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A bifunctional monomer molecularly imprinted electrochemical sensor based on AuNPs@CoNi MOF and electrochemically activated graphite paper for the highly sensitive and specific detection of caffeine

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ABSTRACT: This study presents the development of a high-performance electrochemical sensor predicated on a dual-functional monomer molecularly imprinted polymer (MIP) specific recognition mechanism, designed for the highly sensitive and selective detection of caffeine in beverages. Innovatively, the sensor utilizes electrochemically activated graphite paper (EAGP) as the substrate, which, subsequent to electrochemical modulation, integrates a flexible porous architecture with enhanced electrochemical activity, thereby offering a stable platform for the sensing interface. The sensor integrates a cobalt-nickel metal-organic framework–gold nanoparticle composite (AuNPs@CoNi MOF) as a signal amplification element; exploiting the MOF's elevated specific surface area for effective target molecule enrichment and harnessing the superior conductivity of AuNPs to establish efficient electron transport channels. Density functional theory (DFT) was employed to accurately identify 3-thiopheneacetic acid and *o*-phenylenediamine as the optimal dual-functional monomer pair, establishing a synergistic dual mechanism of “AuNPs@CoNi MOF enhancement coupled with dual-functional monomer MIP specific recognition.” Moreover, azide-alkyne cycloaddition click chemistry was utilized to accomplish oriented and robust covalent linkage between the composite and the EAGP substrate, resulting in a uniform sensing interface. Experimental findings illustrate that the sensor demonstrates excellent analytical performance, characterized by a detection range spanning from 10 nM to 200 μM and a detection limit reaching as low as 1.5 nM. This innovative architecture not only markedly improves detection sensitivity and selectivity but also offers benefits including cost-effectiveness, portability, and operational simplicity, thereby furnishing a novel technical strategy for rapid on-site screening and large-scale caffeine detection in beverages.

Keywords: Caffeine; Molecularly imprinted polymer; Electrochemical sensor; AuNPs@CoNi MOF; Highly sensitive detection

1. Introduction

As a prototypical central nervous system stimulant, caffeine is extensively incorporated as a functional additive in various beverages, including coffee, tea, energy drinks, and carbonated beverages, owing to its

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prominent analgesic, anti-fatigue, and revitalizing properties (Ahmed, El-Zanaty, Galal, & Atta, 2025; X. Li & Guo, 2025). Additionally, it functions as a crucial auxiliary agent in the food processing sector. Moderate caffeine consumption can enhance cognitive alertness; however, excessive intake may precipitate a range of adverse health effects such as anxiety, insomnia, tachycardia, and endocrine dysfunction, posing significant risks particularly to adolescents, pregnant women, and individuals with cardiovascular conditions (Lee, Chua, Voon, Tham, Ho, & Lee, 2026; Lesar et al., 2025; Vukov, Bešter-Rogač, Korošec, Papović, Borović, & Vraneš, 2025). Furthermore, precise regulation of caffeine concentration throughout beverage production and processing critically influences product quality and consumer safety, rendering it an essential quality control parameter within the food industry (Akillioğlu, Köse Korkmaz, & Dönmez Kutlu, 2025; Huang, Wang, & Zhou, 2025). Consequently, the development of highly sensitive and specific methodologies for trace-level caffeine detection in beverages, enabling rapid and accurate quantification, is imperative for safeguarding product integrity and consumer health. To date, analytical techniques including spectroscopy, gas chromatography (GC) (Bresin, Piol, Fabbro, Mancini, Casetta, & Del Bianco, 2015), high-performance liquid chromatography-mass spectrometry (HPLC-MS) (Baud-Camus, Marquet, Soursac, Davrinche, & Farinotti, 2001), and enzyme-linked immunosorbent assay (ELISA) (Mu et al., 2025) have been employed for caffeine quantification. Although these conventional methods demonstrate advantages in sensitivity and accuracy, they are often hindered by laborious sample preparation, operational complexity, and dependency on skilled personnel. Moreover, some approaches necessitate bulky and sophisticated instrumentation, resulting in prolonged analysis times and elevated costs, thereby constraining their applicability for on-site quality control in beverage manufacturing, swift market product screening, and high-throughput sample analysis (Ahmed et al., 2025; Hallaj, Soltani, Mafakheri, & Ghadermazi, 2021; Ullah, Kim, Sheena Mary, & Kwon, 2022). Therefore, the advancement of caffeine detection technologies that are cost-effective, user-friendly, time-efficient, and highly sensitive—addressing the drawbacks of traditional techniques—holds considerable practical significance and application potential for quality assurance in the beverage industry, consumer health protection, and regulatory supervision.

Electrochemical sensing technology, distinguished by its rapid response and operational simplicity, demonstrates significant potential in the detection of trace pollutants (Le, 2026; Qiao et al., 2025; Tan et al., 2026). Vinothkumar et al. synthesized silver vanadate/graphitic carbon nitride nanocomposites via a co-precipitation method and employed them to modify glassy carbon electrodes (GCE), thereby fabricating sensors with high sensitivity toward caffeine detection (Vinothkumar, Poongan, Mandal, & Venkatesh, 2024). In a separate investigation, Madhusudhana et al. utilized zinc oxide/graphene oxide-phenol-formaldehyde amine nanocomposites to functionalize graphite electrodes, enabling precise quantification of caffeine (Madhusudhana, Mohana, Hegde, Swamy, & Shivamurthy, 2022). Nonetheless, sensors based on GCE or conventional graphite electrodes encounter challenges including high cost of commercial electrodes, complex fabrication procedures, and difficulties in scaling up production, which collectively impede their practical field applications. Consequently, the development of novel sensing substrate electrodes that are cost-effective,

facile to prepare, and highly adaptable to environmental conditions is critical for overcoming these technical limitations and can facilitate the progression of detection technologies toward on-site and large-scale deployment (Bruno, Gutiérrez-Capitán, Patella, Aiello, Inguanta, & Fernández-Sánchez, 2026; M. Du et al., 2026; X. Zhang, Miao, Zhou, Zhou, Gan, & Tang, 2025). Besides electrochemical strategies, other advanced sensing platforms including surface-enhanced Raman scattering sensors, fluorescent lateral flow immunoassays, and chiral nanomaterial-based sensors have also been explored for food hazard detection, providing technical supports for rapid and sensitive on-site monitoring (Chao et al., 2026; Liang, Xu, Peng, Ma, & Zhao, 2023; Y.-C. Ouyang, Yeom, Zhao, & Ma, 2024).

In recent years, graphite paper (GP) has gained recognition as a highly promising electrode substrate owing to its low cost, high portability, and excellent electron transport efficiency (Dong et al., 2025; Fan, Hao, & Kan, 2018). It integrates the superior conductivity of graphite with the flexible, porous architecture of paper, while also demonstrating high mechanical strength, robust chemical stability, and strong corrosion resistance, thereby providing a foundation for the miniaturization of sensing technologies (Kamble et al., 2024). However, the intrinsic surface of GP displays limited electrochemical activity, sluggish electrocatalytic kinetics, and a scarcity of active sites, rendering it inadequate to fulfill the requirements of efficient electrochemical reactions. To overcome these limitations, studies have demonstrated that electrochemical modulation techniques—such as oxidation, reduction, or doping—can effectively enhance its electrochemical performance (Ye, Zhou, Jia, Tang, Zhu, & Wan, 2017). Moreover, strategies like etching and pore generation can increase the specific surface area, thereby reinforcing the interfacial interactions between the electrode and analytes.

Regarding the selection and integration of functional materials for sensing interfaces, metal-organic frameworks (MOFs) have emerged as critical functional components for fabricating high-performance sensing platforms due to their high specific surface area and tunable porous structures (Q. Ouyang et al., 2026; Tatlı, Aldoori, Küçükkolbaşı, & Erdemir, 2026; W. Zhang et al., 2025). Concurrently, gold nanoparticles (AuNPs), characterized by excellent conductivity and favorable biocompatibility, are extensively employed in electrochemical sensing, significantly enhancing electron transport efficiency, sensitivity, and target molecule immobilization (Lu et al., 2026; Xiang et al., 2026). It is noteworthy that pure MOF nanomaterials exhibit limited electrochemical conductivity and tend to aggregate on electrode surfaces. Combining them with AuNPs can yield substantial synergistic effects: on one hand, the superior conductivity of AuNPs compensates for the electrochemical deficiencies of MOFs, accelerating interfacial electron transfer and improving sensor response kinetics; on the other hand, the high specific surface area of MOFs provides a stable scaffold for AuNPs, establishing a basis for subsequent immobilization of recognition elements and capture of target molecules.

