

Green Synthesis of Ion-Imprinted Polymers from Oak Gall Extract for Selective Removal of Chromium (III) Ions

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Article Info	ABSTRACT
Article Type Original Article Article History Received: 14 September 2025 Accepted: 19 February 2026 © 2012 Iranian Society of Medicinal Plants. All rights reserved. *Corresponding author fereshtehnematollahi2024@gmail.com fereshteh.nematollahi@iaui.ac.ir 	This study presents a new and eco-friendly approach to water purification through the development of ion-imprinted polymers (IIPs) enhanced with gold nanoparticles, synthesized using the tannin-rich extract of oak galls (<i>Quercus infectoria</i>) as both a natural reducing and stabilizing agent. By integrating biologically derived components with nanostructured materials, the proposed method enables the selective recognition and efficient removal of chromium (III) ions from aqueous solutions, offering a sustainable alternative to conventional synthetic polymer adsorbents and contributing to the advancement of green chemistry-based water treatment technologies. Oak gall extract, rich in tannins, was obtained using the Soxhlet method with a 70% ethanol: acetone solvent mixture. The presence of tannins was verified using the Folin-Ciocalteu method. The extract was used to synthesize gold nanoparticles, which were then integrated into the polymer membrane matrix. Various analytical techniques, including FTIR, FESEM, UV, and XRD, were used to analyze the structural and surface characteristics of the composite material. Optimal removal efficiency was achieved at a chromium concentration of 25 ppm and a flow rate of 1 mL/min, resulting in a 93% removal rate. This method offers a promising green chemistry solution for water treatment, with significant potential to improve water quality and mitigate heavy metal contamination. Keywords: MIPs, Gold nanoparticles, Oak gall extract, Chromium removal, Water treatment
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INTRODUCTION

Ensuring access to clean and safe drinking water is not only a basic human right but also a vital aspect of public health. However, increasing contamination of water sources by various pollutants poses a major global water quality challenge [1]. Traditional water treatment methods face limitations in removing emerging contaminants and specific pollutants effectively [2]. Adopting reverse osmosis technology and ion exchange methods has been suggested as an effective way to provide clean water, especially in developing countries. In Addition, biowaste-derived adsorbents offer sustainable alternatives for heavy metal removal from contaminated water sources [3]. The use of molecularly imprinted polymers (MIPs) in water treatment has gained significant attention because of their ability to selectively and efficiently remove specific contaminants. MIPs are synthetic polymers designed to capture target molecules, making them ideal for wastewater treatment [4]. In recent years, ion-imprinted polymers (IIPs), a subclass of MIPs, have been successfully developed for the selective removal of heavy metal ions including chromium, lead, and cadmium from water, owing to their tailored binding sites and strong metal–ligand interactions [5]. Advances in water-compatible MIPs and techniques such as NMR and dynamic light scattering have improved their effectiveness for water purification. These developments have enhanced MIP effectiveness, with recent studies demonstrating impressive performance metrics including high adsorption capacities and degradation efficiencies for various pollutants [6].

Chromium is a major contaminant in drinking water. Precisely and selectively determining its two primary states, Cr (III) and Cr (VI), is essential due to their distinct toxic impacts, posing an ongoing analytical challenge [7]. Chromium's behavior in marine environments, characterized by diverse oxidation states and potential organic complexes, adds complexity to the detection process [8]. Immediate separation of chromium species after sample collection remains challenging, thereby highlighting the need for selective materials capable of distinguishing Cr (III) from Cr (VI) without relying on chromatographic techniques—a gap that the ion-imprinted polymer approach proposed in this study aims to address. Reviews have examined modern analytical approaches and nanoscale sorbents for chromium speciation. These challenges associated with chromium speciation and selective detection in complex aqueous matrices highlight the need for advanced materials capable of discriminating between chromium oxidation states, thereby motivating the development of ion-imprinted polymers with tailored recognition sites for Cr (III). The selective recognition properties, high stability, and easier preparation of MIPs make them attractive artificial receptors for water treatment applications, though challenges regarding long-term stability and scalability remain [9, 10]. The selective recognition properties, high stability, and easier preparation of MIPs make them attractive artificial receptors for water treatment applications; however, challenges related to long-term stability and scalability remain, which are partially addressed in this study through the use of naturally derived,

cross-linked polymer matrices synthesized under mild conditions. The paper underscores the critical importance of ensuring access to clean water and investigates the potential of molecularly imprinted polymers (MIPs) as an effective tool for water treatment. It introduces a novel approach that employs oak gall extract as a natural, tannin-rich functional component in the preparation of an eco-friendly ion-imprinted polymer for Cr (III) removal. To the best of our knowledge, no previous work has reported the synthesis of ion-imprinted polymers using oak gall extract for Cr (III) removal. Despite the effectiveness of conventional IIPs, their reliance on synthetic monomers and harsh reaction conditions has motivated the exploration of natural, polyphenol-rich materials as sustainable functional components. By integrating plant-derived tannins with nanostructured materials, the present study aims to demonstrate a sustainable pathway for designing selective adsorbents that align with green chemistry principles while maintaining high removal efficiency.

