/GCE: methacrylic acid-Ivermectin@molecularly imprinted polymer/glassy carbon electrode, EG@oPD/MIP/SPGE: Ethylene glycol@*o*-phenylenediamine/molecularly imprinted polymer/screen printed glassy electrode, 4-ABA/ZAN@MIP-GCE: 4-aminobenzoic acid/Zanamivir@molecularly imprinted polymer/glassy carbon electrode.

Jadon et al. reported the first green molecularly imprinted electrochemical sensor for N-nitrosodiethylamine at the femtomolar level in standard and serum samples [86]. Green-synthesized APTES-functionalized ZnO nanoparticles are combined with a chitosan/3-thienyl boronic acid imprinted film. Because the platform incorporates bio-based chitosan, environmentally friendly ZnO nanoparticle synthesis, electropolymerization, and miniaturized electrochemical detection, reducing hazardous reagents, solvent consumption, and analytical waste while maintaining exceptional selectivity, the green aspect is particularly important. Crucially, a 99% Green Analytical Chemistry score quantitatively validated its sustainability, underscoring the sensor as a highly environmentally friendly alternative for rapid on-site screening for carcinogens. Immediate scalability, ease of removal, and field deployment are limited with a traditional glassy carbon electrode. Further research is also needed for batch-to-batch reproducibility, large-scale production, extended storage stability, regeneration/reuse, and end-of-life issues.

The first green molecularly imprinted electrochemical sensor for zanamivir was reported by Cetinkaya et al. [87]. It is made by photopolymerizing 4-aminobenzoic acid on a glassy carbon electrode, enabling extremely sensitive detection in blood and urine with sub-picomolar limits of detection. The straightforward photopolymerization process, low reagent use, minimal exposure to hazardous chemicals, and energy-efficient electrochemical analysis highlight its green credentials, making it a more affordable and ecologically friendly option than traditional techniques. Crucially, AGREEMIP (0.84) and AGREE (0.56) evaluations confirmed the method's sustainability and established the platform as a highly environmentally friendly analytical sensor with significant real-world potential for biofluid monitoring. Also, molecular docking studies identified a favorable 1:1 template-monomer stoichiometry, consistent with the *in silico* prediction.

## 4. Plant-Based materials in MIP fabrication

Although the direct use of functional monomers remains comparatively uncommon, plant-derived natural compounds, such as polyphenols and flavonoids, have been investigated as templates or to enhance selectivity in MIP systems. MIPs can be used as solid-phase adsorbents for flavonoids, polyphenols, terpenoids, and alkaloids, which are abundant in plants and are widely distributed in naturally occurring bioactive substances. Enriching, isolating, purifying, and detecting these natural compounds are essential [92,93].

To detect these bioactive compounds, MIPs have been used as sensors. For example, Song developed MIPs targeting monoterpene phenols in plant essential oils, including a new double-template molecularly imprinted electrochemical sensor (DT-MIP sensor) that simultaneously and selectively detects carvacrol and thymol [94]. Thymol and carvacrol are two monoterpene phenols that have garnered significant interest due to their desirable biological activities for human health, primarily antibacterial, antioxidant, and anti-inflammatory effects. These two substances are critical components of the essential oils of oregano (*Origanum vulgare* L.) and thyme (*Thymus vulgaris* L.), which have long been used for their medicinal, pharmaceutical, and culinary properties. For quality assurance, pharmacological research, and industrial uses in the dietary supplement, personal care product, and pharmaceutical industries, the capacity to identify and measure thymol and carvacrol in plant essential oils and/or extracts is highly desirable. Therefore, their simultaneous detection is vital to both industry and academia. This electrochemical MIP sensor achieves detection limits of 0.11 μM for carvacrol and 0.24 μM for thymol with minimal interference, high accuracy, and simplicity. The dual-template recognition technique, which addresses the challenge of differentiating structurally similar phenolic monoterpenes on a single electrochemical platform, is the main innovation. However, since the sustainability of the TBOT/APTES-based imprinting process was not quantitatively evaluated using recognized green analytical indicators, the method should not be considered a fully green MIP methodology.

In addition to detecting bioactive compounds, natural-based materials have been used to fabricate MIPs. Chitosan from microalgae, fungi, and animal sources is the most prevalent naturally occurring biopolymer and a highly adaptable polysaccharide capable of undergoing a wide range of chemical and biological transformations [95]. It is widely used in the production of electrochemical sensors due to its exceptional properties, including strong adhesion and excellent film-forming ability. Motia and coworkers [96] developed an electrochemical molecularly imprinted sensor based on chitosan capped with gold nanoparticles, using a novel synthesis method to determine butylated hydroxyanisole (BHA) in food products (Fig. 5**A**). This research adheres to green sample-preparation procedures that use minimal solvent for analyte extraction, thereby minimizing chemical waste and associated costs. The limit of detection of this sensor is 0.001 μg $mL^{-1}$, with a linear range of 0.01–20 μg $mL^{-1}$ and an 8% relative standard deviation in food samples. A more environmentally friendly option to traditional synthetic polymer/glassy carbon electrode combinations is the use of chitosan, a naturally occurring polymer, in conjunction with the smaller SPCE platform. However, because the environmental impact of AuNP integration, MIP template removal, solvent consumption, and sensor disposal was not quantitatively assessed, the method cannot be called fully green.