The primary objective in the design of electrochemical sensors is to achieve highly selective detection of target analytes, wherein the selection and engineering of recognition elements are critical.

Molecularly imprinted polymers (MIPs), regarded as "artificial antibodies" endowed with "structural memory" capabilities, occupy a crucial role among the specific recognition elements owing to their remarkable stability, cost-effectiveness, facile fabrication, and superior biocompatibility (Geng et al., 2024; Geng et al., 2025; Yao, Dong, Fu, Li, & Luo, 2024). In comparison with MIPs derived from single functional monomers, those synthesized from dual functional monomers exhibit enhanced advantages: the two distinct functional monomers can synergistically establish robust complementary interactions with the target molecule (caffeine), thereby generating numerous high-affinity, highly selective binding sites within the polymer matrix. This significantly improves the sensitivity of electrochemical MIPs for caffeine determination (Cheng et al., 2025). Furthermore, the cross-linked polymerization of dual functional monomers confers improved mechanical robustness and chemical stability to the MIPs, ensuring that the sensor maintains consistent detection performance even in complex environmental conditions.

Nevertheless, a fundamental technical challenge currently encountered is the efficient and stable integration of the composite recognition system onto GP substrates to fabricate sensing interfaces with uniform performance and high sensitivity. Conventional modification techniques such as physical coating and drop-casting suffer from drawbacks including poor adhesion, heterogeneous distribution of the composite system, and facile loss of active sites, which critically impair the sensor's detection stability and reproducibility. Click chemistry, distinguished by its mild reaction conditions, high selectivity, excellent yields, minimal by-product generation, and outstanding stability of reaction products, presents broad application potential in surface functionalization and precise material assembly (C. Zhang, Tian, Yin, & Zhao, 2024). Among these, the azide-alkyne cycloaddition reaction enables directional and stable covalent bonding between diverse materials, effectively overcoming many limitations associated with traditional modification approaches (S. Li et al., 2026).

Based on this foundation, the present study developed a disposable electrochemical sensing system that employs EAGP as the substrate, a cobalt-nickel metal-organic framework–gold nanoparticle composite (AuNPs@CoNi MOF) as the signal-amplifying element, and MIP derived from a bifunctional monomer as the recognition element, achieving highly sensitive and selective detection of trace caffeine. The system integrates the principal advantages of each component: following electrochemical modification, the GP exhibits a flexible, porous architecture and elevated electrochemical activity, providing a robust support for the sensing interface; the AuNPs@CoNi MOF, via synergistic interactions, harnesses the CoNi MOF's high specific surface area for efficient target enrichment while utilizing the excellent conductivity of AuNPs to establish effective electron-transfer pathways, thereby delivering a stable loading platform and high-efficiency electronic transmission for the recognition layer. Molecular modeling was applied to identify the optimal bifunctional monomer and its stoichiometric ratio, and a MIP thin film was subsequently assembled on the AuNPs@CoNi MOF surface using caffeine as the template. This produces a dual-action mechanism — "AuNPs@CoNi MOF enhancement combined with bifunctional-monomer MIP specific

recognition” — which markedly enhances caffeine capture efficiency and recognition specificity. Concurrently, covalent immobilization via click chemistry was used to directionally and stably anchor the MIP/AuNPs@CoNi MOF composite onto the electrochemically modified GP, yielding a uniform, highly responsive sensing interface that ensures accurate caffeine capture and detection. After systematic characterization and process optimization, the sensor’s reliability was confirmed using real beverage samples under optimal detection conditions. Compared with conventional approaches and prior reports, the system offers distinct technical advantages: a low-cost, highly portable electrode substrate suitable for on-site rapid testing; a sensing architecture that combines structural robustness with application flexibility and can be adapted to multiple target analytes via customized MIP design; and not only an effective tool for precise caffeine control but also broad applicability in food safety monitoring and related fields.

2. Material and Methods

2.1. Instruments and reagents

The relevant instruments and reagents were listed in Supplementary Materials.

2.2 Computational details

To fabricate high-performance electrochemical sensors, we selected methacrylic acid, 3-thiopheneacetic acid, acrylamide, *o*-phenylenediamine, and dopamine as candidate functional monomers for a caffeine MIP film and conducted molecular simulations with Gaussian 16. Geometry optimizations were carried out for the template molecule, each individual functional monomer, the template–monomer binary complexes, and the template–dual-monomer ternary complexes at the restricted B3LYP/6-311G(d) level of density functional theory (DFT); subsequently, the binding energies for each system were computed. Three-dimensional structures of the molecules and complexes were rendered using GaussView 6.0 (Chi, Xiao, Wen, & Tang, 2025).

2.3 Synthesis of CoNi MOF and MIP/AuNPs@CoNi MOF

To prepare CoNi MOF: Accurately weigh 0.485 g of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 0.336 g of $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. Place both salts into a 100 mL beaker containing 40 mL of deionized water and stir magnetically for 30 min until completely dissolved, yielding a clear, homogeneous solution (solution A). In a separate 250 mL beaker, dissolve 6.5 g of 2-MIM in 100 mL deionized water with magnetic stirring for 30 min to obtain a clear ligand solution (solution B). At room temperature, while solution A is stirred continuously, rapidly add solution B to solution A within 30 s and stir vigorously for 3 min. When the mixture becomes milky/opaque—indicating the onset of MOF precipitation—stop stirring and age the mixture at 25 °C for 8 h to allow the coordination reaction to proceed to completion. Transfer the aged mixture to centrifuge tubes and centrifuge at 12,000 rpm for 10 min. Decant the supernatant, add 20 mL deionized water to re-disperse the precipitate by shaking, and centrifuge again under the same conditions. Repeat the washing cycle several times to remove unreacted impurities.

Finally, transfer the washed precipitate to a clean dish and vacuum-dry at 60 °C overnight until thoroughly dry to yield the CoNi MOF product.

To prepare AuNPs@CoNi MOF: disperse 0.10 g of the prepared CoNi MOF powder in 50 mL deionized water in a 100 mL three-neck flask by ultrasonication for 30 min to obtain a uniform suspension. Add 5 mL of 10 mM HAuCl₄ aqueous solution and stir for 30 min to facilitate adsorption onto the CoNi MOF surface. Place the flask in an ice–water bath and add 8 mL of 20 mM sodium citrate solution dropwise. Upon completing the addition, raise the temperature to 60 °C and continue stirring for 2 h. When the solution turns wine-red, transfer to centrifuge tubes and centrifuge at 12,000 rpm for 10 min. Decant the supernatant and wash the precipitate alternately with deionized water and anhydrous ethanol three times. Vacuum-dry the washed product at 60 °C overnight to obtain AuNPs@CoNi MOF powder.

For MIP formation on AuNPs@CoNi MOF: disperse 0.05 g AuNPs@CoNi MOF powder in 30 mL ethanol–water (v/v = 1:1) by ultrasonication for 20 min. Add 0.1 mM of the template molecule caffeine and stir magnetically for 12 h to allow pre-assembly. Then sequentially add 0.4 mM 3-thiopheneacetic acid, 0.5 mM *o*-phenylenediamine, and 2 mM crosslinker EGDMA, and stir for an additional 2 h. Add 20 mg AIBN as the initiator, seal the flask, and carry out polymerization in a 65 °C water bath in the dark with stirring for 24 h. After the reaction, collect the solid by centrifugation and remove the template caffeine by washing/eluting with methanol–acetic acid (v/v = 9:1). Vacuum-dry the final product at 60 °C overnight to obtain the MIP/AuNPs@CoNi MOF composite. As a control (non-imprinted polymer), prepare NIP/AuNPs@CoNi MOF under identical conditions but omit the caffeine during the polymerization.