This study focuses on the development and characterization of a chromium (III) ion-imprinted polymer synthesized using oak gall extract as a tannin-rich functional component. The central hypothesis is that the exceptionally high tannin content and dense phenolic functionalities of oak gall extract can provide a higher density of coordination sites for Cr (III) ions compared to other plant-derived polyphenol sources, thereby enhancing imprinting efficiency and selectivity. Unlike previously reported natural-source-based IIPs, the proposed approach integrates oxidized tannins and gelatin under mild, environmentally benign conditions, offering an eco-friendly and potentially scalable platform for selective Cr (III) removal from aqueous systems. In addition, the effects of key adsorption parameters, including Cr (III) concentration and solution flow rate, were systematically investigated to evaluate and optimize the performance of the synthesized ion-imprinted polymer under solid-phase extraction conditions.

MATERIALS AND METHODS

Oak Gall Extraction

To extract compounds from oak galls from *Quercus infectoria* Oliv. collected in Zagros oak forests of Lorestan Province, the galls were ground into a powder using a laboratory mill. The total extract was obtained through Soxhlet extraction with a solvent mixture of 70% ethanol and acetone (50:50). Specifically, 25 grams of powdered oak galls were placed in a Soxhlet apparatus with 250 milliliters of solvent, and the extraction process lasted for 3 hours [11]. The solvent was then removed from the extract using a rotary evaporator under vacuum at 50 °C and 72 mmHg. The resulting extract was stored at 4 °C for future assessments and molecular template polymer synthesis.

The extraction yield was calculated using the following equation, where Y indicates the extraction efficiency, W is the weight of the extract, and W₀ is the weight of the dried plant material.

$$\text{Formula 1: } Y = \frac{W}{W_0} \times 100$$

The physicochemical properties of the synthesized materials were evaluated using Fourier-transform infrared spectroscopy (FTIR), field-emission scanning electron microscopy (FESEM), X-ray diffraction (XRD), ultraviolet-visible (UV-Vis) spectroscopy, and transmission electron microscopy (TEM).

Test for the Presence of Tannins in the Extract

To initially screen for tannins, 2 milliliters of the extract were mixed with a 10% alcoholic solution of iron (III) chloride. The presence of tannins would cause the solution to change color to green or blue [12]. Subsequently, the total tannin content was quantified using the Folin-Ciocalteu method. Here, 1.0 milliliter of the extract was combined with 5.7 milliliters of distilled water containing 0.5 milliliter of Folin-Ciocalteu reagent. Next, 1 milliliter of a 35% sodium carbonate solution was added, and the volume was adjusted to 10 milliliters with distilled water. After vigorous shaking and a 30-minute incubation at room temperature, the absorbance of the solutions was measured at a wavelength of 700 nanometers using a UV-VIS spectrophotometer (3 repetitions). Standard solutions with tannic acid concentrations ranging from 20 to 100 mg/L were prepared and treated similarly. By plotting the calibration curve, calculating its equation, and substituting the sample's absorbance for Y, the total tannin content of the oak gall extract was determined [13].