Numerous studies on biological activity and sensor applications have used nanoflower structures derived from plants, their extracts, and active ingredients, thereby increasing surface area and enhancing sensitivity. Cetinkaya et al. [97] demonstrated the potential of environmentally friendly sensor design by integrating plant-assisted green synthesis with MIP-based electrochemical sensing platforms. In their study, zinc nanoflower-graphene oxide hybrids (ZnNFs@GO) were synthesized from the root methanol extract of *Alkanna cappadocica* Boiss. & Balansa, providing a green, sustainable alternative to conventional chemical synthesis methods by reducing the use of toxic reagents and energy consumption. SEM images of the synthesized ZnNFs, graphene oxide (GO), and ZnNFs@GO composites are provided to illustrate their morphology (Fig. 5**B**). The ZnNFs@GO composite was combined with 4-aminobenzoic acid (4-ABA) as the functional monomer to fabricate a MIP sensor for the selective detection of the Janus kinase-1 (JAK-1) inhibitor abrocitinib, achieving a detection limit of $2.18 \times 10^{-14}$ M and a linear range of $1.0 \times 10^{-13}$–$1.0 \times 10^{-12}$ M. Similarly, another study developed a MIP-based electrochemical sensor for bortezomib using saffron-derived copper nanoflowers (CuNFs) synthesized from *Crocus sativus* L. The use of plant extracts in nanomaterial synthesis not only minimizes environmental impact but also introduces natural reducing and stabilizing agents, enhancing the sustainability of the process. Scanning electron microscopy (SEM) images of CuNFs clearly show nanoflower morphologies (Fig. 5**C**). The CuNFs/2-acrylamido-2-methyl-1-propanesulfonic acid (AMPS)/MIP-modified electrode showed a femtomolar-level detection limit (29 fM) within a linear range of $2.5 \times 10^{-13}$–$2.5 \times 10^{-12}$ M. Moreover, both studies demonstrate that plant-assisted green synthesis improves sensor sensitivity and selectivity through the self-assembly of high-surface-area nanostructures (e.g., 3D nanoflowers), while offering significant environmental benefits, including reduced chemical waste, lower toxicity, cost-effective scaling from renewable biomass, and more sustainable nanomaterial production for advanced electrochemical sensing applications [98]. The research did not report a comprehensive green analytical assessment using tools such as AGREE, AGREEprep, GAPI, BAGI, Eco-Scale, or AGREEMIP. Although the study is a major step forward for plant-assisted, nanomaterial-supported MIP sensing, the sustainability of the entire analytical process should be considered, rather than only the environmentally friendly synthesis of the Cu nanoflowers.