2.4 Electrochemical activation of GP

Select pristine GP as the substrate and use a precision paper cutter to cut it into uniform 1.0 cm × 2.5 cm strips. To remove adsorbed contaminants and grease from the surface, place the cut GP sequentially in anhydrous ethanol and then in distilled water, ultrasonically cleaning each solvent for 15 min; repeat this cycle three times. After cleaning, dry the samples at room temperature in a fume hood. Tightly seal the non-reactive areas of the dried GP with Kapton tape, leaving a precisely defined 1.0 cm × 1.0 cm exposed window as the working area for the subsequent electrochemical reaction to prevent unwanted regions from participating. Firmly clamp the taped GP with a platinum electrode clamp, ensuring good electrical/contact and that the reaction window remains unobstructed. Immerse the assembly in an electrolytic cell so that the exposed region is fully submerged in a 2.0 M oxalic acid electrolyte, connect to an electrochemical workstation, and apply a constant potential of +6 V for 200 s. After the treatment, remove the electrode, rinse the surface thoroughly with distilled water to remove residual electrolyte, and air-dry at room temperature to obtain EAGP.

2.5 Construction of the MIP/AuNPs@CoNi MOF/EAGP sensing platform

The dried EAGP electrode was immersed in 1 M NaN₃ solution and subjected to a constant current of 20 mA for 30 min. After the reaction, the electrode was removed, sequentially soaked in methanol

and ultrapure water for 5 min each, blown dry with nitrogen, and then vacuum-dried in an oven at 40 °C for 1 h to obtain $-N_3$ functionalized EAGP, which was sealed and stored in the dark.

Separately, 20 mg of MIP/AuNPs@CoNi MOF powder was dispersed in 10 mL DMF and sonicated for 30 min to form a uniform suspension. Propargylamine (8 mM), EDC (10 mM) and NHS (15 mM) were added and the mixture was stirred at room temperature for 12 h to introduce alkyne functional groups onto the MIP/AuNPs@CoNi MOF surface. After reaction, the product was centrifuged at 12,000 rpm for 10 min, washed alternately with anhydrous ethanol and deionized water three times, and vacuum-dried to obtain alkyne-modified MIP/AuNPs@CoNi MOF. Then, 5 mg of the alkyne-modified MIP/AuNPs@CoNi MOF was dispersed in 5 mL deionized water and sonicated for 20 min to prepare a suspension. The azide-modified EAGP electrode was immersed in this suspension, and a click-chemistry catalytic system composed of 0.5 mM $CuSO_4$, 1 mM sodium ascorbate and 0.8 mM triethylamine was added. The reaction was carried out under N_2 protection with shaking at room temperature for 6 h. Via azide–alkyne cycloaddition, covalent bonding between MIP/AuNPs@CoNi MOF and the EAGP was achieved. After the reaction, the electrode was removed, rinsed with deionized water to remove unbound material, and air-dried at room temperature to yield the MIP/AuNPs@CoNi MOF/EAGP electrochemical sensing platform.

2.6 Electrochemical measurement

0.1 M phosphate-buffered saline (PBS) served as the electrolyte for electrochemical characterization of the prepared sensing interface. The employed techniques comprised cyclic voltammetry (CV), electrochemical impedance spectroscopy (EIS), and differential pulse voltammetry (DPV). Measurement parameters were as follows: CV potential scan range -0.6 to 1.0 V; EIS was conducted at the open-circuit potential with an AC excitation amplitude of 10 mV and impedance spectra recorded over the 1 Hz to 100 kHz frequency range; DPV potential scan range -0.4 to $+0.6$ V, with pulse amplitude, pulse width, and sampling width set to 50 mV, 50 ms, and 16.7 ms, respectively.

2.7 Practical application

To assess the applicability and reliability of the MIP/AuNPs@CoNi MOF/EAGP sensing platform in real matrices, commercially available red Bull, tea, and cola were chosen as representative test beverages. Sample preparation proceeded as follows: precisely aliquot varying volumes (1 mL, 5 mL, and 10 mL) of each beverage and mix them with a solvent blend of 0.1 M PBS and anhydrous ethanol. Subject the resulting mixtures to sonication in an ultrasonic bath for 1 h to promote exhaustive extraction and homogeneous dispersion of the target analytes. Transfer the suspensions to centrifuge tubes and centrifuge at 8000 rpm for 15 min to eliminate proteins, colloidal material, and other insoluble contaminants (Vinothkumar et al., 2024). Following centrifugation, collect the supernatant and perform **serial dilution with a total dilution factor (DF) of 1000** using 0.1 M PBS to obtain test solutions with concentrations within the linear range (10 nM–200 μ M) for subsequent electrochemical analysis. For HPLC–MS validation, the same diluted test solutions (DF = 1000) were analyzed using an external standard method with caffeine standards (10 nM–200 μ M).

3. Results and discussion

3.1 Selection of Functional Monomers

The core performance of MIP sensors depends heavily on the judicious selection of functional monomers, which directly determines the efficiency of constructing template-specific recognition sites and their structural stability. This study integrates systematic theoretical calculations and experimental validation to elucidate the molecular interaction mechanisms between caffeine and various functional monomers. Based on DFT calculations, molecular geometries of caffeine and each functional monomer were first optimized (Fig. S1). Binding characteristics between caffeine and the monomers were then quantitatively evaluated using the binding energy formula ($\Delta E = E_{AB} - E_A - E_B$). The calculation results (Table S1) show that, at a 1:1 molar ratio, the complex formed between caffeine and *o*-phenylenediamine exhibits the lowest binding energy (−12.89 kcal/mol). This favorable binding is mainly attributed to a network of multiple hydrogen bonds between the amino hydrogens of *o*-phenylenediamine and the carbonyl oxygens and nitrogen atoms on caffeine's purine ring (Fig. S2).

Notably, when 3-thiopheneacetic acid (bearing a thiophene ring) is used as a fixed functional monomer and combined with *o*-phenylenediamine to form a dual-functional-monomer system, the binding energy of the caffeine–dual-monomer complex decreases further to −20.65 kcal/mol, substantially lower than that of other monomer combinations (Table S2). The pronounced enhancement of binding in this dual-monomer system arises from two key factors: first, the two functional monomers can engage caffeine at different sites in a complementary fashion—*o*-phenylenediamine's amino groups form strong hydrogen bonds with caffeine, while the carboxyl group of 3-thiopheneacetic acid can bind caffeine's active groups through ionic interactions or hydrogen bonding, producing cooperative, complementary binding sites; second, π – π stacking between the thiophene ring of 3-thiopheneacetic acid and the purine ring of caffeine works together with the hydrogen-bond network to stabilize the complex, and the combined steric effects of the two monomers better match caffeine's three-dimensional conformation, further improving binding efficiency (Fig. 1).