Gold Nanoparticle-Mediated Tannin Oxidation

To facilitate the Michael reaction between tannin and gelatin, enabling the synthesis of molecularly imprinted polymer hydrogels for chromium (III) ion adsorption from water, tannin present in the extract must be oxidized. Ma *et al.* (2020) further revealed that during Fenton oxidation, tannin oxidation products can re-complex with Cr (III), establishing a redox cycle and forming highly conjugated Cr (III)-containing materials through carboxyl and hydroxyl group interactions [14]. Tannin-functionalized gold nanoparticles enable selective colorimetric detection of Cr³⁺ ions through aggregation-induced color changes, providing an environmentally friendly detection method [15]. In this study, gold nanoparticles (AuNPs) were incorporated to serve a dual purpose in the ion-imprinted polymer synthesis. Firstly, AuNPs facilitate the partial oxidation of tannin molecules, converting phenolic hydroxyl groups to quinone-like structures that are essential for the Michael-type reaction with gelatin, enabling effective cross-linking within the hydrogel matrix. During AuNP synthesis, tannins act simultaneously as reducing agents (converting Au³⁺ to Au⁰) and stabilizing ligands, ensuring controlled formation of nanoparticles. The concentration of gold salt (1, 2.5, and 5 mM), the percentage of oak gall extract solution (0.1%, 0.25%, and 0.5% v/v), and the weight-to-weight ratio of gold salt solution to extract (80:20, 50:50, and 20:80) were systematically varied and studied. The Taguchi method was applied to design the experiments, selecting three levels for each parameter, resulting in nine experimental setups as recommended by Minitab software. The adsorption of samples at 541 nm, corresponding to the surface plasmon resonance (SPR) of gold nanoparticles, was measured as the response for each experiment (Table 3-3).

Secondly, the embedded AuNPs enhance the structural and functional properties of the polymer by increasing surface area, improving porosity, and strengthening coordination interactions between Cr (III) ions and the polymer via surface-bound hydroxyl and carboxyl groups, thereby improving adsorption efficiency and selectivity. For the preparation of the AuNP-containing polymer, 5.0 mL of freshly prepared AuNP colloidal solution (synthesized under optimized conditions: 2.5 mM Au³⁺, 0.05% v/v oak gall extract, Au³⁺ solution-to-extract ratio of 50:50) was homogeneously dispersed into the gelatin solution prior to the introduction of oxidized tannin. Polymerization and template incorporation steps were subsequently performed as

described, resulting in a hydrogel with uniformly embedded AuNPs within the cross-linked tannin–gelatin network. This approach ensures both the chemical functionality and the structural integrity of the ion-imprinted polymer, while clearly justifying the inclusion of AuNPs in the system.

The Molecular Mold Polymer Synthesis

The hydrogel was synthesized through a Michael reaction between oxidized tannin and gelatin, as described by Osetrov *et al* [16]. Gelatin and oak gall tannin extract were used. Gelatin (3 g) was swollen in a saline buffer solution (10% NaOH) for 2 hours, then dissolved in 37.5 ml of water at 80 °C to form an 8% solution with a pH of 10. Oxidized tannin (0.3 g) was added and stirred vigorously for 1 hour at 80 °C. The solution was poured into a Petri dish and left overnight at room temperature to form the hydrogel. For molecular template polymer synthesis to capture Cr (III) ions, the same procedure was followed, with the addition of 3 ml of a 1000 mg/L Cr (III) solution before adding oxidized tannin. Cr (III) ions acted as template species to create specific binding sites within the polymer matrix. Chromium ions were then extracted using a 2 M NH₄-EDTA solution until their concentration fell below the detection limit, after template removal, the polymer was washed with distilled water and dried at 40 °C before further use [17].

Adsorption of Chromium (III) Ions via the SPE Method

For this purpose, 1 gram of the synthesized molecularly imprinted polymer was loaded into a 5-milliliter syringe, sealed at the end with compacted glass wool. Subsequently, 5 milliliters of solutions containing Cr (III) ions at various flow rates, controlled by a valve attached to the column's end, were introduced. The adsorption of Cr (III) ions was measured using a Varian AA 200 atomic adsorption spectrometer. To optimize adsorption efficiency, both the concentration of the Cr (III) solution and the flow rate through the column were tested as variables. Concentration levels of 5, 10, 25, 50, and 100 ppm, along with flow rates of 0.5, 1, 2, 3, and 5 milliliters per minute, were used. The adsorption percentage of Cr (III) ions was calculated with the following formula:

$$\text{Formula 2: } y = \left(\frac{C_0 - C_x}{C_0} \right) \times 100$$

In this context, (y) represents the percentage of Cr (III) ion absorbed by the molecularly imprinted polymer, (C_x) indicates the concentration after passing through the SPE column, and (C_0) denotes the concentration before passing through the SPE column.

Prior to column packing, the dried ion-imprinted polymer was gently ground and sieved to obtain particles with a size range of 100–250 µm. For SPE experiments, 1.0 g of the polymer was packed into a 5 mL polypropylene syringe (internal diameter ≈ 8 mm), resulting in a packed bed height of approximately 15 mm. The polymer bed was secured between two layers of compacted glass wool to prevent material loss and ensure uniform flow distribution.