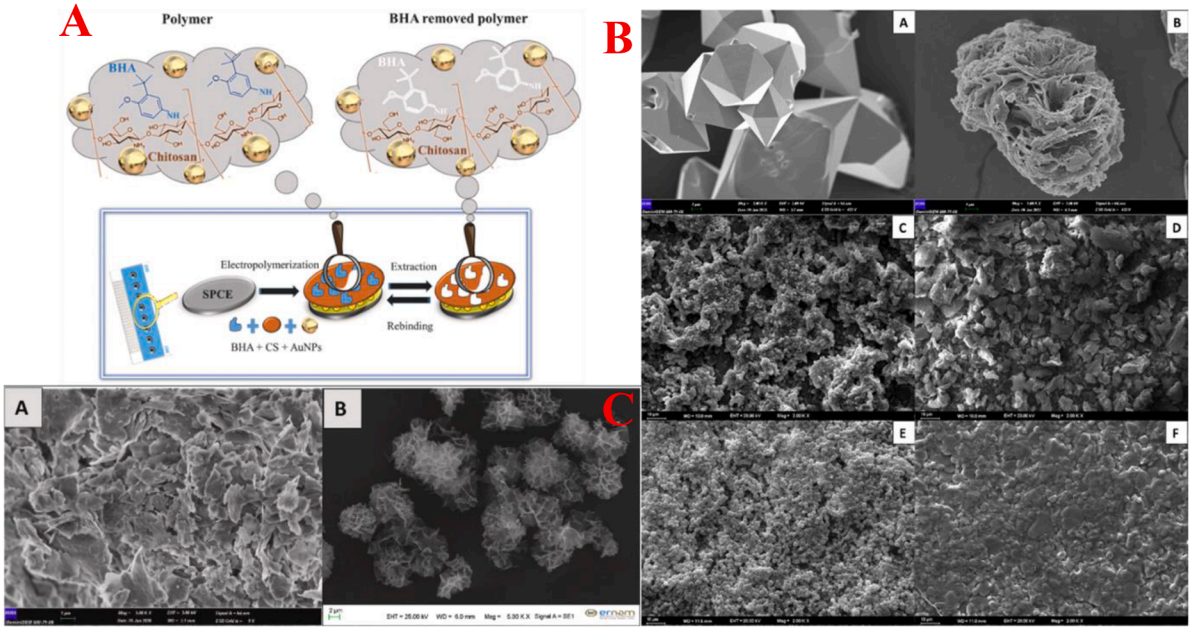



**Fig. 5. A)** Schematic representation of the proposed molecular architecture of the BHA-imprinted sensor. Reprinted from Ref [96] with permission from Elsevier. **B)** SEM images of ZPO (A); ZnNFs; (B), (C); ZnNfs@GO, (D); GO, (E); ABR/4-ABA/ZnNFs@GO/MIP/GCE, (F); 4-ABA/ZnNFs@GO/NIP/GCE. Reproduced from Springer Nature (Open access).(Access date: 10 May 2025 [97]. **C)** SEM micrographs of CPO crystals (A) and CuNFs (B). Reprinted from Ref [98] with permission from Elsevier.

## 5. Electrochemical MIP sensor development and analytical application of plant-based MIPs

Electrochemical MIP sensors based on plant-derived or plant-assisted materials have recently attracted growing attention for their ability to combine high molecular selectivity with environmentally friendly synthesis routes, offering sustainable and efficient platforms for sensitive analytical applications. Table 3 summarizes the experimental parameters of selected plant-assisted MIP-based analytes.

The study by Wang et al. [99] introduces an MIP-based electrochemical sensor for enrofloxacin, employing nitrogen-doped carbon dots derived from the invasive aquatic weed *Pontederia crassipes* Mart. (syn. *Eichhornia crassipes*) known as water hyacinth. This strategy enables high sensitivity and selective recognition of the target antibiotic, demonstrating strong recovery for trace-level detection of enrofloxacin in environmental water and aquaculture samples. Nevertheless, reliance on complex nanocomposites and multi-component fabrication processes may limit large-scale applicability and raise concerns about nanoparticle disposal. In a complementary green-materials-oriented approach, the eco-friendly synthesis of nitrogen- and sulfur co-doped reduced graphene oxide (N,S-rGO) using *Centaurea cheiranthifolia* Willd. (all-flower-leaved knapweed or wallflower cornflower) extract as a biogenic reducing agent highlights an alternative pathway toward sustainable electrochemical sensing (Fig. 6**A**). Comprehensive physicochemical and morphological characterization (UV–Vis, XRD, SEM, XPS, and Raman) confirmed the successful formation of the N,S-rGO nanomaterial, which was subsequently integrated into a carbon paste electrode for the electrochemical detection of metronidazole. DPV revealed a wide linear range (5–500 μM) and a low detection limit (0.076 μM), attributed to enhanced π-electron delocalization, increased electroactive site density, and improved electron-transfer kinetics induced by dual heteroatom doping. The sensor demonstrated excellent selectivity and

**Table 3**
Summary of MIP-based studies for the detection of selected analytes.

| Analyte | Sensor | Linear range | LOD | Real samples | Recovery % | Ref |
|---|---|---|---|---|---|---|
| Enrofloxacin | MIP/CS/N—CDs/MWCNTs | 0.05–100.0 μM | 0.0343 μM | Fish flesh | 95.79–110.59 | [99] |
| | | | | Lake water | 97.22–106.75 | |
| HCT | rGO/MIP/SPCE | 5.0 −100.0 μM | 1.8 μM | Water | 84.00–95.80 | [100] |
| Rutin | Zn-MOF/PBA/ MIP/GCE | 1.0 −200.0 nM | 0.43 nM | Buckwheat tea | 87.92–116.93 | [101] |
| | | | | Wheat | 92.90–119.30 | |
| Metronidazole | N,S-rGO@CPE | 5.0–500.0 μM | 0.076 μM | Human urine | 95.6–102.4 | [102] |
| | | | | Tap water | 96.3–101.2 | |
| Quercetin | MMIP/MGCE | 0.01–25.00 μM | 0.50 nM | *Sophora japonica* L. buds | 94.00–107.40 | [103] |
| | ($Fe_3O_4$@$VSiO_2$@GO) | 25–1000.00 μM | | Onion | 98.65–102.80 | |
| | | | | Apple | 98.78–105.80 | |
| Indole-3-acetic acid | Blade-style MIP | 5.0 −100.00 μM | 0.1 μM | Tomato leaves | 96.80–109.10 | [104] |
| D-Glucose | NanoMIP fiber wire-based sensor | $1.0 \times 10^{-1}$–$1.0 \times 10^{-6}$ M | $7.94 \times 10^{-8}$ M | Tomato | NA | [105] |
| BOS | MIP@Co-Vit $B_3$−MOF/CPE | $0.048–2.1 \times 10^{6}$ μg $L^{-1}$ | 0.015 μg $L^{-1}$ | Tomato | 99.84–100.00 | [106] |
| | | | | Grap | 99.85–100.00 | |
| | | | | Berries | 98.59–99.83 | |

Co-Vit $B_3$−MOF: Cobalt vitamin $B_3$ metal organic framework, CPE: Carbon paste electrodes, MMIP/MGCE: Magnetic molecularly imprinted polymers/magnetic glass carbon electrode, $VSiO_2$: Vinyl-functionalized silica, GO: Graphene oxide, CS: Chitosan, MWCNTs: Multi-walled carbon nanotubes, N—CDs: Nitrogen-doped carbon dots, rGO: Reduced graphene oxide, SPCE: Screen printed carbon electrode, PBA: Phenylboronic acid, MOF: Metal-organic framework, N, S-rGO: Nitrogen- and sulfur-co-doped reduced graphene oxide, CCPE: *Centaurea cheiranthifolia* Willd. plant extract.

