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Adsorption of Chromium, Copper, and Arsenic (CCA) from Wood Treatment Wastewater using Magnetic Molecularly Imprinted Polymer (MMIPs)

(Penjerapan Kromium, Kuprum dan Arsenik (CCA) daripada Air Sisa Rawatan Kayu menggunakan Polimer Tercetak Molekul Bermagnet (MMIPs))

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ABSTRACT

The wood treatment industry generates wastewater containing toxic metals such as chromium (Cr), copper (Cu), and arsenic (As), posing risks to the environment and human health. Conventional treatment methods like chemical precipitation and ion exchange face limitations in selectivity, cost, and secondary waste production. Magnetic Molecularly Imprinted Polymers (MMIPs) have emerged as an innovative approach in water treatment technology. MMIPs combines the specificity of molecular binding from molecular imprinting (MIP) technology with the ease of separation using magnetic fields, making it suitable for industrial wastewater treatment applications. Although MMIPs have been studied in various applications, the use of these materials in the simultaneous removal of Cr, Cu, and As from wood treatment wastewater is still underexplored. This study focuses on the development of a modified MMIPs designed with specific binding sites for the simultaneous removal of Cr, Cu, and As from wood treatment wastewater. MMIPs was synthesised by modifying Fe_3O_4 magnetic nanoparticles with methacrylic acid (MAA) and ethylene glycol dimethacrylate (EGDMA) via a chemical co-precipitation method, and characterised using FTIR analysis. Operational parameters including solution pH (3-10); adsorbent dosage (0.05-0.20 g); contact time (5-20 min); and elution solvents (methanol, ethanol, acetone) were optimised. FTIR analysis shows peaks formed around 2900 cm^{-1} and ~1630 cm^{-1} in indicates the successful synthesis of MMIPs. FTIR confirmed functional groups such as –COOH and –OH involved in metal binding. The FESEM analysis shows the presence of spherical, porous structures with small granules while the pore diameter is 13.7 nm while the surface area is 50.4 m^2/g from the BET analysis further indicated that the MMIPs were successfully synthesised. The results showed that MMIPs removed over 90% of Cr, Cu, and As at optimum conditions which are pH 8, 0.20 g dosage, and 20-min contact time, with methanol being the most effective eluent. The LOD obtained was 0.63, 0.85, and 0.69, respectively for Cr, Cu, and As. The LOQs obtained were 1.65, 1.86, and 2.58, respectively, for Cr, Cu and As. The study demonstrates MMIP's potential as a selective, cost-effective, and environmentally friendly solution for industrial wastewater treatment.

Keywords: Arsenic (As); chromium(Cr); copper (Cu); magnetic molecularly imprinted polymer (MMIPs); wastewater treatment; wood treatment industry

ABSTRAK

Industri rawatan kayu menggunakan bahan pengawet seperti kromium (Cr), kuprum (Cu) dan arsenik (As) yang menghasilkan air sisa toksik yang berisiko kepada alam sekitar dan kesihatan manusia. Kaedah rawatan konvensional seperti pemendakan kimia dan pertukaran ion mempunyai kekangan dari segi selektiviti, kos dan penghasilan sisa sekunder. Kajian ini membangunkan Polimer Tercetak Molekul Magnetik (MMIPs) dengan tapak pengikatan khusus untuk penyingkiran serentak Cr, Cu dan As daripada air sisa industri. MMIPs disintesis melalui pemendakan kimia menggunakan nanozarah magnetik (Fe_3O_4) yang diubah suai dengan asid metakrilik (MAA) dan etilena glikol dimetakrilat (EGDMA) dan dicirikan menggunakan analisis FTIR. Parameter seperti pH (3-10), dos penjerap (0.05-0.20 g), masa sentuhan (5-20 minit) dan jenis pelarut elusi diuji bagi mengenal pasti keadaan optimum. Analisis FTIR menunjukkan puncak yang terbentuk sekitar 2900 cm^{-1} dan ~1630 cm^{-1} yang menandakan keberhasilan sintesis MMIPs. Analisis FESEM menunjukkan kewujudan struktur sfera yang berliang dengan butiran halus, manakala diameter liang berukuran

13.7 nm dan luas permukaan sebanyak 50.4 m²/g berdasarkan analisis BET turut mengesahkan bahawa MMIPs telah berjaya disintesis. Hasil kajian menunjukkan MMIPs mampu menyingkirkan lebih daripada 90% logam pada keadaan yang optimum iaitu pada pH 8, dos 0.20 g dan masa sentuhan 20 minit dengan metanol sebagai pelarut elusi paling berkesan. LOD yang diperoleh ialah 0.63, 0.85 dan 0.69 masing-masing bagi Cr, Cu dan As. LOQ yang diperoleh pula ialah 1.65, 1.86 dan 2.58 masing-masing bagi Cr, Cu dan As. Kajian ini membuktikan potensi MMIPs sebagai teknologi rawatan air sisa yang selektif, boleh diguna semula dan mesra alam, selari dengan keperluan piawaian antarabangsa dan dasar kelestarian alam sekitar.