The column was preconditioned with distilled water before sample loading. Flow rates were controlled using a valve attached to the column outlet to maintain stable hydrodynamic conditions during adsorption experiments.

Nanoparticle Identification

UV-visible Spectroscopy

The formation of gold nanoparticles was confirmed by UV–V is spectroscopy. The colloidal solution displayed a ruby-red color,

characteristic of spherical AuNPs. The absorption spectrum exhibited a distinct surface plasmon resonance (SPR) peak at $\lambda_{\text{max}} = 533$ nm, indicating the successful reduction of Au³⁺ ions by tannin molecules. The single, symmetric peak suggests a uniform distribution of nanoparticles without aggregation [18].

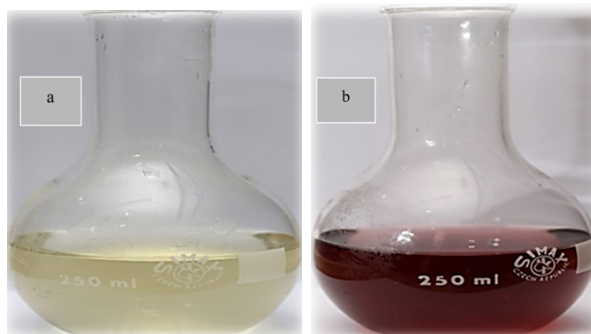


Fig. 1 color change of (a) Au³⁺ to (b) gold nanoparticles

Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR spectroscopy was utilized to detect alterations in functional groups resulting from tannin oxidation during nanoparticle formation. To assess these changes, FT-IR spectroscopy was performed on the extract before and after nanoparticle formation [19].

X-ray Diffraction (XRD) Spectroscopy

XRD analysis was conducted to confirm the formation and crystalline structure of the synthesized gold nanoparticles. The colloidal suspension was centrifuged at 13,000 rpm, and the obtained precipitate was washed and dried at 50 °C before analysis. The dried nanoparticle powder was examined using a Seifert 3003PTS X-ray diffractometer equipped with a Cu K α radiation source ($\lambda = 1.5406$ Å) over a 2θ range of 10–90°. The diffraction pattern (Fig. X) displayed characteristic peaks at $2\theta = 38.2^\circ, 44.4^\circ, 64.6^\circ,$ and 77.5° , corresponding to the (111), (200), (220), and (311) planes, respectively, confirming the face-centered cubic (FCC) crystalline structure of metallic gold [20].

Transmission electron microscopy (TEM)

Transmission electron microscopy (TEM) is a valuable tool for analyzing the morphology and size of nanoparticles [21]. It offers high-resolution images

that show the shape, size, and internal structure of nanoparticles [22]. TEM is often used to determine the size distribution of nanoparticles for applications like drug delivery systems [21]. Additionally, TEM can observe chemical reactions in solution, revealing insights into nanoparticle growth mechanisms [23]. TEM analysis was performed to examine the morphology and size distribution of the synthesized gold nanoparticles. The TEM images (Fig. 7) revealed that the particles were predominantly spherical and well dispersed, with smooth surfaces and uniform contrast. The average particle diameter was approximately 20 ± 5 nm, confirming the nanoscale dimensions and homogeneous size distribution of the gold nanoparticles. These observations support the successful reduction of Au³⁺ ions by the tannin components of the oak gall extract and are consistent with the XRD results indicating a face-centered cubic (FCC) crystal structure

a: Before the addition of extract b: After increasing the extract concentration

RESULTS AND DISCUSSION

Synthesis of Gold Nanoparticles and Tannin Oxidation

The interaction between tannin and gold ions was confirmed by the color change of the solution and the appearance of a distinct absorption peak at 533 nm in the UV-V is spectrum, corresponding to the surface plasmon resonance (SPR) of gold nanoparticles (Fig. 1). Gold nanoparticle synthesis using tannin oxidation as a reducing and stabilizing agent has been explored in various studies. Verma²¹ utilized the citrate reduction method for the uniform synthesis of gold nanoparticles, whereas both Nadhifah [24] and Roy [25] employed different approaches to synthesize gold nanoparticles with specific characteristics. Octaviana [26] investigated the synthesis of gold nanoparticles using modified bilimbi leaf extract with 2,4,6-triazine-1,3,5-trithiol for a particular application as a melanin sensor. These studies collectively demonstrate the potential of tannin oxidation in gold nanoparticle synthesis and the need for further research to optimize reaction conditions.