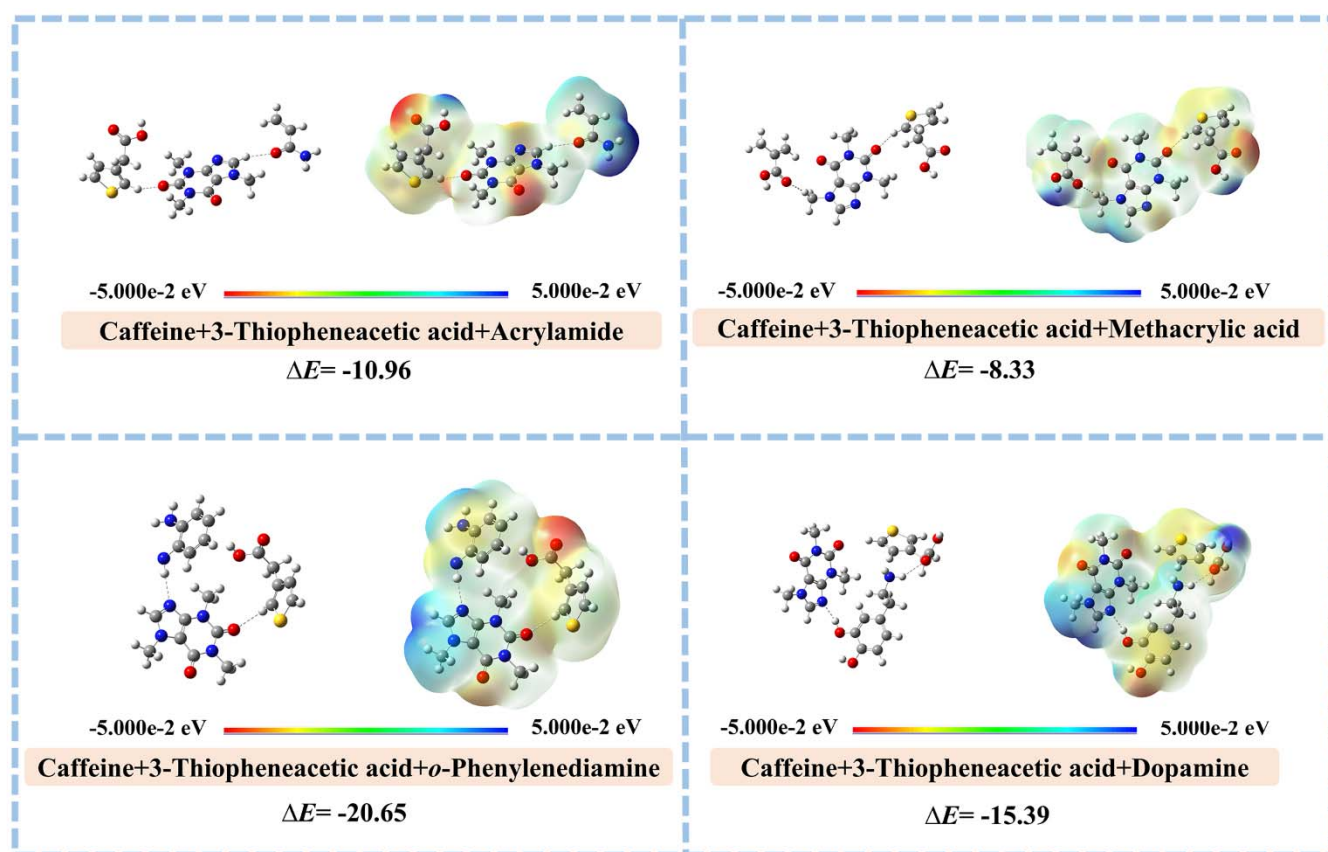


Figure 1. Optimized structure (RB3LYP) and electrostatic potential (ESP) of (A) Caffeine + 3-thiopheneacetic acid + Acrylamide; (B) Caffeine + 3-thiopheneacetic acid + Methacrylic acid; (C) Caffeine + 3-thiopheneacetic acid + *o*-Phenylenediamine and (D) Caffeine + 3-thiopheneacetic acid + Dopamine.

Molecular electrostatic potential analysis further reveals that the nitrogen atoms in caffeine's purine ring and the amino hydrogens act as primary electron-donor sites, whereas the carbonyl oxygens and electron-deficient regions of the purine ring serve as electron-acceptor sites in the interactions. These results indicate that monomer–template binding is a complex process governed by multiple, cooperative factors, including hydrogen bonding, π – π stacking, electrostatic interactions, and spatial conformational matching. Compared with single-monomer systems, the core advantages of the dual-functional-monomer approach can be summarized as three points: (1) expansion of cooperative binding sites—complementary intermolecular forces increase monomer–template binding strength; (2) enhanced specificity of recognition sites—steric complementarity of the dual monomers more precisely matches the template conformation, reducing formation of non-specific binding sites; (3) improved stability of recognition sites—synergistic multiple intermolecular forces maintain complex stability and lower dissociation probability, providing a reliable template for the precise formation of specific recognition sites during subsequent polymerization.

Based on the above theoretical screening results, the 3-thiopheneacetic acid/*o*-phenylenediamine pair was directly adopted for the subsequent experimental preparation of MIP, without additional comparative experiments of other monomer systems.

3.2 Characterization of MIP/AuNPs@CoNi MOF

SEM was employed to systematically and intuitively characterize the stepwise modification of MIP/AuNPs@CoNi MOF. As shown in Fig. 2A, the pristine CoNi MOF displays a well-defined lilac-flower-like morphology, with petals arranged as orderly stacked thin lamellae. This three-dimensional porous architecture provides abundant spatial sites and structural support for subsequent AuNPs loading and uniform MIP deposition, while creating channels that facilitate target-molecule transport and recognition, thereby establishing a robust structural foundation. XRD (Fig. 3A) further confirmed the crystalline nature of the CoNi MOF. The diffraction peaks closely match the simulated pattern of ZIF-L, and characteristic diffraction peaks located at 44.3° , 51.8° and 76.1° are attributed to the (111), (200) and (220) crystal planes of the CoNi alloy (JCPDS no. 01-1259). No diffraction peaks derived from separated Co or Ni species or physical mixtures are detected (X. Du, Lan, Wu, Pan, & Wu, 2024; H. Li et al., 2025). Sharp peaks without discernible impurity signals confirm the successful synthesis of CoNi MOFs possessing a well-defined crystal structure, high crystallinity, and elevated purity.

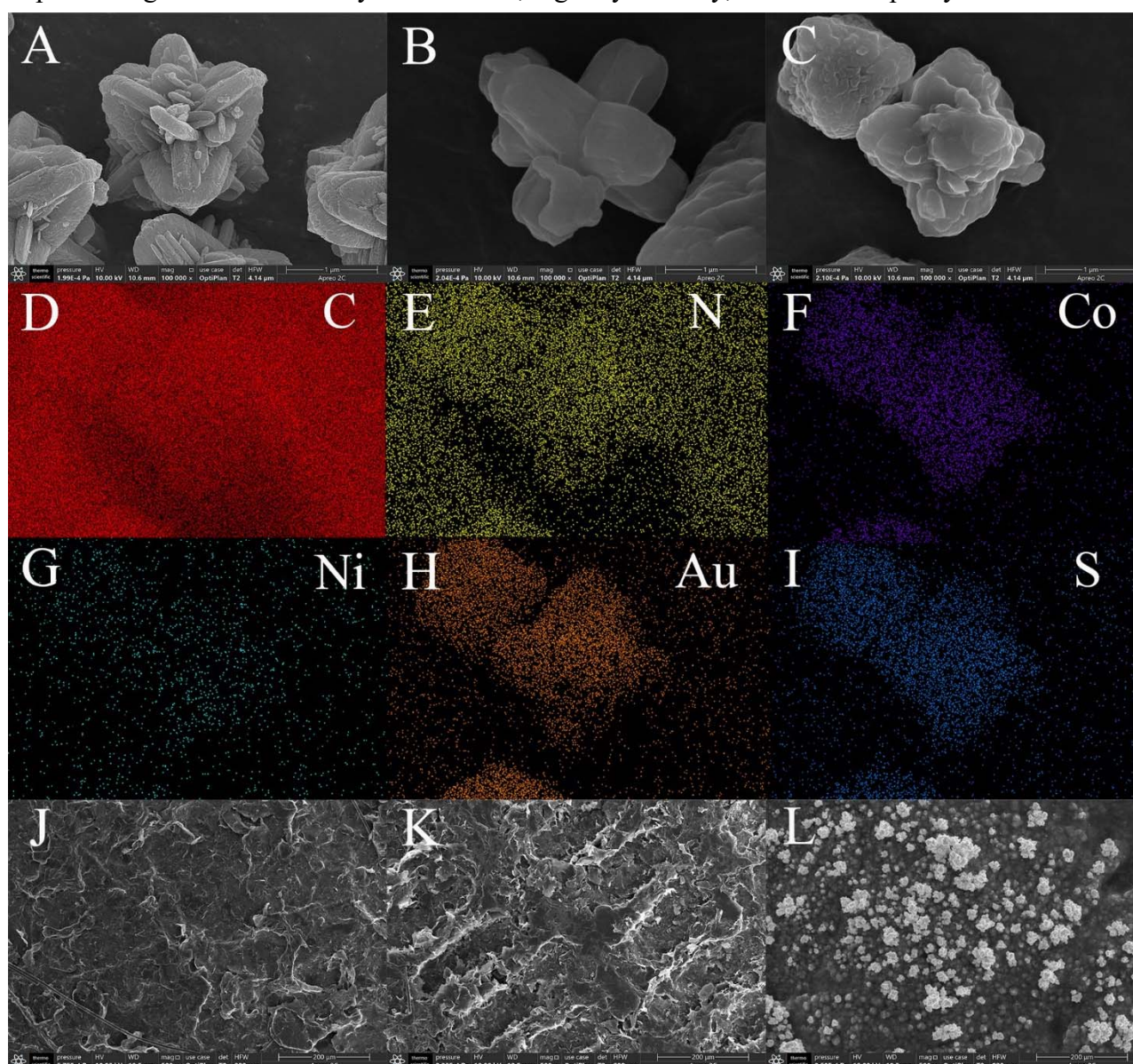


Figure 2. SEM images of (A) CoNi MOF, (B) AuNPs@CoNi MOF and (C) MIP/AuNPs@CoNi MOF; (D-I) EDS-elemental mapping of C, N, Co, Ni, Au and S; SEM images of (J) GP, (K) EAGP and (L) MIP/AuNPs@CoNi MOF/EAGP.

