Iranian Journal of Analytical Chemistry
Volume 11, Issue 2, September 2024 (163-172) Original Research Article

مجله ایرانی شیمی تجزیه
دوره ۱۱، شماره ۲، مهرماه (۱۷۲-۱۶۳)

Molecularly Imprinted Polymer-Based Electrochemical Sensor for the Specific Sorption and Detection of Folic Acid in Biological Matrices and Food Samples

Majid Arvand*[,1], Akram Pourhabib[2], Bahar Arvand[3]
1. Electroanalytical Chemistry Laboratory, Faculty of Chemistry, University of Guilan, Namjoo Street, P.O. Box: 1914–41335, Rasht, Iran
2. Education Organization of Guilan Province, Farhang Square, P.O. Box: 41849-83111, Rasht, Iran
3. School of Medicine, Guilan University of Medical Sciences, Rasht, Iran

Received: 25 June 2024 **Accepted:** 28 August 2024
DOI: 10.30473/IJAC.2025.74192.1317

Abstract
This study presents an innovative biomimetic sensor leveraging molecularly imprinted polymers (MIPs) for folic acid detection, combining advanced materials and electrochemical design for enhanced performance. The sensor employs methacrylic acid monomers polymerized onto a polymeric surface, integrated with graphite powder and paraffin oil to form a robust carbon paste electrode. Key strengths include its Nernstian response (19.2 mV decade^{-1}) across a wide concentration range (5×10^{-9} to 1×10^{-3} mol L^{-1}) and an impressively low detection limit of 1×10^{-9} mol L^{-1}, surpassing many conventional methods. The design eliminates the need for additional reagents or complex instrumentation, prioritizing cost-effectiveness and simplicity. Novel aspects lie in the MIP-graphite-paraffin oil composite, which enhances stability and selectivity while enabling rapid sensor regeneration through surface polishing. The sensor demonstrates remarkable long-term stability and reproducibility, critical for real-world applications in pharmaceutical samples. Its ability to discern folic acid from interferents, validated in diverse matrices, underscores its practicality for clinical diagnostics and food quality control. By merging MIP specificity with electrochemical transduction, this work advances portable, high-sensitivity sensing platforms for routine analysis.

Keywords
Folic Acid; Molecularly Imprinted Polymer; Electrochemistry; Potentiometric Transduction; Tablet; Serum.

1. INTRODUCTION

Folic acid, known by various names such as folate, vitamin M, vitamin B9, and vitamin Bc, is a water-soluble form of vitamin B9. Although folic acid itself lacks biological activity, its significance lies in its conversion to dihydrofolic acid in the liver, leading to the production of tetrahydrofolate and other derivatives. Vitamin B9 (comprising folic acid and folate) plays a vital role in numerous physiological processes [1]. It is essential for DNA synthesis, DNA repair, DNA methylation, and acts as a cofactor in various biological reactions. Particularly, folic acid is crucial for facilitating rapid cell division and growth during infancy and pregnancy. Both children and adults require folic acid for the production of healthy red blood cells and the prevention of anemia [2]. Several analytical techniques, such as HPLC [3], HPLC-MS/MS [4], thermogravimetry [5], spectrophotometry [6], colorimetry [7-8], fluorescence [9], and electrophoresis [10] have been commonly employed for the quantification of folic acid. However, these methods often suffer from high costs and time-consuming processes due to lengthy extraction and purification steps [11].

Molecularly imprinted polymers (MIPs) have been extensively investigated as recognition elements in sensor development, as reviewed in multiple articles. Various transducers, including electrochemical, optical, mass-sensitive, thermometric, and magnetometric systems, have been designed to integrate with MIP thin films or micro/nanoparticles [12–15]. The preparation of MIPs involves polymerizing functional monomers in the presence of template molecules and initiators. Subsequently, the template molecules are extracted, resulting in the creation of binding sites with specific molecular memory capable of recognizing the imprinted molecules [16]. These accessible binding sites possess complementary shape and functional group characteristics to the original template molecule within the polymeric

* Corresponding author:
M. Arvand; E-mail: arvand@guilan.ac.ir

network [15]. Among the available methods for MIP preparation, the non-covalent approach, which relies solely on non-covalent interactions between the template and functional monomers, offers broad applicability due to the absence of restrictions on the size, shape, or chemical nature of the imprinted molecule. The cost-effective production of highly selective artificial receptors with favorable mechanical, thermal, and chemical properties makes MIPs highly desirable as chemoreceptors [17–19]. MIPs possess several advantages over natural receptors, including stability under extreme pH and temperature conditions, biological stability, low cost, and reusability. Consequently, MIPs have found diverse applications in chromatography [20], artificial antibodies [21], solid-phase extraction [22], and electrochemical sensors [23–27].

Compared to recently reported non-electrochemical techniques for the determination of organic and pharmaceutical compounds [28–30], electrochemical methods have attracted significant attention in analytical applications owing to their cost-effectiveness, high sensitivity, and operational simplicity [31–36]. In this context, potentiometric sensors offer selectivity and portability, making them promising analytical tools for point-of-care applications. This inherent method is characterized by its simplicity, precision, accuracy, and cost-effectiveness, with minimal reagent consumption. It can be applied to turbid, viscous, and colored solutions, and does not require washing steps before signal detection. Additionally, analytes can be captured from complex mixtures without prior purification [37]. From an environmental standpoint, potentiometric sensors are considered green analytical approaches as they eliminate the need for organic solvents and generate negligible volumes of wastewater with minimal environmental impact in terms of composition and volume [38].

Carbon paste electrodes (CPEs) are widely employed conductive matrices for the fabrication of chemically modified electrodes (CMEs) by simply mixing graphite/binder paste with the desired modifier. CPEs offer advantages such as low background current, ease of fabrication, and rapid renewal at a low cost [39].