To optimize reaction conditions, the effects of Au^{3+} ion concentration, extract volume percentage, and Au^{3+} solution to extract ratio were investigated. The Taguchi experimental design method was used to minimize tests. Levels were set based on the literature and conducted in 3 levels with nine experiments (Table 1). Light adsorption at 533 nm wavelength corresponding to gold nanoparticle SPR was measured. Adsorption spectra from experiments 1 to 9 are shown in Figure 2, with optimal conditions depicted in Figure 3 for the Au^{3+} ion and oak gall extract reaction.

Table 1 SPR adsorption rate for each test

Test	Adsorption	Test	Adsorption	Test	Adsorption
Test 1	0.006	Test 4	0.506	Test 7	0.008
Test 2	0.194	Test 5	0.193	Test 8	0.021
Test 3	0.054	Test 6	0.299	Test 9	0.001

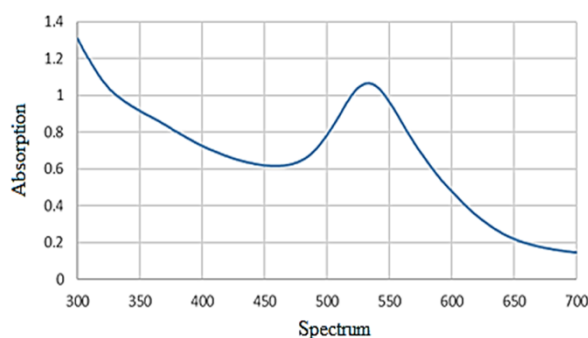


Fig. 2 UV-VIS spectrum in optimal conditions

By inputting the adsorption rates of each designed experiment into the Minitab software, the optimal value (1.064) listed in Table 2 was identified for the synthesis of gold nanoparticles using oak gall extract.

Table 2 Optimal values for the synthesis of gold nanoparticles by oak gall extract

Optimal values	Parameter
mM 2.5	Au^{3+} solution concentration
0.1%	Extract percentage (V/V)
50: 50	Ratio of Au^{3+} solution: extract

The optimal synthesis conditions were determined based on Taguchi signal-to-noise ratio analysis and were selected strictly from the predefined factor levels (Au^{3+} concentration: 2.5 mM; extract percentage: 0.1% v/v; Au^{3+} solution-to-extract ratio: 50:50). No intermediate extract concentrations were evaluated. The analysis of the FT-IR spectrum of oak gall extract (Fig. 4) reveals the presence of hydroxyl groups (broad, 3361 cm^{-1}) and a carbonyl group (1723 cm^{-1}). Similarly, the examination of the FT-IR spectrum of oak gall extract (Fig. 5) also demonstrates the existence of hydroxyl groups (broad, 3361 cm^{-1}) and a carbonyl group (1723 cm^{-1}).