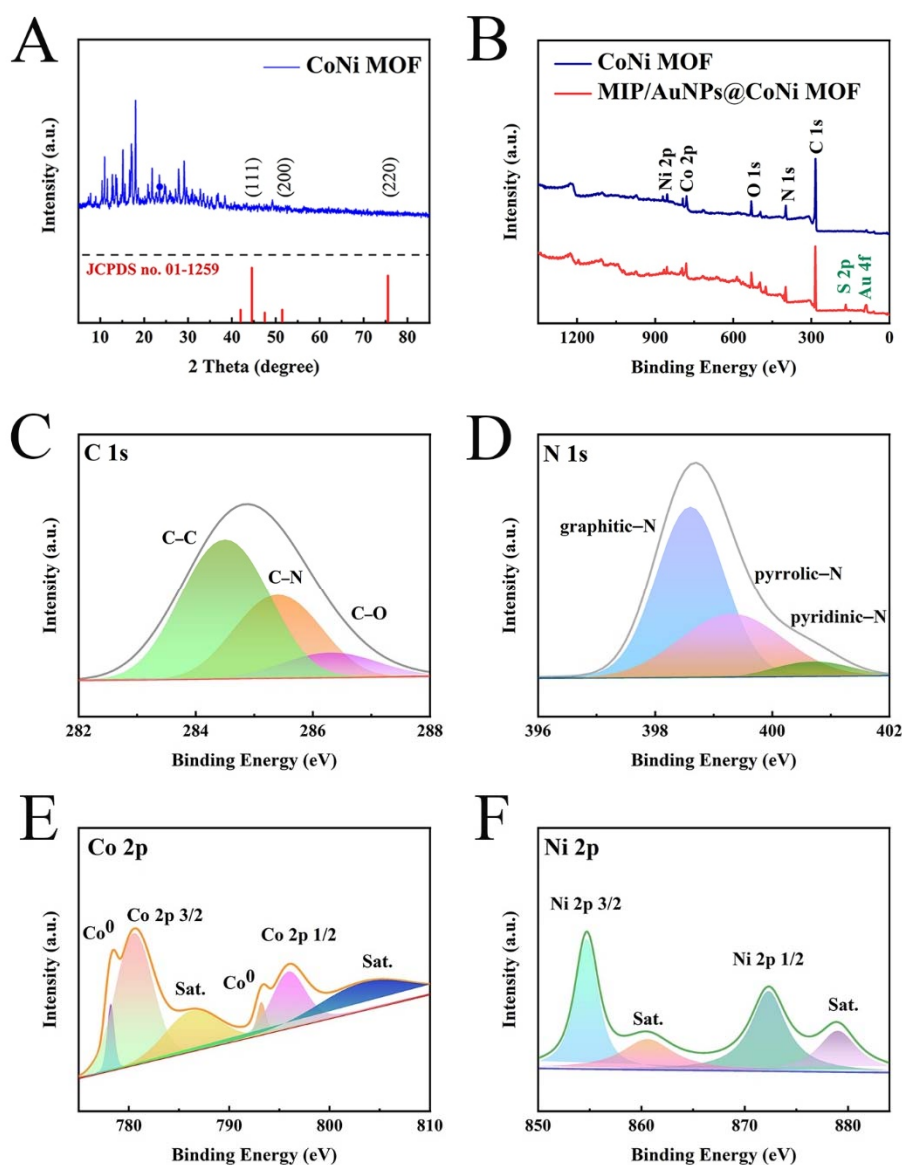


Figure 3. (A) XRD patterns of CoNi MOF; (B) XPS spectra of CoNi MOF; (C) C 1s; (D) N 1s; (E) Co 2p and (F) Ni 2p core-level XPS spectra of CoNi MOF.

The XPS survey spectrum of the CoNi MOF (Fig. 3B) indicates that Co, Ni, C, N, and O constitute the elemental composition, and the **quantitative atomic contents are measured as 3.7% Co, 2.8% Ni, 61.37% C, 28.95% N, and 3.18% O**, respectively. These observations corroborate coordination of metal ions ($\text{Co}^{2+}/\text{Co}^{3+}$, Ni^{2+}) to the 2-MIM ligand, yielding a stable MOF framework. In the high-resolution spectra, the C 1s profile (Fig. 3C) exhibits peaks at 284.2 eV (C–C), 285.1 eV (C–N), and 286.1 eV (C–O). The C–N feature directly evidences coordination between the ligand and metal ions; the C–O signal likely reflects minor surface oxidation or oxygen-containing functional groups in the ligand, and the C–C peak corresponds to the ligand's aromatic backbone. The N 1s spectrum (Fig. 3D) can be deconvoluted into pyridinic-N, pyrrolic-N, and graphitic-N components. Graphitic-N, owing to its superior conductivity, enhances internal electron transport and thereby benefits the composite's electrochemical performance, whereas pyridinic-N and pyrrolic-N contribute to structural stability via coordination with metal ions. The Co 2p spectrum (Fig. 3E) exhibits peaks at 781.2 eV (Co 2p_{3/2}) and 797.1 eV (Co 2p_{1/2}), indicative of $\text{Co}^{2+}/\text{Co}^{3+}$ valence states, together with additional signals

at 781.9 eV and 800.51 eV assignable to Co–N_x bonds, signifying stable coordination between Co ions and ligand nitrogen atoms. The Ni 2p spectrum (Fig. 3F) displays peaks at 854.7 eV (Ni 2p_{3/2}) and 873.1 eV (Ni 2p_{1/2}), consistent with Ni²⁺, alongside satellite peaks at 863.2 eV and 881.6 eV, characteristic of ligand-coordinated Ni²⁺. Collectively, these high-resolution spectra substantiate the successful synthesis of the CoNi MOF.

Following in situ formation of AuNPs on the CoNi MOF surface, the morphology changed markedly (Fig. 2B): the originally smooth petal surfaces became roughened by **uniformly distributed AuNPs without obvious aggregation**, indicating successful and homogeneous loading of AuNPs. After deposition of the MIP layer on AuNPs@CoNi MOF, the surface became denser and thicker, forming a **continuous and uniform coating** (Fig. 2C), indicative of MIP wrapping. SEM elemental mapping clearly detected S and Au homogeneous signals (Fig. 2H, I): the uniform Au signal confirms homogeneous distribution of gold nanoparticles, while the uniform S signal demonstrates successful incorporation and coating of the sulfur-containing functional monomer 3-thiopheneacetic acid-based MIP layer. XPS characterization (Fig. 3B) further corroborated fabrication of MIP/AuNPs@CoNi MOF: the appearance of Au 4f and S 2p peaks in the survey spectrum is consistent with SEM mapping and collectively provides sufficient and reliable evidence for successful stepwise modification.