This study presents the development of a potentiometric sensor based on a carbon paste electrode incorporating MIPs. The proposed scheme enables sensitive, simple, and cost-effective detection of the analyte-receptor binding event without requiring additional reagents or instruments. The sensor is synthesized using methacrylic acid (MAA) as the functional monomer, cross-linked with ethylene glycol dimethacrylic acid (EGDMA) in the presence of the template molecule. The sensing material is then combined with graphite powder and paraffin oil. The resulting sensor demonstrates successful determination of folic acid in biological matrices and food samples.

2. EXPERIMENTAL

2.1. Materials and methods

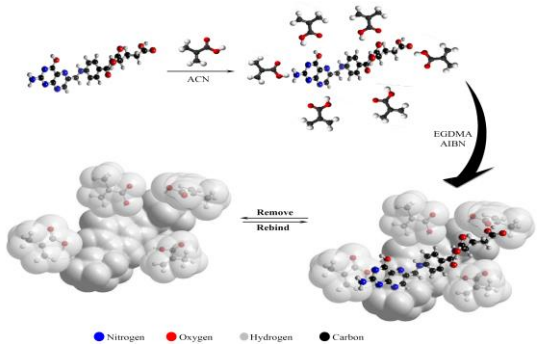
Deionized (DI) water with a conductivity of less than 10 μS cm^{-1} was utilized throughout the experiments. All chemicals employed were of analytical grade and used without further purification. Folic acid was obtained from Sobhan Pharmacy Company (Rasht, Iran) and utilized as received. Methacrylic acid, acetonitrile (ACN), methanol, acetone, acetic acid, sodium hydroxide (NaOH), hydrochloric acid (HCl), and nitrate salts of all cations employed were sourced from Merck (Darmstadt, Germany). Ethylene glycol dimethacrylic acid was obtained from Fluka (Buchs, Switzerland), while 2,2'-azobisisobutyronitrile (AIBN) was sourced from Aldrich (Milwaukee, WI, USA). All other chemicals utilized were of analytical reagent grade. A 1×10^{-2} mol L^{-1} stock solution of folic acid was prepared by accurately weighing 44.1 mg of the yellow standard powder, dissolving it in a beaker of 5.0 mL of DI water, and using the necessary volume of sodium hydroxide (conc.) to adjust the pH in between 7.0 to 8.0. After the powder was dissolved completely, the solution was quantitatively transferred into a 10 mL amber volumetric flask and stored at 4 ºC away from light. Dilutions of the stock solution to obtain less concentrated standards were prepared by appropriate dilution with water.

2.2. MIP and NIP preparation with precipitation polymerization

The process of imprinting and subsequent removal of folic acid from the imprinted polymer is depicted in Scheme 1. The molecularly imprinted polymer for folic acid was prepared by combining 78.0 μL (0.915 mmol) of MAA, 721.5 μL (3.82 mmol) of EGDMA, 88 mg (0.198 mmol) of folic acid, and 14.5 mg (0.088 mmol) of AIBN in 10 mL of ACN. The mixture was homogeneously dispersed using ultrasonic bath sonication (Ultrasonic UTD35-Falc, Via Piemonte, Italy). Following sonication, the mixture was purged with nitrogen gas for 10 minutes, and the glass tube was sealed under this nitrogen atmosphere. The sealed tube was then placed in a water bath maintained at 60 °C for 20 hours [23]. Subsequently, the obtained polymer was ground, sieved, and the particles were collected. Prior to template removal, the particles were washed with NaOH. The template was extracted by sequentially washing the MIP particles three times in 15 mL of a methanol/acetic acid solution (10:1, v/v; composed of 98%

DOI: 10.30473/IJAC.2025.74192.1317

methanol and pure acetic acid) for 1 hour each time, followed by two washes in 15 mL of pure water for 1 hour each. The resulting MIP particles were then dried until a constant weight was achieved. The template removal process created cavities within the polymer, enabling specific sorption of the template molecule. Additionally, the removal of residual monomers, oligomers, and initiator fragments from the polymer occurred. Non-imprinted polymers (NIPs) were also synthesized using the same procedure, with the exclusion of the template folic acid from the formulation.



Scheme 1. Schematic representation of the MIP synthesis.

2.3. Preparation of the MIP carbon paste electrode

A chemically modified carbon paste electrode was prepared by thoroughly blending 20 mg of the molecularly imprinted polymer, 50 mg of high-purity graphite, and paraffin oil in a plastic Petri dish. The blending process continued until a uniformly moist paste was achieved, which was then utilized for the construction of the sensor. To ensure optimal electrode performance, the prepared paste was carefully packed into the tip of a Teflon tube, taking care to eliminate any potential air gaps that could contribute to increased electrode resistance. In order to establish electrical contact, the tip of a pencil was inserted into the opposite end of the tube. The external surface of the electrode was smoothed using gentle paper abrasion. To obtain a fresh electrode surface, the electrode was polished by rubbing it against a smooth sheet of paper.

2.4. Potentiometric measurements

All potentiometric measurements were performed using a digital multimeter (DT 9208 A) at ambient temperature. The electrochemical cell configuration employed for the measurements was as follows: Hg/Hg_2Cl_2; KCl (sat'd) || sample solution | carbon paste electrode. To prepare the modified electrode surface, it was initially conditioned by immersing it in a 1.0×10^{-3} mol L^{-1} folic acid solution at a pH of 3.0 for a duration of 12 hours. Subsequently, the electrode was rinsed with DI water for 30 seconds. The electromotive force (emf) values of each electrode were then measured in solutions with a fixed pH. Increasing concentrations of folic acid were obtained by introducing aliquots of a 1.0×10^{-2} mol L^{-1} standard folic acid solution. The potential readings were recorded once the emf had stabilized within ±0.2 mV, and the resulting emf values were plotted against the logarithm of the folic acid concentration. Calibration plots derived from these measurements were subsequently utilized to determine unknown concentrations of folic acid.