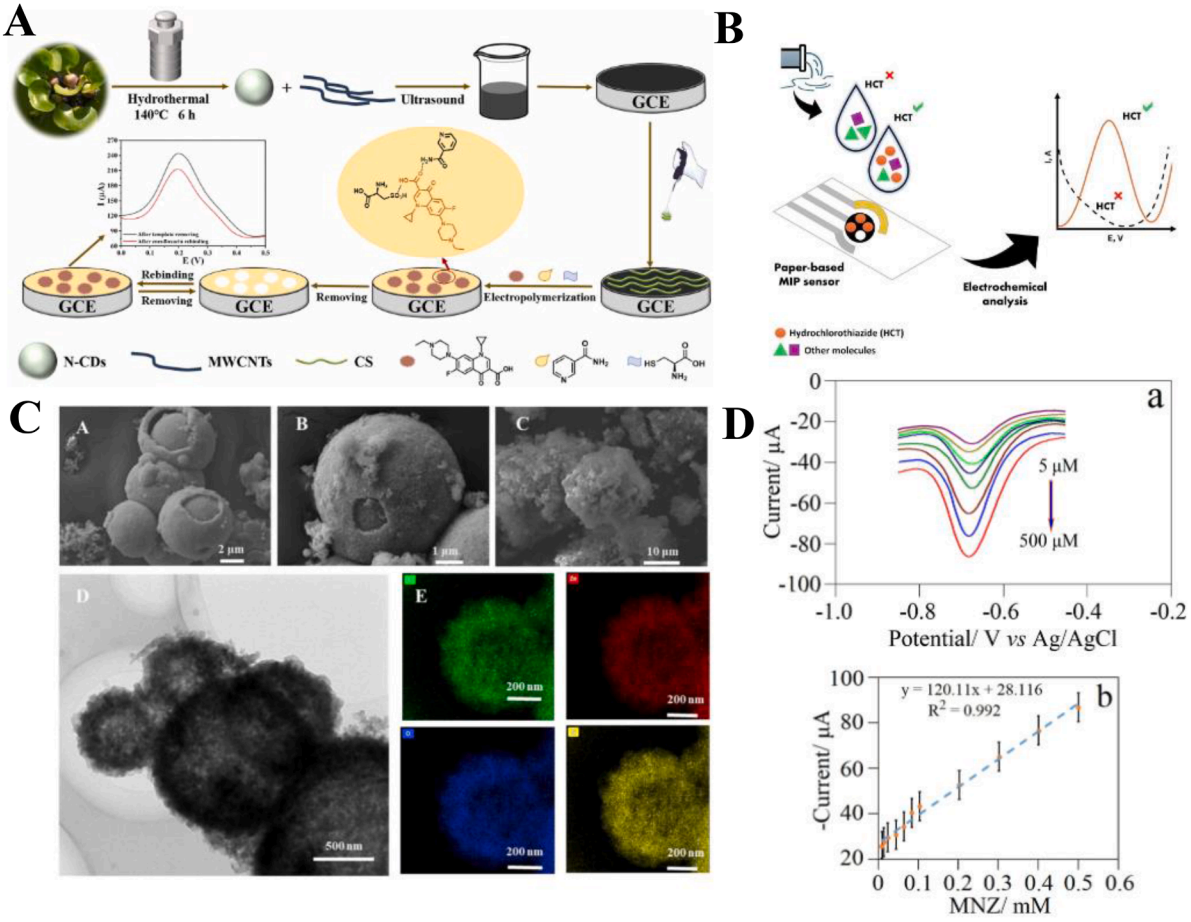



**Fig. 6. A)** Schematic representation of the fabrication process of the MIP-based electrode sensor. Reprinted from Ref [99] with permission from Elsevier. **B)** Schematic illustration of the proposed method. Reprinted from Ref [100] with permission from Elsevier. **C)** SEM images of (A, B) Zn-MOF and (C) Zn-MOF/PBA; (D) TEM image and (E) elemental mapping of Zn-MOF. Reprinted from Ref [101] with permission from Elsevier. **D)** DPV analysis of N,S-rGO@CPE in 0.1 M PBS (pH 7.0) containing metronidazole (5–500 μM) (a), and the calibration plot of peak current as a function of metronidazole concentration (b). Reprinted from Ref [102] with permission from Elsevier.

reproducibility, and satisfactory recovery in environmental (tap water) samples, underscoring its robustness for real-sample analysis. Moreover, these studies illustrate how biomass-derived and plant-mediated nanomaterial synthesis strategies can deliver high analytical performance while advancing sustainability and green chemistry objectives in environmental and pharmaceutical electrochemical sensing. The entire sensor remains a multicomponent nanocomposite comprising MWCNTs, biomass-derived N—CDs, chitosan, and a molecularly imprinted layer; nevertheless, the use of invasive biomass and comparatively benign functional monomers constitutes a crucial sustainability-oriented approach. However, there was no quantitative evaluation of the entire analytical process using recognized greenness metrics.