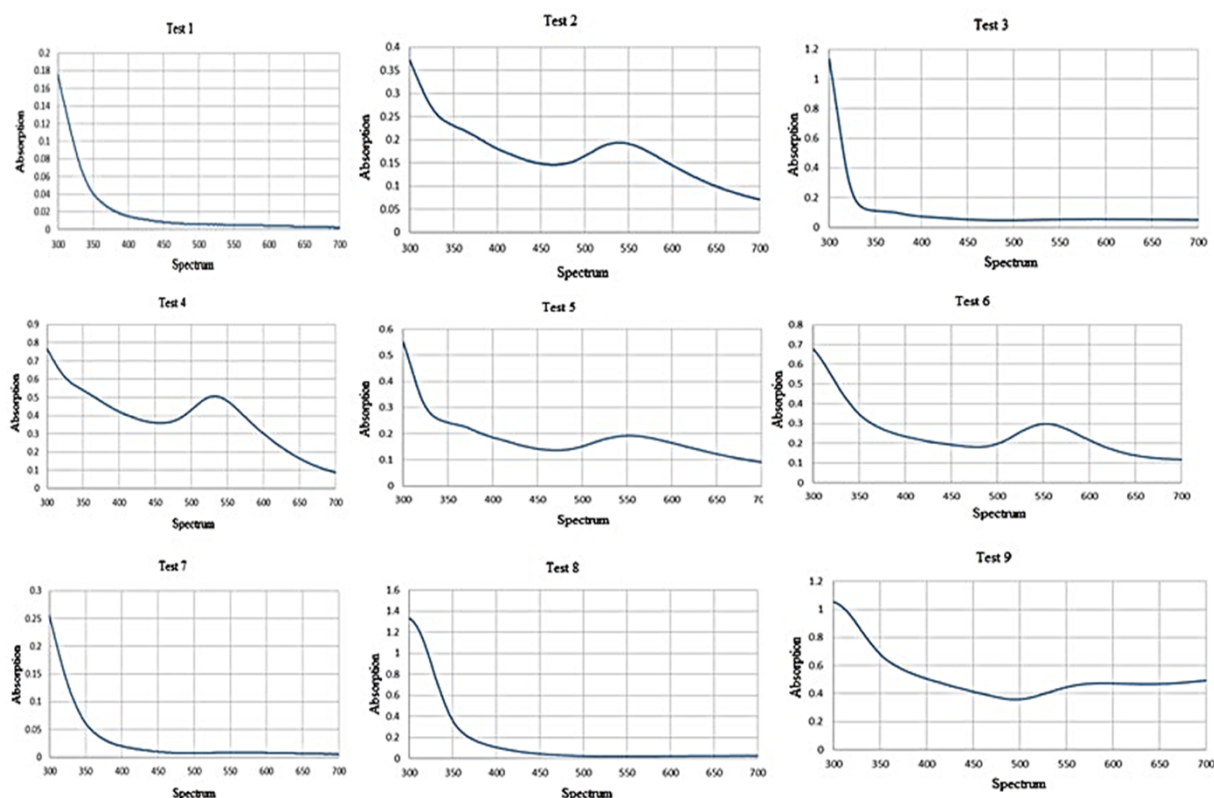


Fig. 3 Adsorption spectrum of solutions obtained from tests 1 to 9.

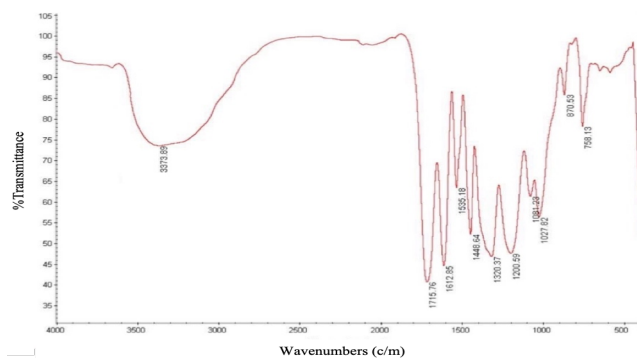


Fig. 4 FT-IR spectrum of gold nanoparticle–oak gall extract composite

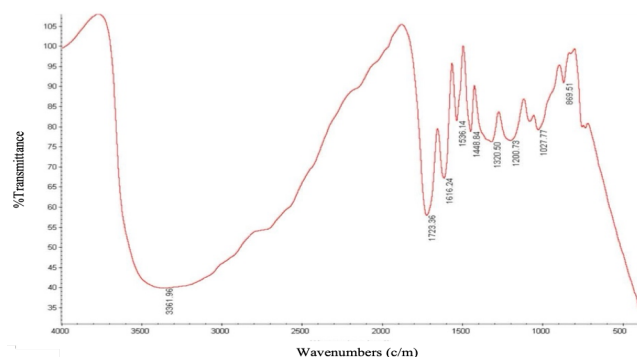


Fig. 5 FT-IR spectrum of oak gall extract

Colloidal gold nanoparticle solutions underwent X-ray diffraction (XRD) spectroscopy to confirm synthesis and determine their crystalline structure. Figure 6 displays the XRD spectrum of the nanoparticles compared to their standard pattern. The presence of peaks at 2θ angles of 38.28, 44.5, 66.30, and 77.59 degrees, corresponding to the Bragg reflections of 111, 200, 220, and 311, respectively, signifies the formation of crystals with the Face-Centered Cubic (FCC) structure. Transmission electron microscopy (TEM) imaging (Fig. 7) shows predominantly spherical nanoparticles with occasional variations in morphology.

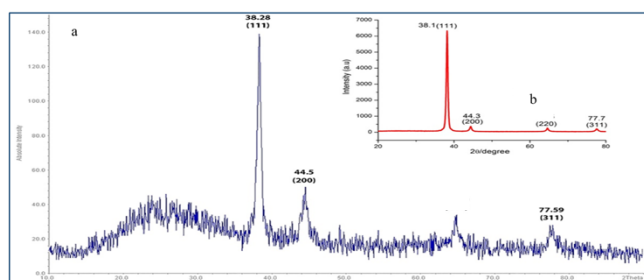


Fig. 6 XRD spectrum of synthesized gold nanoparticles (a) and standard pattern (b).