2.5. Infrared spectroscopy

The infrared spectra for the materials were recorded on a Thermo-Nicolet Nexus 870 FT–IR spectrometer using KBr disk in the range 4000–500 cm^{-1}. The number of scans was 32 for both sample and background. The resolution was set to 4 cm^{-1}.

2.6. Thermogravimetric analysis

Thermogravimetric analysis (TGA) serves as a valuable technique for assessing the thermal stability of materials. By subjecting a substance to a defined temperature range, one can observe any changes in mass. In the case of a thermally stable species, no significant mass loss is expected, resulting in a TGA trace with a negligible slope. Additionally, TGA provides insight into the upper temperature limit at which a material can be effectively utilized, as degradation processes commence beyond this threshold.

In this study, TGA was conducted on MIPs, specifically on unwashed MIP particles, followed by MIP particles subjected to a washing step, and ultimately on non-imprinted polymer (NIP) particles. Each particle sample, weighing approximately 2–3 mg, was subjected to a controlled temperature ramp of 20 °C min^{-1}, ranging from 35 to 600 °C, under a continuous flow of nitrogen gas at a rate of 70 mL min^{-1}. The TGA measurements were performed using a Shimadzu TGA-50H thermal analyzer.

2.7. Sample preparation

2.7.1. Preparation of tablets for assay

Ten tablets were meticulously weighed and subsequently crushed before being thoroughly mixed using a mortar and pestle for a duration of 15 minutes. An accurately measured portion of the resulting powder, equivalent to achieving a concentration of 10^{-4} mol L^{-1}, was carefully weighed. Then, 25 mL of a 0.1 mol L^{-1} NaOH solution and an appropriate volume of water were added to the powder. The mixture was subjected to ultrasonic treatment for 10 minutes and subsequently filtered through a 0.45 µm Millipore filter (Gelman Sciences, Rossdorf, Germany). The initial portion of the filtrate was discarded, and the

DOI: 10.30473/IJAC.2025.74192.1317

remaining solution was transferred to a 50 mL volumetric flask and diluted to the mark with water.

2.7.2. Preparation of apple juice

A sample of apple weighing 7.831 g was carefully weighed and then ground into a fine powder. Subsequently, approximately 5 mL of distilled water and 1 mol L^{-1} NaOH were added to the powdered apple, resulting in the formation of a homogeneous mixture. The mixture was then subjected to ultrasonic treatment for a duration of 10 minutes, followed by filtration through Whatman filter paper to obtain a clarified solution.

2.7.3. Preparation of serum sample

Drug-free human serum was acquired from the Iranian Blood Transfusion Service located in Rasht, Iran. Prior to treatment, the serum sample was thawed to achieve ambient temperature, approximately 25 °C. Varying volumes of a folic acid standard solution were added to 20 mL of the serum sample. The emf generated by each solution was measured using the suggested electrode. Subsequently, the concentration of folic acid was determined by applying the corresponding regression equation at pH 3.0.

3. RESULTS AND DISCUSSION

3.1. FT–IR study

The infrared spectra of NIP, both the unleached and leached MIPs, exhibited similar characteristic peaks, indicating a resemblance in the backbone structure of the various polymers (Fig. 1). The presence of hydrogen bonding with the -COOH group of methacrylic acid was observed, resulting in the identification of O-H stretching and bending vibrations at 3350 cm^{-1} and approximately 1508 cm^{-1}, respectively. In the IR spectrum of folic acid, the bands observed at around 1495 cm^{-1} were attributed to the C=C stretching vibrations of the aromatic ring of folic acid, while the band at 3180 cm^{-1} corresponded to the N-H stretching vibration. Notably, two distinct differences were observed between the IR spectra of the leached and unleached MIPs. In the leached polymer, a band was observed around 3010 cm^{-1}, and another band was observed around 1198 cm^{-1}. However, in the spectrum of the unleached polymer, these bands were shifted, and corresponding peaks were observed at approximately 2890 cm^{-1} and 1110 cm^{-1}, respectively. The presence of folic acid contamination in the unleached MIP sensors is evident in Fig. 1, where the bands assigned to folic acid can be observed. Notably, these peaks are absent in the leached MIP spectrum. These differences provide evidence that the imprint molecule (folic acid) has been effectively leached from the MIP during the solvent extraction step.

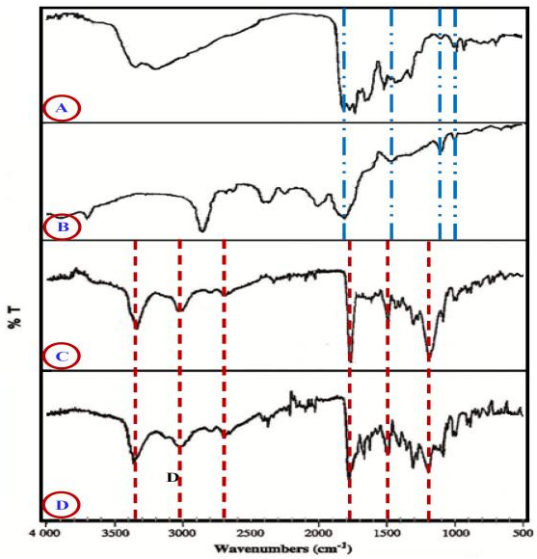


Fig. 1. FT–IR spectra of folic acid (A), unleached MIP (B), leached MIP (C) and NIP polymers (D) (average of 32 scans from 4000 to 500 cm^{-1}, with background correction, and room temperature/humidity control).