3.3 Characterization of EAGP

SEM images indicate that pristine GP has a comparatively planar microstructure (Fig. 2J), whereas electrochemically activated EAGP exhibits pronounced folding, increased surface roughness, and localized delamination of graphite flakes (Fig. 2K). These morphological changes provide more favorable structural conditions for material–electrolyte interfacial contact and charge transport. In the XRD pattern (Fig. S3A), both GP and EAGP display a sharp, intense diffraction peak at 26.3°, attributed to the (002) graphite plane; however, this peak is attenuated in EAGP, suggesting that electrochemical activation in acidic media disrupts the original high crystallinity of graphite and diminishes its crystalline order. FTIR spectra (Fig. S3B) show new C–O and C=O bonds in EAGP, which confirm surface carboxylation and imply the introduction of additional oxygen-containing functional groups, such as hydroxyls and ethers, during activation, thereby enriching surface active sites. Raman spectroscopy was used to quantitatively evaluate the structural defects of GP before and after electrochemical activation. As shown in Fig. S3C, both samples exhibit characteristic D (~1350 cm⁻¹, defect/disordered carbon) and G (~1580 cm⁻¹, sp²-hybridized graphitic carbon) bands. The I_D/I_G ratio, a key metric for defect density, increases significantly from 0.36 for pristine GP to 0.91 for EAGP, confirming the introduction of abundant structural defects and electroactive sites during activation. Notably, the well-preserved sharp G band of EAGP demonstrates that the intrinsic graphitic framework and high electrical conductivity are maintained, which is essential for excellent electrochemical sensing performance. XPS analysis further corroborates these structural and chemical modifications (Fig. S3D–H): in the C 1s core-level spectrum, pristine GP predominantly exhibits a peak at 284 eV corresponding to sp²-hybridized C–C bonds, whereas EAGP, while retaining part of that signal, presents a C–O component near 286 eV and a

C=O component near 288 eV; in the O 1s spectrum, EAGP shows distinct peaks at ~530 eV and ~532 eV with intensities markedly higher than those of pristine GP, directly demonstrating a substantial increase in surface oxygen content and the successful incorporation of oxygen-containing functional groups following electrochemical activation. The strong oxidative species generated during electrochemical activation attack the interlayer C–C covalent bonds in graphite: they disrupt the crystalline lattice, inducing layer folding, delamination and development of a porous architecture, which significantly increases specific surface area and porosity and thus the electrode–electrolyte contact area; concomitantly, oxidative reactions introduce polar moieties such as carboxyl and hydroxyl groups, which enhance hydrophilicity to reduce interfacial contact resistance and modulate the electronic structure—thereby shortening charge-transport pathways and lowering charge-transfer barriers. Collectively, these effects synergistically improve the electrochemical performance of GP, rendering it a superior sensing substrate.

3.4 Fabrication and electrochemical characterization of the MIP/AuNPs@CoNi-MOF/EAGP sensing platform

EAGP increased the surface roughness while preserving the substrate's excellent conductivity and flexibility. As a sensor substrate, EAGP's abundant porosity and high specific surface area provide an optimal interfacial scaffold for the uniform deposition of functional nanomaterials. Based on this, CoNi MOF was synthesized, and AuNPs were subsequently deposited onto its surface via a reduction method to form an AuNPs@CoNi MOF composite nanostructure. Thereafter, molecular imprinting was performed on the surface of AuNPs@CoNi MOF using 3-thiopheneacetic acid and *o*-phenylenediamine as bifunctional monomers and caffeine as the template molecule, yielding the MIP/AuNPs@CoNi MOF composite material. The resulting composite integrates the synergistic recognition afforded by the bifunctional monomers, the high electrical conductivity of the gold nanoparticles, and the large specific surface area of the CoNi MOF, thereby enhancing electron-transfer kinetics and the sensor's sensitivity toward the target analyte. Finally, the MIP/AuNPs@CoNi MOF composite was covalently anchored to the EAGP substrate via azide–alkyne cycloaddition click chemistry, achieving robust integration of the functional layer and the substrate (Fig. 2L shows numerous spherical/flower-like nanoclusters uniformly dispersed on the substrate surface). Collectively, these modifications yielded a high-performance MIP/AuNPs@CoNi MOF/EAGP electrochemical sensor capable of highly selective and sensitive quantitative detection of caffeine.

In this study, the electrochemical performance of the modified electrodes was systematically investigated by CV and EIS to elucidate the synergistic mechanism of each component, with the quantitative parameters summarized in Table S3. As shown in Fig. 4A, electrochemical activation generated a rough, porous morphology on the GP surface; the EAGP exhibited larger redox peak currents than pristine GP, indicating that activation substantially enhanced the electron-transfer kinetics. After modification with the **integrated MIP/AuNPs@CoNi MOF composite**, the redox peak currents of MIP/AuNPs@CoNi MOF/EAGP increased further, with an additional pronounced enhancement after extraction of the template molecules. This improvement is attributed to the high electrical conductivity of AuNPs, the pronounced

porosity of the CoNi MOF, and the three-dimensional network provided by the bifunctional-monomer-based MIP, which together facilitate charge and mass transport and thereby augment the sensor's electrochemical responsiveness. The current response of independently synthesized NIP/AuNPs@CoNi MOF/EAGP was significantly lower than that of the MIP-modified electrode, reflecting the superior ability of the imprinted structure to promote efficient electron transport and specific recognition.

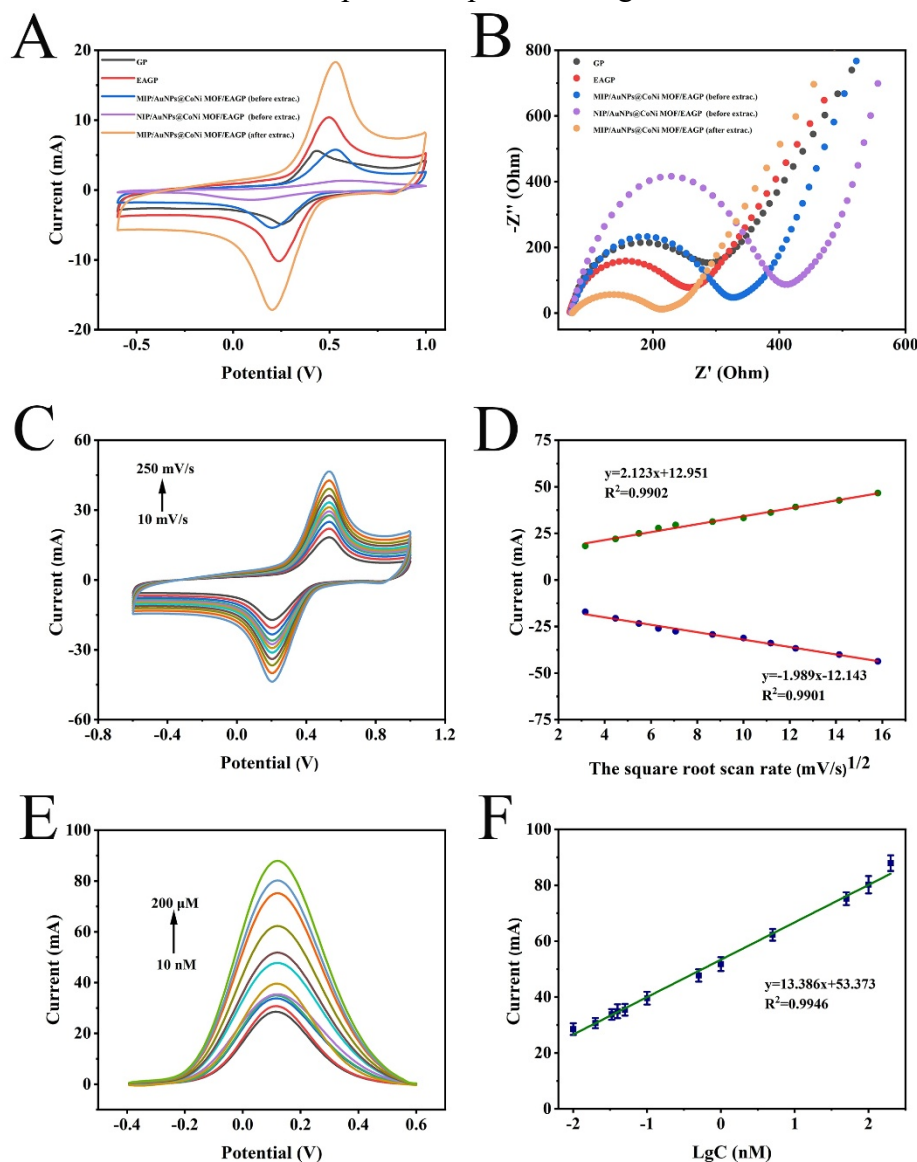


Figure 4. (A) CV and (B) EIS of GP, EAGP, MIP/AuNPs@CoNi MOF/EAGP (before extrac.), NIP/AuNPs@CoNi MOF/EAGP (before extrac.) and MIP/AuNPs@CoNi MOF/EAGP (after extrac.); (C) CV current response at different scanning rates; (D) Linear relationship between redox peak current and square root of the scanning rate; (E) DPV of caffeine from 10 nM to 200 μM at MIP/AuNPs@CoNi MOF/EAGP and (F) Linear calibration graph for MIP/AuNPs@CoNi MOF/EAGP.