Kata kunci: Arsenik (As); industri rawatan kayu; kromium (Cr); kuprum (Cu); polimer tercetak molekul magnetik (MMIPs); rawatan air sisa

INTRODUCTION

The wood treatment industry uses preservatives such as chromated copper arsenate (CCA) to increase wood's resistance to biological degradation. However, this process also produces wastewater containing toxic heavy metals such as chromium (Cr), copper (Cu), and arsenic (As) that are harmful to human health and the environment (Oladimeji et al. 2024). These metals are bioaccumulative and toxic, and persist in the ecosystem for long periods, posing serious challenges to wastewater management. Conventional treatment methods such as chemical precipitation and ion exchange are often inadequate due to lack of selectivity, high operating costs, and the production of polluting secondary sludge (Ayach et al. 2024). Therefore, the development of new selective, reusable, and environmentally friendly adsorbents is urgently needed.

Magnetic Molecularly Imprinted Polymers (MMIPs) have emerged as an innovative approach to water treatment. MMIPs combine the specificity of molecular binding from molecular imprinting (MIP) technology with the ease of separation using magnetic fields, making it suitable for industrial wastewater treatment applications (Yang et al. 2023). The recognition sites formed in MMIPs enable the selective removal of target metals in complex aqueous environments (Metwally et al. 2021).

Although MMIPs have been studied in various applications, the use of these materials in the simultaneous removal of Cr, Cu, and As from wood treatment wastewater is still underexplored. This study aims to synthesise and characterise MMIPs modified with CCA and optimise the adsorption operating parameters such as pH, adsorbent dosage contact time, and type of elution solvent (Figure 1). The results of this study are expected to contribute to more sustainable wastewater treatment solutions that are in line with international standards such as the World Health Organization (WHO 2022) and the United States Environmental Protection Agency (USEPA 2026).

MATERIALS AND METHODS

CHEMICALS AND REAGENTS

The chemicals used in this study included iron (II) chloride tetrahydrate ($FeCl_2 \cdot 4H_2O$), iron(III) chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), ammonium hydroxide (NH_4OH), methacrylic acid (MAA), ethylene glycol dimethacrylate (EGDMA), and azobisisobutyronitrile (AIBN). The metal templates consisted of chromium(III) chloride ($CrCl_3$), copper(II) sulfate ($CuSO_4$), and sodium arsenate (Na_3AsO_4). All materials were of analytical grade and were supplied by Sigma-Aldrich (Malaysia).

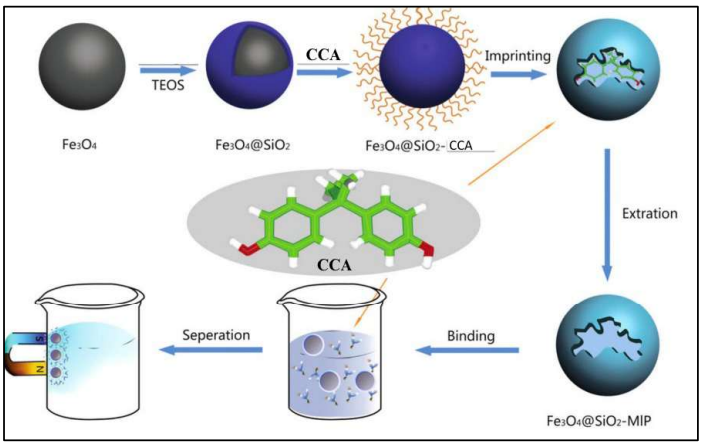


FIGURE 1. Schematic illustration of magnetic molecularly imprinted polymer (MMIPs) synthesis and CCA adsorption process

INSTRUMENTATION AND ANALYTICAL CONDITIONS

The functional groups of the synthesised materials were analyzed using a Fourier Transform Infrared Spectrometer (FTIR, *Thermo Nicolet 6700, USA*) in transmittance mode (%T) over a wavenumber range of 4000-400 cm^{-1} with a resolution of ±4 cm^{-1} over 40 scans. Morphological structure and surface characteristics were examined at magnifications ranging from 200× to 10,000× by a Field Emission Scanning Electron Microscopy equipped with Energy-Dispersive X-ray Spectrometry (FESEM-EDX, *Merlin-Zeiss, Germany*). The specific surface area, average pore size, and pore volume were evaluated using a Brunauer–Emmett–Teller (BET) surface area analyzer (3Flex, *Micromeritics Instrument, USA*) via nitrogen gas adsorption–desorption isotherms at 77K. Concentrations of heavy metals (Cr, Cu, and As) in solution were measured using an Atomic Absorption Spectrophotometer (AAS, *PinAAcle 900T, USA*) operating with standard air-acetylene/nitrous oxide–acetylene flames. Sample pH adjustments were monitored using a benchtop pH meter (*Mettler-Toledo,* Switzerland).