3.2. TG characteristics of MIP

Thermogravimetric analysis was employed to investigate the thermal stability of the synthesized polymers and to assess the impact of imprinting on their stability. The weight loss profiles of both leached and unleached MIP particles, along with the corresponding non-imprinted polymer, were monitored up to a temperature of 600 °C. It was observed that all materials underwent complete decomposition prior to reaching 550 °C (Fig. 2).

Upon analyzing the TGA results for the unleached MIP particles, two distinct decomposition stages were identified. The initial mass loss, occurring between 80 and 150 °C, was attributed to the decomposition of the unreacted monomer and the cross-linker. Subsequently, a second decomposition stage commenced at approximately 230 °C, which was linked to the degradation of folic acid. This observation aligns with the known melting point of folic acid, estimated to be around 250 °C.

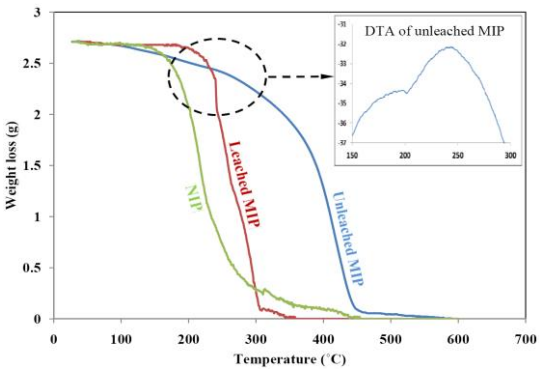


Fig. 2. TGA plots of the NIP, unleached and leached MIP particles. Inset: DTA plot of unleached MIP particles.

DOI: 10.30473/IJAC.2025.74192.1317

Table 1. Optimization of carbon paste ingredients for the folic acid sensor based on MIP.

ISE	Graphite (%w/w)	MIP (%w/w)	Slope (mV decade^{-1})	Linear range (mol L^{-1})	Detection limit (mol L^{-1})
CPE_1	69.9	5.4	13.7	2×10^{-7}– 1×10^{-3}	8×10^{-8}
CPE_3	64.5	10.8	17.9	1×10^{-8}– 1×10^{-4}	7×10^{-9}
CPE_2	59.1	16.1	23.3	8×10^{-7}– 2×10^{-4}	2×10^{-7}
CPE_4	53.8	21.5	19.2	5×10^{-9}– 1×10^{-3}	1×10^{-9}
CPE_5	48.4	26.9	15.5	2×10^{-8}– 5×10^{-4}	1×10^{-8}
CPE_6	43.0	32.2	14.9	2×10^{-8}– 5×10^{-4}	1×10^{-8}

3.3. Effect of MIP particles to carbon paste ratio

The ratio of MIP particles to graphite was identified as a critical factor influencing the performance of the sensor, as it directly impacts the number of available binding sites for the selective rebinding of folic acid. The findings presented in Table 1 clearly demonstrate that the carbon paste electrode (CPE_4) with an optimal weight ratio of MIP particles to graphite exhibited the most favorable performance characteristics (Fig. 3).

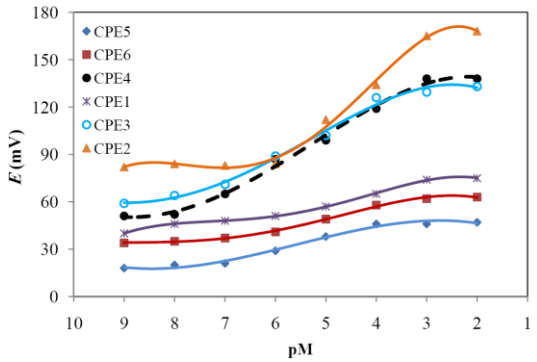


Fig. 3. Optimization of paste ingredients for the folic acid sensor based on MIP to graphite weight ratio: (CPE_1) 7.69%, (CPE_2) 16.7%, (CPE_3) 27.3%, (CPE_4) 40%, (CPE_5) 55.6%, and (CPE_6) 75%.

3.4. Effect of temperature

The influence of temperature on the performance of the MIP-based folic acid electrode was investigated by examining changes in electrode behavior at various test solution temperatures: 5, 15, 20, and 35 °C. Standard cell potentials (E^o_{cell}) were determined at each temperature by extrapolating the calibration plots to the point where the folic acid concentration (p[folic acid]) reached zero. These E^o_{cell} values were then utilized, along with eq. 1, to calculate the isothermal temperature coefficient $(dE^o/dt)_{cell}$ of the cell [40]:

$$E^o_{cell} = E^o_{cell(25\ °C)} + (dE^o/dt)_{cell}(t - 25) \quad (1)$$

Plotting E^o_{cell} against (t–25) yielded a linear relationship, with the slope of the line representing the isothermal temperature coefficient of the cell. In this study, the obtained value was determined to be -1.23 mV °C^{-1}. The standard potentials of the reference electrode (Hg/Hg_2Cl_2; KCl (sat'd)) were determined using eq. 2:

$$E^o_{Hg/Hg2Cl2} = 0.241 - 0.00066(t - 25) \quad (2)$$

To calculate the standard potentials of the MIP-based folic acid electrode at different temperatures, eq. 3 was employed:

$$E^o_{reference} + E^o_{cell} = E^o_{electrode} \quad (3)$$

Plotting $E^o_{electrode}$ against (t–25) resulted in a linear relationship, and the slope of the line represented the isothermal temperature coefficient of the MIP-based folic acid electrode. The calculated coefficient was found to be -1.02 mV °C^{-1}. The relatively small values of $(dE^o/dt)_{cell}$ and $(dE^o/dt)_{electrode}$ indicate the high thermal stability of the electrode within the investigated temperature range.