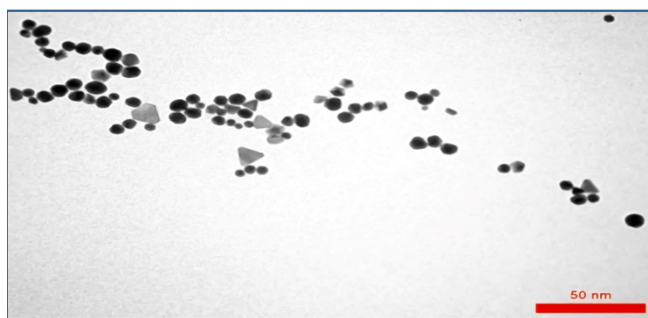


Fig. 7 TEM image of nanoparticles

Molecular Mold Polymer

The synthesis of the molecularly imprinted polymer was conducted as per the provided method's third step. To validate the polymerization reaction, the resulting product was subjected to FT-IR spectroscopy (Fig. 8 and 9). The adsorption bands in the FT-IR spectrum corresponding to carbon linkages (CH_3 , CH_2) of the molecularly imprinted polymer appear at 2922 and 2800 cm^{-1} , respectively, exhibiting greater intensity compared to the peaks present in the gelatin spectrum. Similarly, the peak attributed to carboxylic groups is observed around 1708 cm^{-1} . The emergence of the peak at 1440 cm^{-1} indicates the formation of cross-links in the synthesized polymer, attributed to the presence of the $\text{CH}=\text{N}$ group. Peaks at 921 and 874 cm^{-1} , corresponding to $-\text{CH}$ groups in benzene rings of tannin, are formed due to the formation of new bonds between gelatin and tannin. Another evidence of the reaction between gelatin amine groups and tannin is the shift from 3446 cm^{-1} (gelatin) to 3617 cm^{-1} (cross-linked hydrogels).

Optimization of Extraction Conditions

To optimize extraction conditions, two parameters, Cr (III) ion solution concentration and flow rate through the SPE column, were studied. Table 3 displays the concentration of Cr (III) ions post-SPE column passage.

As depicted in Figure 10, the adsorption percentage graph of a 25 ppm solution of Cr (III) ions varies with the flow rates of the solution within the SPE column. Utilizing the optimal flow rate diagram, the rate in milliliters per minute was established.