EIS data (Fig. 4B) corroborate these observations: the pristine GP exhibits the largest charge-transfer resistance (R_{ct}), indicative of substantial impediment to electron transfer; EAGP shows a markedly reduced R_{ct} , consistent with the CV results indicating enhanced conductivity. Subsequent modification with the integrated MIP/AuNPs@CoNi MOF composite led to a further decrease in the R_{ct} of MIP/AuNPs@CoNi MOF/EAGP, with the lowest R_{ct} observed after template extraction. The R_{ct} of NIP/AuNPs@CoNi MOF/EAGP was notably higher than that of the MIP-modified electrode. This

difference arises because the imprinted cavities in MIP provide unobstructed pathways for electron transfer, while the non-imprinted NIP structure lacks such specific channels, resulting in greater interfacial resistance.

Furthermore, the sensor's electrochemical kinetics and sensing behavior were systematically characterized. CV responses of the composite were recorded at scan rates ranging from 10 to 250 mV/s (Fig. 4C). As shown in Fig. 4C, increasing the scan rate produces concomitant increases in the redox peak currents and causes the electrode peak potentials to shift away from the equilibrium potential owing to alterations in surface concentration, indicating that the electrochemical reaction at the MIP/AuNPs@CoNi MOF/EAGP interface is quasi-reversible. When the peak currents were plotted against the square root of the scan rate (Fig. 4D), both the oxidation and reduction peaks exhibited strong linear correlations, where x denotes the square root of the scan rate (oxidation: $y=2.123x+12.951$, $R^2=0.9902$; reduction: $y=-1.989x-12.143$, $R^2=0.9901$). These findings indicate that the surface redox process on MIP/AuNPs@CoNi MOF/EAGP is diffusion-controlled.

The superior electrochemical performance of the sensing interface can be attributed to the multilayer synergistic enhancement mechanism among EAGP, AuNPs@CoNi MOF, and bifunctional monomer MIP. First, EAGP provides a highly porous, structurally stable, and conductive substrate with abundant active sites and enlarged surface area, enabling efficient immobilization of the composite material and accelerating basal electron transfer. Second, AuNPs@CoNi MOF acts as a dual-functional signal amplifier: the CoNi MOF offers high porosity and large specific surface area for target enrichment, while AuNPs significantly improve electrical conductivity and accelerate electron migration across the interface. Third, the bifunctional monomer MIP provides highly specific and high-affinity recognition sites via synergistic hydrogen bonding, π - π stacking, and electrostatic interactions, ensuring selective capture of caffeine. Together, the three components produce a sequential, cooperative enhancement effect: EAGP stabilizes the interface, AuNPs@CoNi MOF amplifies the signal, and bifunctional MIP guarantees specific recognition. This synergistic mechanism greatly improves sensitivity, response speed, and selectivity of the sensor.

In addition, the redox peak potential (E_p) and the natural logarithm of the scan rate ($\ln v$) exhibited a good linear relationship (Fig. S4), which can be expressed by the equations: $E_{pa}=0.0026\ln v+0.5148$ ($R^2=0.9913$) and $E_{pc}=0.0033\ln v+0.1940$ ($R^2=0.9901$), respectively. According to the Ravillon equation, the slopes of the E_{pa} and E_{pc} plots correspond to $2.3RT/n(1-\alpha)F$ and $2.3RT/n\alpha F$, respectively. Based on this, the electron transfer coefficient (α) was calculated to be 0.51, and the electron transfer number (n) was determined to be 1. Combined with the pH-dependent electrochemical results, the redox reaction at the sensor interface is confirmed to be a one-electron, one-proton transfer process.

3.5 Optimization of experimental parameters for the MIP/AuNPs@CoNi MOF/EAGP

To achieve an optimal and stable signal response of the MIP/AuNPs@CoNi MOF/EAGP sensor, key parameters were systematically optimized and classified into two categories: parameters for imprint layer formation (molar ratio of caffeine and monomer, polymerization pH, washed time, adsorbed time) and

electrochemical testing parameter (scan rate). All experiments were performed in three independent replicates, with error bars and relative standard deviation (RSD) calculated to ensure reliability and reproducibility.

Molar ratio of caffeine to dual monomers (Fig. 5A): The molar ratio of template to functional monomers directly determines the formation efficiency and uniformity of imprinted cavities. With increasing molar ratio, the peak current difference (ΔI_p) increased gradually and reached the maximum at the ratio of 1:4:5 (caffeine : 3-thiopheneacetic acid : o-phenylenediamine). Excessively high template content leads to incomplete removal and cavity blockage, while insufficient template reduces the number of effective recognition sites. **Scan rate (Fig. 5B):** As an electrochemical testing parameter, scan rate affects the peak current intensity and signal stability. ΔI_p reached the maximum at 50 mV/s, which balances sufficient mass transport and clear signal output without obvious peak distortion. **Polymerization pH (Fig. 5C):** pH affects the interaction between caffeine and dual functional monomers as well as the polymerization efficiency. ΔI_p reached the maximum at pH 7.4, which maintains stable hydrogen bonding and electrostatic interactions during pre-assembly and ensures intact imprinted cavity structure. **Elution time (Fig. 5D):** Adequate elution removes template molecules while preserving cavity integrity. ΔI_p reached the maximum at 40 min, indicating complete template removal. Over-elution may damage the imprinted structure and reduce recognition ability. **Adsorption time (Fig. 5E):** Sufficient time is required for caffeine to rebind with imprinted cavities. ΔI_p reached the maximum at 25 min, indicating rapid and sufficient recognition. Prolonged time may cause slight matrix swelling and reduced response. Statistical analysis shows that all optimal conditions exhibit high reproducibility with RSD < 5%, confirming the reliability of the selected parameters.

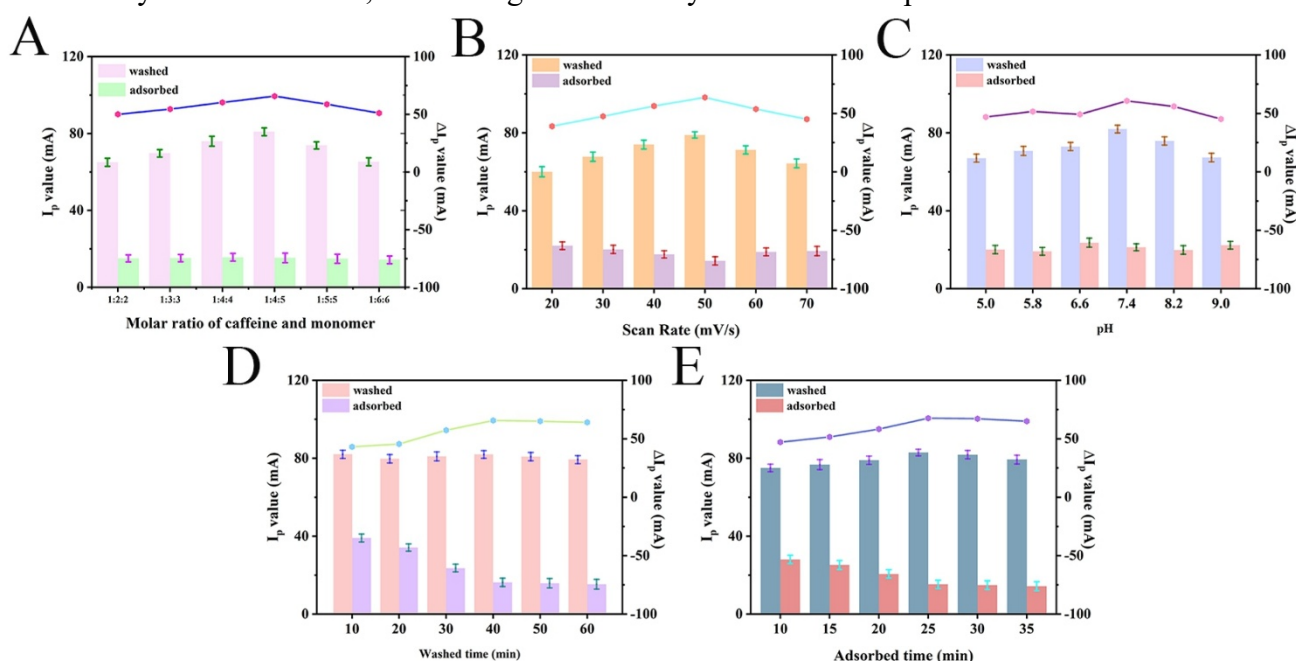


Figure 5. Effect of (A) molar ratio of caffeine: 3-thiopheneacetic acid: o-phenylenediamine; (B) scan rates; (C) pH value of electropolymerization and adsorption solution; (D) washed time and (E) adsorbed time on the ΔI_p adsorbing 100 μ M caffeine in PBS solution.