3.5. Effect of pH

The potentiometric response of the folic acid sensor is influenced by the degree and nature of folic acid ionization, which is dependent on the pH of the solution. Folic acid possesses three ionizable functional groups: NH_2 (pK_1=4.65), NH (sulfonamide) (pK_2=6.75), and (pK_3=9) at 25 °C. Accordingly, folic acid can exist in three different forms: cationic, neutral non-ionized, and anionic, depending on the pH of the environment.

To investigate the impact of pH on the potentiometric response, emf measurements were conducted on folic acid solutions ranging from 1×10^{-2} to 1×10^{-9} mol L^{-1}, with pH values varying from 2.0 to 9.0. The desired pH levels were achieved by making small additions of saturated NaOH or concentrated HCl solutions. The overall behavior of the sensor's response is depicted in Fig. 4. The observed changes in slope at higher pH values (pH > 3) can be attributed to the formation of non-protonated folic acid species. Notably, the MIP-based electrode exhibited the most favorable analytical performance at pH 3.0. It displayed higher slopes, near-Nernstian behavior, and lower detection limits, with an average slope of approximately 19.2 mV decade^{-1}. Consequently, a pH of 3.0, stabilized with citrate-buffered solution, was selected as the optimal condition for further

DOI: 10.30473/IJAC.2025.74192.1317

folic acid determination using the proposed electrode.

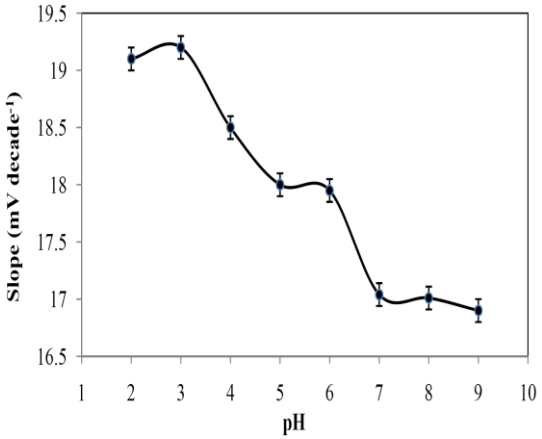


Fig. 4. The effect of pH on the potentiometric response of MIP-based carbon paste sensor.

3.6. Response time and lifetime

The response time of an electrode is defined as the average duration required for the electrode potential to reach a response within ±1 mV of the final equilibrium value. In this study, the response time was determined to be 25 seconds. This finding suggests that the complexation process between the analyte and the MIP was kinetically rapid. It indicates that the overall free energy barrier for the transition from the free to the complexed states was sufficiently small to facilitate swift complexation.

Repeated calibrations conducted for each sensor demonstrated several desirable characteristics. These included low potential drift, long-term stability, and negligible changes in the sensor's response. The sensors were stored and conditioned in a 1×10^{-2} mol L^{-1} folic acid solution with a pH of 3. Notably, the detection limit, response time, linear range, and calibration slope exhibited reproducibility within ±3% of their original values over a period of at least 4 months. These results underscore the robustness and reliability of the sensors, highlighting their suitability for practical applications in folic acid detection and analysis.

3.7. Sensor selectivity

The selectivity behavior of ion-selective electrodes is determined by the ion exchange constants, which rely on the selectivity of complexation and the standard free energies of the respective ions in both the aqueous and organic phases [41]. To achieve selectivity, it is crucial to employ ligands that strongly bind to the desired species while exhibiting weak interactions with other species [42]. The selectivity mechanism primarily revolves around stereospecific and electrostatic factors. Potentiometric selectivity coefficients were evaluated using two methods: the separate solution method (SSM) and the matched potential method (MPM), with a fixed interference. The resulting selectivity coefficients were documented in Table 2 and calculated using the following equations:

$$K_{I,J}^{Pot} = a_I^{(1-(\frac{1}{Z_J}))} e^{(E_J - E_I)/S} \quad \text{(SSM)} \quad (4)$$

$$K_{I,J}^{Pot} = \frac{\Delta a_I}{a_J} \quad (\Delta a_I = a'_I - a_I) \quad \text{(MPM)} \quad (5)$$

In eq. 4, E_I represents the electrode potential in a 1.0×10^{-3} mol L^{-1} folic acid solution (a_I), E_J denotes the potential of the electrode immersed in a 1.0×10^{-3} mol L^{-1} concentration of the interfering species with a charge of Z, and S represents the practical slope obtained from calibration experiments. Equation 5 incorporates the initial (a'_I) and final (a_I) activities of the primary ion, as well as the activity of the interfering ion (a_J). In practice, a known quantity of primary ion (folic acid) is introduced into a reference solution, and the resulting potential is measured. These methods provide insights into the preferential interaction of folic acid with various organic and inorganic species commonly found in biological and food samples, such as substances present in plasma (e.g., glucose, KCl) and certain anticholinesterase drugs (e.g., gabapentin, sertraline hydrochloride, citalopram).

Table 2. Selectivity coefficients obtained for the MIP-based sensor.

Interferent	$-\log K_I^{MPM}$	$-\log K_I^{SSM}$
Cu^{2+}	3.6	3.5
Mg^{2+}	3.7	3.9
K^+	4.9	4.2
Al^{3+}	3.1	2.9
Pb^{2+}	3.6	3.2
Zn^{2+}	3.5	3.3
Glucose	4.2	5.0
Uric acid	3.5	4.4
Gabapentin	4.8	3.3
Citalopram	4.3	3.8
Serteraline	5.0	4.6
Ascorbic acid	4.2	4.1

3.8. Analytical applications

3.8.1. Analysis of folic acid tablets

The potentiometric procedure described in this study was effectively employed for the determination of folic acid in tablets. The obtained data, utilizing the calibration curve approach, were subjected to statistical comparison with the labeled amounts indicated on the tablets. The results of this comparison are presented in Table 3.