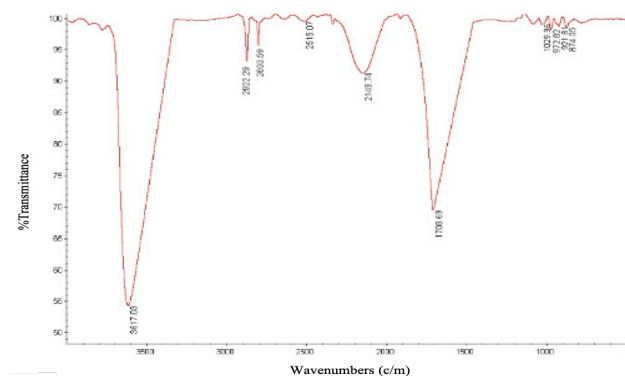


Fig. 8 Infrared spectrum of gelatin

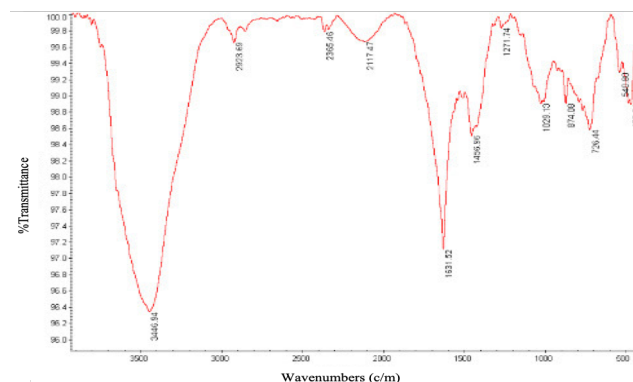


Fig. 9 Infrared spectrum of the synthesized hydrogel

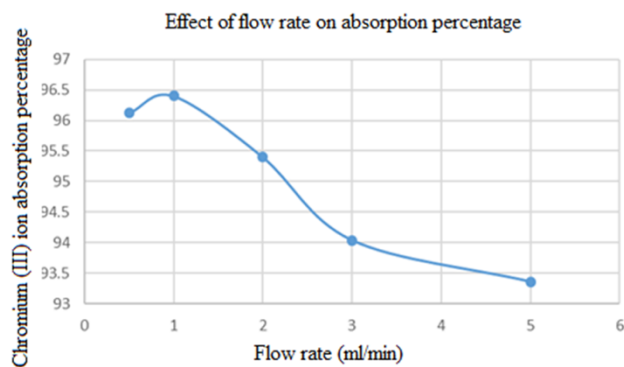


Fig. 10 Adsorption percentage of Cr (III) ions at 25 ppm versus flow velocities

Table 3 Adsorption rate of Cr (III) + ions for 25 ppm concentration at different flow rates

Flow rate (ml/min)	Initial concentration (ppm)	Secondary concentration (ppm)	Adsorption percentage of Cr (III) ion
0.5	25	24.03	96.12
1	25	24.10	96.40
2	25	23.85	95.40
3	25	23.51	94.04
5	25	23.34	93.36

Experiments were conducted on real water samples under optimized conditions to evaluate the synthesized polymer's efficacy in absorbing Cr (III). The method demonstrated an efficiency of 93% for polluted water, indicating satisfactory results and suggesting the potential use of this molecularly imprinted polymer for chromium III ion removal.

In related studies, Björkegren [27] and Goyal [28] investigate the use of emulsion liquid membranes (ELMs) for heavy metal extraction. Björkegren focuses on hexavalent chromium removal using a palm oil-based ELM, while Goyal²⁸ employs a hydrophobic ionic liquid and TOMAC for chromium removal. These studies highlight ELMs' effectiveness in enhancing extraction efficiency. Additionally, Chakraborty [29]. In comparison with previous studies, the present method demonstrates superior adsorption performance and eco-friendliness. Dakova *et al.* (2022) reported a Cr (III)-imprinted hydrogel membrane containing Au nanoparticles that achieved approximately 85% removal efficiency under optimal conditions [17]. Similarly, Trzonkowska *et al.* (2022) developed an ion-imprinted polymer for Cr (III) determination with an efficiency of about 88% [30]. In contrast, the oak gall-derived ion-imprinted polymer synthesized in this work reached 93% removal efficiency, indicating enhanced adsorption capacity and selectivity. This improvement can be attributed to the high tannin content of oak gall extract, which provides abundant phenolic and hydroxyl groups for metal ion coordination and facilitates nanoparticle stabilization. Moreover, the synthesis process employed here uses only natural, biodegradable components and mild reaction conditions, underscoring its environmental sustainability compared with the synthetic monomers and solvents used in previous reports. Introduced a new dynamic solid-phase extraction method using ion-imprinted polymers for selective separation and determination of Cr (III) ions in water samples. Another study developed a novel method for determining chromium species in water samples using electrothermal atomic adsorption spectrometry. Two ion-imprinted polymers containing the Cr (III)-1,10-phenanthroline complex were prepared for the selective separation of Cr (III)

ions, demonstrating high efficiency and repeatability in retaining Cr (III) ions from solutions under specified conditions. These methods were successfully applied to determine chromium in water samples.

In summary, the developed method using the polymer synthesized from oak gall extract exhibits good properties in separating Cr (III) ions, surpassing some methods reported in the literature [31, 32]. We reported a method efficiency of 93% for contaminated water. This molecularly imprinted polymer can be effectively utilized for the removal of chromium (III) ions. Further studies are required to test reusability and selectivity of the polymer in mixed-ion systems.

CONCLUSIONS

This study demonstrated the successful synthesis of gold nanoparticles and a chromium (III) ion-imprinted polymer (Cr-IIP) using oak gall extract as a natural source of tannins. The developed material exhibited a 93% Cr (III) removal efficiency under optimized conditions (25 ppm concentration and 1 mL min⁻¹ flow rate), which is higher than values reported in similar studies such as Dakova *et al.* (2022) and Trzonkowska *et al.* (2022). The enhanced adsorption capacity and selectivity are attributed to the abundant hydroxyl and phenolic groups in tannins that facilitate metal ion coordination and nanoparticle stabilization.

Although the process shows strong potential as a green and sustainable method for heavy-metal removal, certain limitations remain. The reusability and long-term stability of the polymer need to be further assessed, and its selectivity toward other competing metal ions should be investigated in future work. Overall, this research provides a promising framework for developing eco-friendly, tannin-based ion-imprinted polymers for selective and efficient removal of toxic metals from aqueous environments.

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