3.6 Detection performance of MIP/AuNPs@CoNi MOF/EAGP

Under optimized conditions, the analytical performance of the MIP/AuNPs@CoNi MOF/EAGP sensor was assessed using caffeine standard solutions spanning 10 nM to 200 μ M. Fig. 4E displays

DPV current responses at varying caffeine concentrations; the current increases progressively with concentration, indicating a concentration-dependent sensor response. Fig. 4F shows the fitted calibration plot of current versus the logarithmic concentration of caffeine (LgC), which exhibits an excellent linear correlation ($y=13.386x+53.73$, $R^2=0.9946$), indicating a stable quantitative response across the examined concentration range. Using a signal-to-noise criterion of $S/N=3$, the limit of detection (LOD) for caffeine was determined to be 1.5 nM. To further demonstrate the sensor's performance advantage, its key analytical parameters were compared with reported electrochemical caffeine detection methods (Table S4). The results indicate that the present sensor exhibits marked superiority, offering both a wider linear range and a lower LOD relative to the reported methods. Moreover, the highly crosslinked MIP network facilitates rapid adsorption and desorption of caffeine molecules, conferring sensitivity that substantially exceeds that of existing molecularly imprinted electrochemical approaches. Notably, compared with previously reported MOF–MIP electrochemical sensors (Jiang, Wang, Xu, Mao, Xu, & Wang, 2026; Suo et al., 2026), the proposed sensor further integrates synergistic signal amplification from AuNPs@CoNi MOF and a uniquely designed bifunctional monomer recognition system, rather than only improving porosity or conductivity alone. By systematically optimizing the recognition unit via DFT screening, the sensor achieves more efficient target binding and stronger specificity, which collectively enhances its overall analytical performance beyond conventional MOF–MIP platforms.

In summary, the MIP/AuNPs@CoNi MOF/EAGP sensor integrates the interfacial support of the EAGP substrate, the electrochemical activity of AuNPs@CoNi MOF, and the specific recognition properties of the MIP, resulting in a high-performance electrochemical sensing platform characterized by elevated sensitivity, an expanded linear range, and rapid response, and demonstrating strong potential for quantitative caffeine determination.

3.7 The specificity, stability, repeatability, and applicability of MIP/AuNPs@CoNi MOF/EAGP

To assess the selectivity of the MIP/AuNPs@CoNi MOF/EAGP sensor toward the target analyte caffeine, several structurally related compounds (theobromine, adenine, glutamine, theophylline, and purine) were examined. Under identical concentration conditions, the current-response profiles of MIP/AuNPs@CoNi MOF/EAGP were compared with those of a non-imprinted polymer-modified electrode (NIP/AuNPs@CoNi MOF/EAGP); the results are presented in Fig. S5. The MIP/AuNPs@CoNi MOF/EAGP exhibited a substantially higher current response for caffeine than for the other structural analogues. By contrast, the NIP/AuNPs@CoNi MOF/EAGP produced uniformly low current responses for caffeine and the analogues, with no significant differences among the analytes. These observations indicate that the template-derived imprinted cavities in the MIP, templated with caffeine, afford selective recognition of the target molecule, whereas the NIP, which lacks complementary recognition sites, cannot discriminate caffeine from structurally similar compounds. Specificity was further quantified by calculating the imprinting factor $IF=I_{MIP}/I_{NIP}$, where I_{MIP} and I_{NIP} denote the current responses of the MIP- and NIP-modified electrodes, respectively. As shown

in the curves in Fig. S5, the imprinting factor for caffeine is markedly higher than those for the other analogues, thereby corroborating the high specificity of MIP/AuNPs@CoNi MOF/EAGP for caffeine and its capacity to minimize interference from structurally related species.

Stability and reproducibility are essential metrics for assessing the analytical performance of electrochemical sensors. We evaluated the long-term stability of the MIP/AuNPs@CoNi MOF/EAGP sensor by storing it at 4 °C and recording its current response to caffeine at concentrations of 10^{-2} , 10^{-1} , and 10^1 μ M every 3 days over a 27-day interval. The results (Fig. S6A) indicate that after 27 days of storage the sensor's current responses remained at a high fraction of their initial values, demonstrating excellent long-term storage stability of the MIP/AuNPs@CoNi MOF/EAGP sensor. Reproducibility was assessed using six independently prepared sensors tested in caffeine solutions at the same concentrations (10^{-2} , 10^{-1} , and 10^1 μ M). The six sensors exhibited relative standard deviation (RSD) below 2.56% (Fig. S6B), indicating a highly reproducible fabrication process.

To evaluate the applicability of MIP/AuNPs@CoNi MOF/EAGP in real samples, beverage matrices (red bull, tea, and cola) were employed in spike-and-recovery experiments. Caffeine standard solutions at three levels (1, 5, and 10 μ M) were spiked into the different beverage samples, which were then pretreated and analyzed with the sensor. Recoveries ranged from 96.9% to 104.3% with RSD of 2.1%–4.3%. Results were validated by HPLC–MS, and good agreement was observed between the two methods.

Overall, these findings demonstrate that the MIP/AuNPs@CoNi MOF/EAGP sensor can accurately and reliably detect caffeine in complex, real-world matrices, offering a straightforward and efficient electrochemical approach for rapid quantitative analysis of caffeine in food and beverages. As a disposable, single-use electrochemical platform, it ensures high accuracy and reliability by employing a fresh electrode for each test, thus avoiding potential interference caused by repeated regeneration. Although the electrode can be regenerated through simple washing, single-use operation is still recommended for rapid, on-site, and high-precision screening in practical applications.

4. Conclusions

In this study, we developed a high-performance electrochemical sensor for accurate caffeine quantification by integrating an EAGP substrate, a AuNPs@CoNi MOF synergistic composite, and a bifunctional-monomer molecularly imprinted recognition system. DFT screening identified the bifunctional monomer pair 3-thiopheneacetic acid and *o*-phenylenediamine, which form ternary complexes with caffeine exhibiting binding energies down to -20.65 kcal/mol. Via synergistic hydrogen bonding, π – π stacking, and electrostatic interactions, these monomers establish high-affinity recognition sites. Furthermore, by exploiting the covalent-bonding afforded by click chemistry, we addressed common limitations of conventional modification methods—namely weak adhesion and heterogeneous functional-layer distribution—thereby establishing a robust covalent linkage between MIP/AuNPs@CoNi MOF and the EAGP. Experimental evaluation demonstrated that the sensor exhibits superior analytical performance, featuring a linear detection

range of 10 nM to 200 μ M and a limit of detection of 1.5 nM. It also showed robust long-term stability (stable response over 27 days), high reproducibility (RSD < 2.56%), and effective anti-interference capacity. Spike-recovery assays on real beverage samples yielded recoveries of 96.9%–104.3%, which are in strong agreement with HPLC–MS results. Importantly, relative to conventional detection techniques and MIP sensors employing single functional monomers, the present sensor attains concurrent enhancements in sensitivity, specificity, and practicality via a multi-component synergistic mechanism. The electrode substrate is inexpensive and straightforward to fabricate, rendering the system amenable to on-site deployment. It shows great application prospects in the field of on-site food safety detection, enabling rapid, real-time, and portable monitoring of target analytes in complex food matrices. Moreover, the modular design enables facile extension of the platform: by selecting appropriate MIP templates and functional-monomer combinations, analytical strategies for other food contaminants can be rapidly developed, underscoring broad applicability in food-safety monitoring.

Acknowledgements

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