3.8.2. Analysis of apple juice

To assess the applicability of the proposed method to real samples, apple juice was selected as a representative matrix containing folic acid. Sample preparation was carried out following the procedure outlined in Section 2.7.2. A suitable volume of fruit juice (20 mL of apple juice) was

DOI: 10.30473/IJAC.2025.74192.1317

Table 3. Folic acid assay in biological matrices and food samples by means of the described potentiometric procedure.

Sample	Claimed value (mg/tablet)	Amount added (μg mL^{-1})	Found (μg mL^{-1})	Recovery (%)	Relative error (%)
Tablet	1	–	0.97 (mg)	–	-3
		1 (mg)	2.03 (mg)	101.5	1.5
		2 (mg)	2.91 (mg)	97	-3
Apple juice	–	–	167.2	–	–
		5	170.6	99.1	-0.9
		10	179.3	101.2	4.1
		15	185.9	102	2.0
Serum	–	–	3.7	–	–
		5	8.6	98.8	-1.1
		10	14.2	103.6	3.6
		15	19.3	103.2	3.2

introduced into an electrochemical cell and adjusted to pH 3. The recovery studies, which provide valuable insights into the accuracy of the method, are summarized in Table 3.

3.8.3. Folic acid assay in spiked blood serum

The proposed potentiometric procedure was successfully implemented for the determination of folic acid in spiked human serum. The recovery studies, which serve as indicators of the method's sensitivity and precision, are presented in Table 3. The obtained recoveries ranged from 98% to 102% for the spiked serum samples. Based on these results, it can be concluded that the suggested method exhibits both sensitivity and precision for the determination of folic acid in this biological matrix.

4. CONCLUSIONS

This study showcases the development of a molecularly imprinted polymer-based carbon paste electrode and its successful implementation for the determination of folic acid. The proposed method exhibited favorable characteristics including high sensitivity, excellent selectivity, and a broad linear range, enabling its application in the analysis of folic acid in pharmaceutical preparations and biological samples. Notably, the folic acid sensor demonstrated remarkable long-term stability, further enhancing its practical utility. The accuracy, reproducibility, simplicity, and selectivity exhibited by the recommended folic acid sensor highlight its potential for application in quality control analysis and clinical laboratories. The method's comprehensive performance attributes, along with its sensitivity to folic acid and ability to discern it from interfering species, make it a valuable tool in various analytical settings.

ACKNOWLEDGMENT

The authors are highly grateful to the post-graduate office of Guilan University for the support of this work.

REFERENCES

[1] Y. Shulpekova, V. Nechaev, S. Kardasheva, A. Sedova, A. Kurbatova, E. Bueverova, A. Kopylov, K. Malsagova, J. Dlamini, and V. Ivashkin, The concept of folic acid in health and disease, *Molecules* 26 (2021) 3731.

[2]D.F. Pereira, E.R. Santana, and A. Spinelli, Electrochemical paper-based analytical devices containing magnetite nanoparticles for the determination of vitamins B2 and B6, *Microchem. J.* 179 (2022) 107588.

[3]J. Jastrebova, C. Witthöft, A. Grahn, U. Svensson, and M. Jägerstad, HPLC determination of folates in raw and processed beetroots, *Food Chem*. 80 (2003) 579–588.

[4]D. Sun, Y. Jin, Q. Zhao, C. Tang, Y. Li, H. Wang, Y. Qin, and J. Zhang, Modified EMR-lipid method combined with HPLC-MS/MS to determine folates in egg yolks from laying hens supplemented with different amounts of folic acid, *Food Chem*. 337 (2021) 127767.

[5]A. Vora, A. Riga, D. Dollimore, and K.S. Alexander, Thermal stability of folic acid, *Thermochim. Acta* 392 (2002) 209–220.

[6]R. Matias, P.R.S. Ribeiro, M. Sarraguça, and J.A. Lopes, A UV spectrophotometric method for the determination of folic acid in pharmaceutical tablets and dissolution tests, *Anal. Methods* 6 (2014) 3065–3071.

[7]Z. Yang, F. Gong, Z. Yu, D. Shi, S. Liu, and M. Chen, Highly sensitive folic acid colorimetric sensor enabled by free-standing molecularly imprinted photonic hydrogels, *Polym. Bull*. 79 (2021) 1–15.

[8]Y. Peng, W. Dong, L. Wan, and X. Quan, Determination of folic acid via its quenching effect on the fluorescence of MoS_2 quantum dots, *Microchim. Acta* 186 (2019) 605.

[9]P. Anastasopoulos, T. Mellos, M. Spinou, T. Tsiaka, and M. Timotheou-Potamia, Chemiluminometric and fluorimetric determination of folic acid, *Anal. Lett*. 40 (2007) 2203–2216.

[10]S. Zhao, H. Yuan, C. Xie, and D. Xiao, Determination of folic acid by capillary

electrophoresis with chemiluminescence detection, *J. Chromatogr. A* 1107 (2006) 290–293.

[11]B. Batra, V. Narwal, V. Kalra, M. Sharma, and J. Rana, Folic acid biosensors: A review, *Process Biochem*. 92 (2020) 343–354.

[12].Y. Huang, T.C. Tsai, J.L. Thomas, M.H. Lee, B.D. Liu, and H.Y. Lin, Urinalysis with molecularly imprinted poly(ethylene-co-vinyl alcohol) potentiostat sensors, *Biosens. Bioelectron*. 24 (2009) 2611–2617.