In another study, Rebelo et al. [100] developed a paper-based MIP electrochemical sensor for hydrochlorothiazide (HCT). This antihypertensive pharmaceutical is frequently detected in both influent and effluent from wastewater treatment plants (WWTPs) and in receiving aquatic environments. Given that the revised Urban Wastewater Treatment Directive classifies HCT as a priority substance and mandates a minimum removal efficiency of 80%, the development of rapid, decentralized, and cost-effective monitoring tools has become increasingly important. To address this need, the authors employed a simple, low-cost paper substrate integrated with inkjet-printed electrodes, using reduced graphene oxide (rGO) to enhance the electrochemical performance of the working electrode. The molecularly imprinted layer was formed *via* electropolymerization of 4-aminobenzoic acid in the presence of HCT, providing selective recognition sites for the target analyte (Fig. 6**B**). DPV revealed a linear response range of 5.0–100 μmol $L^{-1}$ and a detection limit of 1.8 μmol $L^{-1}$ with the MIP layer ensuring high selectivity and minimal interference from coexisting pharmaceuticals. When applied to spiked wastewater treatment plant effluent and tap water samples, the sensor achieved satisfactory recoveries ranging from 84.0% to 95.8%, confirming its analytical reliability for environmental monitoring. Overall, this platform aligns strongly with sustainability and green chemistry principles through the use of renewable paper materials, minimal reagent consumption, and scalable fabrication. However, its relatively higher detection limit and potential mechanical fragility may limit performance in more complex or harsh matrices. Nonetheless, the study demonstrates a practical, environmentally responsible approach to on-site HCT analysis that supports regulatory compliance and enhances environmental protection strategies.

The PBA-grafted Zn-MOF/MIP sensor developed by Wang et al. [101] for sensitive detection of rutin employs a sophisticated dual-recognition strategy that combines metal-organic frameworks (MOFs), phenylboronic acid (PBA), and MIPs to enhance both surface area and binding specificity. The successful construction of the hierarchical sensing architecture was confirmed through comprehensive morphological and structural characterization, which revealed a well-defined porous Zn-MOF structure and a uniform MIP coating on the MOF surface. At the same time, elemental mapping showed homogeneous distributions of Zn, C, O, and B, indicating effective PBA functionalization (Fig. 6**C**). In this design, the synthesized Zn-MOF is functionalized with phenylboronic acid, thereby expanding the

recognition interface and strengthening interactions with adjacent diol-containing compounds, such as rutin. At the same time, the MIP layer provides highly specific molecular recognition through shape- and functionality-complementary imprinted cavities. This synergistic dual-recognition approach, increasingly adopted in sensor development, improves selectivity and mitigates interference in complex matrices. Under optimized conditions, the sensor exhibits an ultrawide, sensitive detection range from 1 nM to 200 nM, with an exceptionally low detection limit of 0.43 nM, highlighting its strong potential for practical analytical applications. However, the approach has several drawbacks from a green analytical chemistry perspective. Hydrothermal synthesis and traditional organic solvents such as DMF are used to create Zn-MOF, and subsequent PBA functionalization, electrode modification, MIP formation, and template removal constitute a quite complicated multi-step fabrication process.

Nevertheless, despite its outstanding analytical performance, incorporating MOF precursors, boronic acid functionalization, and a multi-step synthesis may entail higher energy consumption and greater material complexity, raising concerns about scalability and long-term sustainability compared to more straightforward or more environmentally benign sensing platforms. Finally, the N, S-doped reduced graphene oxide sensor for metronidazole detection reported by Turunc et al. [102] employs an environmentally benign synthesis strategy in which *C. cheiranthifolia* extract serves as a biogenic reducing agent to obtain heteroatom-co-doped graphene. The successful formation and structural features of the N, S-rGO nanomaterial were comprehensively verified by UV–Vis, XRD, SEM, XPS, and Raman analyses, confirming effective heteroatom incorporation and the restoration of graphitic domains. The resulting nanomaterial was integrated into a carbon paste electrode (N, S-rGO@CPE) and used for the electrochemical sensing of metronidazole, where DPV showed a wide linear response from 5 to 500 μM and a low detection limit of 0.076 μM (Fig. 6**D**). Simultaneous nitrogen and sulfur doping promoted π-electron delocalization, increased the population of electroactive sites, and accelerated electron-transfer kinetics, thereby significantly enhancing electrocatalytic activity. In addition to its green synthesis and high conductivity, the sensor exhibited excellent selectivity, reproducibility, and analytical reliability, achieving satisfactory recoveries in spiked tap water samples. Additionally, this study highlights the potential of eco-friendly N,S-rGO-based platforms as sustainable, sensitive, and practical alternatives for pharmaceutical analysis and on-site electrochemical sensing applications.