[13]F.T.C. Moreira, A.H. Kamel, J.R.L. Guerreiro, and M.G.F. Sales, Man-tailored biomimetic sensor of molecularly imprinted materials for the potentiometric measurement of oxytetracycline, *Biosens. Bioelectron*. 26 (2010) 566–574.

[14]F.T.C. Moreira, R.A.F. Dutra, J.P.C. Noronha, and M.G.F. Sales, Myoglobin-biomimetic electroactive materials made by surface molecular imprinting on silica beads and their use as ionophores in polymeric membranes for potentiometric transduction, *Biosens. Bioelectron*. 26 (2011) 4760–4766.

[15]M. Arvand, and F. Alirezanejad, Sulfamethoxazole-imprinted polymeric receptor as ionophore for potentiometric transduction, *Electroanalysis* 23 (2011) 1948–1957.

[16]U. Lad, S. Khokhar, and G.M. Kale, Electrochemical creatinine biosensors, *Anal. Chem*. 80 (2008) 7910–7917.

[17]L. Wang, M. Pagett, and W. Zhang, Molecularly imprinted polymer (MIP) based electrochemical sensors and their recent advances in health applications, *Sens. Actuators Rep*. 5 (2023) 100153.

[18]G. Siciliano, M.S. Chiriacò, F. Ferrara, A. Turco, L. Velardi, M.A. Signore, M. Esposito, G. Gigli, and E. Primiceri, Development of an MIP based electrochemical sensor for TGF-β1 detection and its application in liquid biopsy, Analyst 148 (2023) 4447–4455.

[19]O.T. Vu, Q.H. Nguyen, T.N. Phan, T.T.T. Luong, K. Eersels, P. Wagner, and L.T.N. Truong, Highly sensitive molecularly imprinted polymer-based electrochemical sensors enhanced by gold nanoparticles for norfloxacin detection in aquaculture water, *ACS Omega* 8 (2023) 2887–2896.

[20]K. Hosoya, Y. Shirasu, K. Kimata, and N. Tanaka, Molecularly imprinted chiral stationary phase prepared with racemic template, *Anal. Chem*. 70 (1998) 943–945.

[21]N. Lavignac, C.J. Allender, and K.R. Brain, Current status of molecularly imprinted polymers as alternatives to antibodies in sorbent assays, *Anal. Chim. Acta* 510 (2004) 139–145.

[22]P.A.G. Cormack, M.M. Ariffin, E.I. Miller, and R.A. Anderson, Molecularly imprinted solid-phase extraction of diazepam and its metabolites from hair samples, *Anal. Chem*. 79 (2007) 256–262.

[23]. Arvand, and H. Asadi Samie, A biomimetic potentiometric sensor based on molecularly imprinted polymer for the determination of memantine in tablets, *Drug Test. Anal.* 5 (2013) 461–467.

[24]M. Arvand, and F. Alirezanejad, New sensing material of molecularly imprinted polymer for the selective recognition of sulfamethoxazole in foods and plasma and employing the Taguchi optimization methodology to optimize the carbon paste electrode, *J. Iran Chem. Soc.* 10 (2013) 93–105.

[25]M. Arvand, and P. Fallahi, Man-tailored biomimetic sensor of molecularly imprinted materials for the potentiometric measurement of rivastigmine in tablets and biological fluids and employing the taguchi optimization methodology to optimize the MIP-based membranes, *Electroanalysis* 24 (2012) 1852–1863.

[26]M. Arvand, and P. Fallahi, Voltammetric determination of rivastigmine in pharmaceutical and biological samples using molecularly imprinted polymer modified carbon paste electrode, *Sens. Actuators B: Chem*. 188 (2013) 797–805.

[27]V. Ayerdurai, M. Cieplak, and W. Kutner, Molecularly imprinted polymer-based electrochemical sensors for food contaminants determination, *Trends Anal. Chem.* 158 (2023) 116830.

[28]M. Hosseini, A high-performance ionic liquid-based microextraction (ILBME) method for the trace determination of paroxetine as a pharmaceutical pollutant in environmental and biological samples, Anal. Methods 16 (2024) 8457–8470.

[29]M. Hosseini, A. Rezaei, M. Soleymani, Homogeneous solvent-based microextraction method (HSBME) using a task-specific ionic liquid and its application to the spectrophotometric determination of fluoxetine as pharmaceutical pollutant in real water and urine samples, *Chem. Pap.* 78 (2024) 8195–8210.

[30]M. Hosseini, R. Castillo, M. Soleymani, A novel magnetic-assisted ionic liquid-based microextraction method (MA-ILBME): Specific design system for sensitive spectrophotometric analysis of paracetamol as a pharmaceutical pollutant in environmental samples, *Talanta* 286 (2025) 127486.