Recent advances in molecularly imprinted polymer-based electrochemical sensors (MIP/ECS) underscore their transformative potential for environmental monitoring and plant analysis. Liu et al. [103] developed a $Fe_3O_4$/graphene oxide-integrated MIP sensor for quercetin (a plant-derived flavonoid), achieving an ultralow LOD of 0.50 nM and dual linear ranges of 0.01–25 μM ($R^2 = 0.9973$) and 25–1000 μM ($R^2 = 0.9997$), successfully detecting this antioxidant in plant-derived foods and environmental matrices, highlighting its utility for monitoring bioactive compounds in ecosystems (Fig. 7**A**). Lin et al. [104] designed blade-style MIP sensors for in vivo monitoring of indole-3-acetic acid (IAA) in tomato plants (Fig. 7**B**), with an LOD of 0.1 μM, enabling non-destructive, real-time assessment of plant hormone dynamics under varying environmental conditions. Vurro et al. [105] employed nanoMIP-functionalized organic electrochemical transistors to selectively track D-glucose in tomato plants in field conditions, providing insights into plant metabolic responses to environmental stressors such as drought (Fig. 7**C**). Tarek et al. [106] developed a MOF-modified MIP

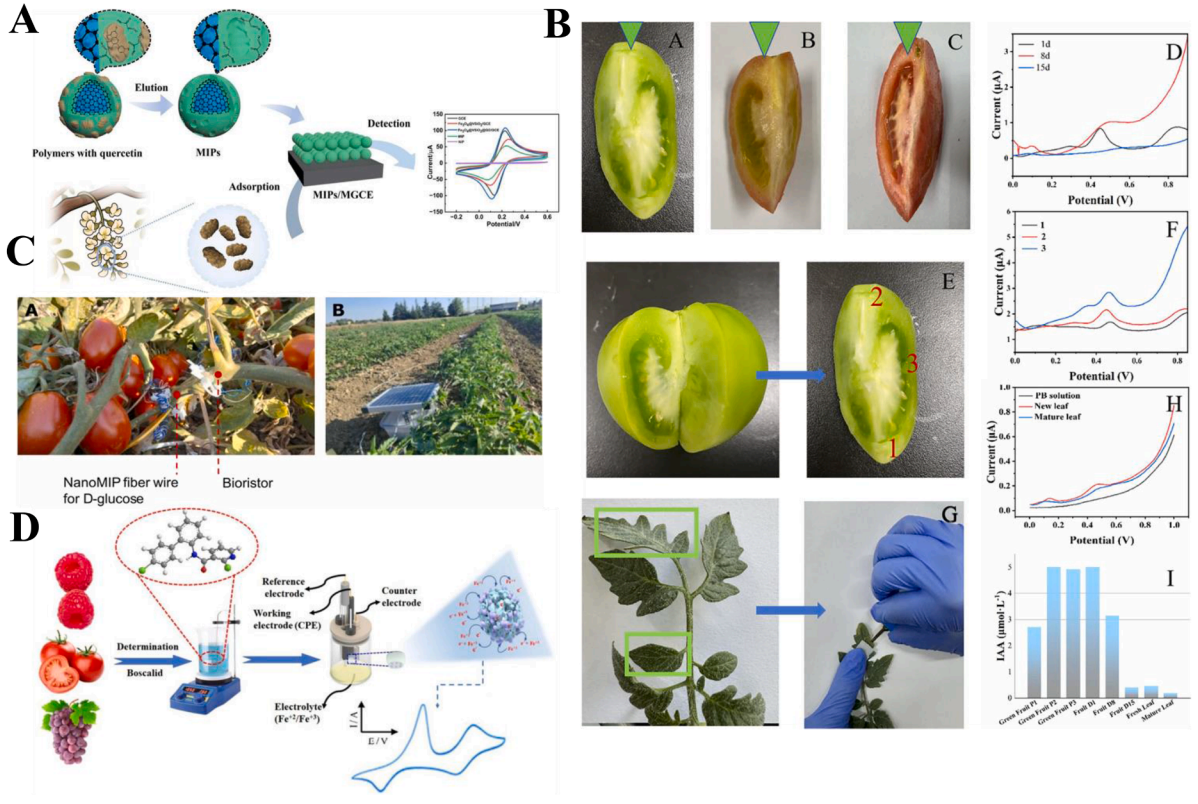



**Fig. 7. A)** Schematic diagram of the preparation of the developed sensor. Reprinted from Ref [103] with permission from Elsevier. **B)** Images of tomato fruits at different storage days (A, B, C) and their corresponding electrochemical responses measured by MIP sensors (D). Images of a tomato fruit at different positions (E) and the corresponding electrochemical responses (F). Images of tender and mature tomato leaves (G) and their electrochemical responses obtained using hydrogel sampling followed by MIP sensor incubation (H). (I) Calculated IAA content in tomato fruits and leaves. Reprinted from Ref [104] with permission from Elsevier. **C)** Field implementation of sensors in tomato plants. (A) NanoMIP fiber-wire OECT for D-glucose detection alongside a conventional bioristor. (B) Field control unit. Reproduced from Elsevier (Open access). Access date: 20 March 2025 [105] **D)** Schematic representation of MIP@Co-Vit B3-MOF fabrication and the gate-controlled electrochemical measurement of BOS. Reprinted from Ref [106] with permission from Elsevier.

sensor for detection of boscalid, a fungicide belonging to the carboxamide chemical class widely used to control *Botrytis cinerea* (gray mold) and powdery mildew in crops such as grapes, tomatoes, and berries, in environmental samples, achieving an LOD of 4.58 × $10^{-11}$ mol $L^{-1}$ and 97.42–100.08 % recovery, enabling precise monitoring of agrochemical residues in soil and water, which is critical for assessing environmental contamination and food safety (Fig. 7**D**). Moreover, these studies demonstrate that MIP-based sensors offer ultralow detection limits, high selectivity, and reliable applications for both plant studies and the sensitive detection of environmental pollutants, supporting sustainable agriculture and ecosystem protection.

Elshafey and colleagues developed a reusable MIP-based electrochemical sensor that uses chitosan-supported palladium nanostructures (Pd/CS) and polyaniline to detect chlorfluazuron in food and soil samples [107]. The sensor demonstrates exceptional sensitivity with a LOD of 0.6 × $10^{-14}$ M and high recovery rates (90.89–103.34%) in diverse real samples. The MIP sensor showed long-term stability over four weeks and reusability up to six cycles of rebinding and regeneration. Key limitations of this research are the limited reusability, which only allows for six cycles before noticeable performance loss, limiting long-term practical applications, and four weeks of storage stability may not be enough for commercial deployment.

Hybrid engineering of MXene nanosheets/acidified MWCNTs was applied in an MIP sensor for acetaminophen detection in complex biological fluids, as examined by Zeng et al. [108]. By combining an electropolymerized poly-o-phenylenediamine-MIP with $Ti_3C_2T_x$/aMWCNT composites, MXene restacking is effectively addressed while electron transport and target-specific identification are improved. This hybrid platform enables a low limit of detection of 3.3 nM. The key innovation of this research is a 3D interconnected conductive network that enhances electron transfer and improves electrochemical sensing signals. But the multicomponent fabrication strategy may limit scalability, and validation using clinical samples and structurally related interferents is still needed to establish the sensor's practical selectivity. Another MIP sensing platform based on reduced graphene oxide (RGO), a tetrathiafulvalene-based covalent organic framework (TT-COF), and silver nanoparticles (AgNPs) was designed by Yang et al. for the sensitive detection of bisphenol A (BPA) in food samples [109], showing a linear range from 0.25 to 500 nM and a low detection limit of 0.09 nM. The composite material has an electron-rich surface and well-organized channels, creating a three-dimensional porous, conductive framework that greatly improves electron-transfer efficiency. Also, the electrochemical response signal at the interface is then further amplified by electrodepositing AgNPs onto this framework. However, the sensor has selectivity limitations due to structural similarities with BPS and BPAF; it exhibits cross-reactivity with bisphenol analogs, so that when samples contain more than one bisphenol molecule, this reduces its specificity. The study primarily demonstrates usefulness for milk samples, so it has limited validation across diverse food matrices.

Multilayer paper-based electrochemical analytical devices (PAD) have recently attracted significant research interest. The first integrated multilayer ePAD simultaneously detects nitrite, nitrate, and N-nitrosamines on a single platform, addressing the limitation of existing sensors, which typically detect only individual analytes, as reported by Kusonpan et al. [110]. They design a synergistic material that combines bimetallic FeCo-MOFs with gold nanoparticles, enhancing electron transfer and sensing sensitivity. Integration of MIP with FeCo-MOFs provides highly specific recognition sites for NDPhA detection, ensuring selectivity against structurally related nitrosamines. The device's practical usability was tested using processed meat samples, yielding relative recoveries of 93.9–108.9%. While the research article has excellent analytical performance, prior to electrochemical detection, nitrate must be reduced to nitrite with zinc assistance, which adds complication. Moreover, it takes several washing cycles to completely extract the NDPhA template.

One important component of the green bark of woody vascular plants, *p*-coumaric acid (*p*-CA), was detected for the first time using a triethoxymethylsilane-based molecularly imprinted polymer (TMS@G-MIP) sensor integrated with a graphite electrode by Mukherjee et al. [111]. TMS monomer with distinct functional groups that react with *p*-CA through hydrolysis and condensation to form permanent bonding sites and π-π stacking, achieving a wide detection range (0.1–200 μM) with LOD of 0.0175 μM and LOQ of 0.058 μM. The integration of DPV and convolutional neural networks enables accurate prediction of *p*-CA concentration. The authors list several restrictions, including time-consuming electrode preparation and environmental sensitivity, as temperature and pH might affect performance.