DOI: 10.30473/IJAC.2025.74192.1317

[31]J.M. Diaz-Cruz, N. Serrano, C. Pérez-Ràfols, C. Ariño, and M. Esteban, Electroanalysis from the past to the twenty-first century: challenges and perspectives, *J. Solid State Electrochem*. 24 (2020) 2653–2661.
[32]M. Saber-Tehrani, A. Pourhabib, S. Waqif Husain, and M. Arvand, Electrochemical behavior and voltammetric determination of quercetin in foods by graphene nanosheets modified electrode, *Anal. Bioanal. Electrochem*. 5 (2013) 1–18.
[33]J. Baranwal, B. Barse, G. Gatto, G. Broncova, and A. Kumar, Electrochemical sensors and their applications: A review, *Chemosensors* 10 (2022) 363.
[34]Z. Mosayebzadeh, R. Ansari, A. Mohammad-khah, and M. Arvand, Electrochemical preparation of a copper ion selective electrode based on polypyrrole conducting polymer doped with Ponceau 4R azo dye, *Anal. Bioanal. Electrochem*. 5 (2013) 109–129.
[35]S.M. Khoshfetrat, P. Seyed Dorraji, L. Fotouhi, M. Hosseini, F. Khatami, H.R. Moazami, K. Omidfar, Enhanced electrochemiluminescence biosensing of gene-specific methylation in thyroid cancer patients' plasma based integrated graphitic carbon nitride-encapsulated metal-organic framework nanozyme optimized by central composite design, *Sens. Actuators B: Chem*. 364 (2022) 131895.
[36]S.M.Khoshfetrat, M. Moradi, H. Zhaleh, M. Hosseini, Multifunctional methyl orange-delaminated Ti_3C_2 MXene for non-enzymatic/metal-free electrochemical detection of hydrogen peroxide and hydrazine, *Microchem. J.* 205 (2024) 111382.
[37].M. El-Kosasy, M.Y. Salem, M.G. El-Bardicy, and M.K. El-Rahman, Miniaturized membrane sensors for the determination of rivastigmine hydrogen tartrate, *Chem. Pharm. Bull*. 56 (2008) 753–757.
[38]R. Joseph, and K. Girish Kumar, Differential pulse voltammetric determination and catalytic oxidation of sulfamethoxazole using [5,10,15,20-tetrakis(3-methoxy-4-hydroxy phenyl)porphyrinato] Cu(II) modified carbon paste sensor, *Drug Test. Anal*. 2 (2010) 278–283.
[39]M. Arvand, and T.M. Gholizadeh, Simultaneous voltammetric determination of tyrosine and paracetamol using a carbon nanotube-graphene nanosheet nanocomposite modified electrode in human blood serum and pharmaceuticals, *Colloids Surf. B* 103 (2013) 84–93.
[40]L.I. Antropov, Theoretical Electrochemistry, Mir: Moscow, 1972.
[41]E. Bakker, and E. Pretsch, Potentiometry at trace levels, *Trends Anal. Chem*. 20 (2001) 11–19.
[42]E. Bakker, P. Buhlmann, and E. Pretsch, Carrier-based ion-selective electrodes and bulk optodes. 1. General characteristics, *Chem. Rev*. 97 (1997) 3083–3132.

DOI: 10.30473/IJAC.2025.74192.1317

Iranian Journal of Analytical Chemistry 11 (2024) 163-172

حسگر الکتروشیمیایی بر پایه پلیمر چاپ مولکولی برای جذب اختصاصی و آشکارسازی فولیک اسید در ماتریس های بیولوژیکی و نمونه های غذایی

مجید آروند[1*]، اکرم پورحبیب[2]، بهار اروند[3]

۱ . دانشکده شیمی، دانشگاه گیلان، رشت، ایران

۲ . آموزش و پرورش استان گیلان، رشت، ایران

۳. دانشکده پزشکی، دانشگاه علوم پزشکی گیلان، رشت، ایران

* E-mail: arvand@guilan.ac.ir

تاریخ دریافت: ۵ تیر ۱۴۰۳ **تاریخ پذیرش:** ۷ شهریور ۱۴۰۳

چکیده

این مطالعه یک حسگر زیست تقلیدی نوآورانه را ارائه می‌دهد که از پلیمرهای قالب مولکولی (MIPs) برای تشخیص فولیک اسید استفاده می‌کند و مواد پیشرفته و طراحی الکتروشیمیایی را برای عملکرد بهتر ترکیب می‌نماید. این حسگر از مونومرهای متاکریلیک اسید پلیمریزه شده روی یک سطح پلیمری، که با پودر گرافیت و روغن پارافین ادغام شده‌اند، برای تشکیل یک الکترود خمیر کربنی استفاده می‌کند. نقاط قوت کلیدی آن شامل پاسخ نرنستی ($۱۹،۲\text{mV decade}^{-1}$) در گستره غلظتی وسیع ($۱۰^{-۹} \times ۵$ تا $۱۰^{-۳} \times ۱$ مول بر لیتر) و حد تشخیص بسیار پایین $۱۰^{-۹} \times ۱$ مول بر لیتر است که از بسیاری از روش‌های مرسوم پیشی می‌گیرد. این طراحی نیاز به معرف‌های اضافی یا ابزار دقیق پیچیده را از بین می‌برد و مقرون به صرفه بودن و سادگی را در اولویت قرار می‌دهد. جنبه‌های بدیع در کامپوزیت MIP–گرافیت–روغن پارافین نهفته است که پایداری و گزینش‌پذیری را افزایش می‌دهد و در عین حال امکان بازسازی سریع حسگر را از طریق صیقل دادن سطح فراهم می‌کند. این حسگر پایداری و تکرارپذیری بلندمدت قابل توجهی را نشان می‌دهد که برای کاربردهای دنیای واقعی در نمونه‌های دارویی بسیار مهم است. توانایی آن در تشخیص فولیک اسید از گونه های تداخل‌کننده، که در ماتریس‌های متنوع اعتبارسنجی شد، بر کاربردی بودن آن برای تشخیص‌های بالینی و کنترل کیفیت مواد غذایی تأکید می‌کند. با ادغام ویژگی MIP با تبدیل الکتروشیمیایی، این کار بسترهای حسگری قابل حمل و با حساسیت بالا را برای آنالیزهای روتین ارائه می دهد.

کلید واژه ها

فولیک اسید؛ پلیمر چاپ مولکولی؛ الکتروشیمی؛ تبدیل سیگنال پتانسیومتری؛ قرص؛ سرم.

DOI: 10.30473/IJAC.2025.74192.1317