These studies highlight the delicate balance between achieving high analytical performance and maintaining material simplicity, sustainability, and practical applicability in environmental monitoring. While advanced nanocomposites and multifunctional materials such as nitrogen- and sulfur-doped graphene, metal-organic frameworks, and MIPs offer exceptional sensitivity and selectivity for detecting pharmaceuticals and bioactive compounds at trace levels, they often introduce complexities in synthesis, scalability, and environmental impact. Conversely, eco-friendly approaches leveraging biomass-derived materials and paper-based platforms prioritize sustainability and ease of fabrication but may face limitations in detection limits or durability in complex matrices. In summary, these studies demonstrate that MIP-based ECSs, particularly those incorporating plant-derived or eco-friendly nanomaterials, provide highly sensitive, selective, and reliable platforms for environmental monitoring, enabling trace-level detection of pollutants and agrochemicals in water, soil, and food matrices, while supporting sustainable, green analytical practices.

## 6. Conclusion, limitations, and future aspects

MIPs have emerged as versatile, highly selective materials for recognizing plant-based materials and for environmental monitoring. Their unique ability to mimic natural molecular recognition, combined with their stability, reusability, and adaptability, positions them as ideal candidates for electrochemical sensors and other analytical platforms. The integration of green molecular recognition principles into MIP synthesis, using renewable monomers, plant-derived polymers, environmentally benign solvents, and eco-friendly polymerization techniques, has enhanced both the sustainability and analytical performance of sensors. Plant-assisted MIPs not only reduce the environmental footprint but also introduce novel functional properties that improve sensitivity, selectivity, and field applicability. Computational approaches enhance mechanistic understanding while strongly supporting green chemistry principles by minimizing trial-and-error experimentation, thereby conserving reagents, energy, and time. In parallel, analytical greenness metrics help identify methodological weak points, optimize sample preparation, and systematically compare the environmental performance of analytical methods. Together, these innovative computational and evaluation tools significantly contribute to environmental sustainability and the advancement of greener analytical practices [83].

Future developments in MIP-based sensors are expected to emphasize the integration of Point-of-Care and Lab-on-a-Chip technologies. These modern platforms will enable highly portable, miniaturized, and rapid detection systems capable of continuous, real-time monitoring of environmental contaminants with high sensitivity and selectivity [112]. The incorporation of artificial intelligence, machine learning, and analytical greenness metrics will facilitate predictive sensor design, optimization of polymerization strategies, greenness evaluation, and real-time data analysis, enabling adaptive, intelligent environmental monitoring systems [113]. Future research should focus on scalable, sustainable polymerization techniques and on stimulus-responsive MIPs that enable reversible, controllable sensing, thereby extending sensor reusability and reducing material waste. Synergistic combinations with green-synthesized nanomaterials will further enhance sensitivity and selectivity, while maintaining environmental compatibility.

Furthermore, these innovations are expected to bridge the gap between laboratory research and practical industrial and field applications, establishing plant-assisted, green MIP electrochemical sensors as central tools for eco-friendly, high-performance environmental monitoring.

Alongside recent technological advancements, significant obstacles, including the limited mechanical robustness and conductivity of natural polymers, the unpredictability of materials obtained from biomass, storage stability, and the scalability of green fabrication techniques, real-sample validation, standardized protocols for MIP synthesis, and integration into portable, miniaturized, and multiplexed platforms must be rigorously assessed. Finding a balance between analytical performance and environmental sustainability is a significant limitation. A sustainable analytical approach does not always follow from the use of renewable materials or more environmentally friendly synthesis conditions unless the entire workflow, including reagent use, energy requirements, template removal, electrode manufacturing, and waste generation, is considered.

Ultimately, the future of MIP-based technologies is intrinsically linked to the broader adoption of sustainable and green chemistry principles. The adoption of plant-derived monomers, biodegradable polymers, and environmentally benign solvents in polymer synthesis can drastically reduce the ecological footprint of sensor fabrication. By minimizing the use of toxic reagents, energy-intensive procedures, and hazardous waste, green MIPs align with global environmental objectives while enhancing biocompatibility and safety for field applications. Stimulus-responsive and recyclable MIPs, combined with plant-assisted nanomaterials, enable durable, low-impact electrochemical sensors for long-term environmental monitoring. Integrating sustainability at every stage, from material selection and polymerization to device operation, ensures that MIP-based electrochemical sensors contribute to eco-friendly analytical practices, supporting cleaner ecosystems and responsible resource management. Such strategies represent a paradigm shift in sensor development, demonstrating that high-performance molecular recognition can coexist with environmental stewardship and green innovation, paving the way for truly sustainable and intelligent sensing platforms.

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## CRediT authorship contribution statement

**Merve Yence:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Ahmet Cetinkaya:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Ilkay Erdogan Orhan:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Sibel A. Ozkan:** Writing – review & editing, Supervision.

## 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.

## Data availability

No data was used for the research described in the article.

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