SYNTHESIS OF MAGNETIC MOLECULARLY IMPRINTED POLYMERS (MMIPs)

SYNTHESIZING BASIC MNPs

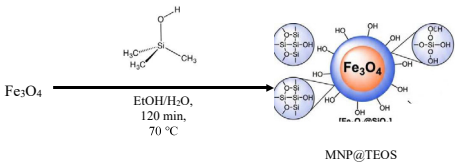
Magnetic nanoparticles (MNPs) were synthesised via a chemical co-precipitation method adapted from Muñoz-Leon et al. (2025). $FeCl_2{\cdot}4H_2O$ (6.4 g) and $FeCl_3{\cdot}6H_2O$ (15.2 g) were dissolved in 320 mL of distilled water and stirred at 90.0 °C and 1500 rpm for 2 h. Subsequently, 100 mL of aqueous ammonia was added, and the mixture was stirred for another 2 h until a black precipitate formed.

$$Fe^{2+} + 2Fe^{3+} + 20H^{-} = Fe_3O_4 + 4H_2O \qquad (1)$$

After cooling to room temperature, the MNPs were washed repeatedly with hexane and hot distilled water, magnetically separated, and oven-dried at 70 °C for 24 h. The dried MNPs were ground into fine powder and stored in a clean, dry container.

SYNTHESIS OF SILICA-COATED MNPs (MNP@TEOS)

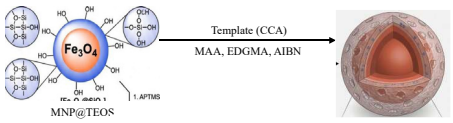
Pre-synthesised magnetic nanoparticles (MNPs) were coated with tetraethyl orthosilicate (TEOS) to form silica-coated MNPs (MNPs@TEOS). A total of 4.0 g of MNPs were dispersed in 150 mL of ethanol–water (1:1, v/v) and stirred for 30 min. Subsequently, 16.0 g (16 mL) of TEOS was added, and the mixture was stirred at 70.0 °C and 1500 rpm for 2 h. The TEOS:MNPs molar ratio was maintained at 4:1 to achieve optimal surface modification (Ilustration 2). After cooling to room temperature, the particles were magnetically separated, washed repeatedly with hexane and hot distilled water, then oven-dried at 70 °C for 24 h. The final product was ground into a fine powder and stored in a dry container.



(2)

SYNTHESIS OF MMIPs

MMIPs were synthesised by dissolving 1 g each of $CrCl_3$, $CuSO_4$, and Na_3AsO_4 (as template metals) in 20 mL of acetonitrile, followed by the addition of 2 mL methacrylic acid (MAA) as the functional monomer. The mixture was stirred for 8 h at room temperature to form metal–monomer complexes. Then, 1 g of MNPs@TEOS was added along with 20 mL ethylene glycol dimethacrylate (EDMA) as crosslinker and 2 g azobisisobutyronitrile (AIBN) as initiator. Polymerization was initiated at 60 °C for 20 min, followed by 24 h of curing at room temperature. The resulting composite was magnetically separated, washed thoroughly with 0.1 M EDTA and hot water to remove unreacted materials and templates, then oven-dried at 50 °C for 24 hours. The final product was ground into a fine powder and stored for further use in heavy metal adsorption. Illustration (3) shows the synthesis of MMIPs by polymerization.



(3)

OPTIMISATION OF PARAMETERS FOR CHROMIUM, COPPER, AND ARSENIC ADSORPTION

SAMPLE pH

Solution pH significantly influences adsorption by affecting the ionisation state of functional groups, adsorbent surface charge, and metal ion stability. In this study, the effect of pH on the adsorption of Cr, Cu, and As will be investigated over a pH range of 2-10 at room temperature, following the method of Li, Wang and Row (2018). pH adjustment will be carried out using 0.01 M HCl and 0.01 M NaOH. A fixed volume of 10 mL CCA solution (10 ppm) and 0.15 g of adsorbent will be used, with stirring at 250 rpm for 20 min. The optimal pH is expected to enhance interaction between the metal ions and the adsorbent's active sites.

ADSORBENT DOSAGE

The amount of adsorbent used plays a key role in determining the removal efficiency of heavy metals. This study will explore the influence of dosage ranging

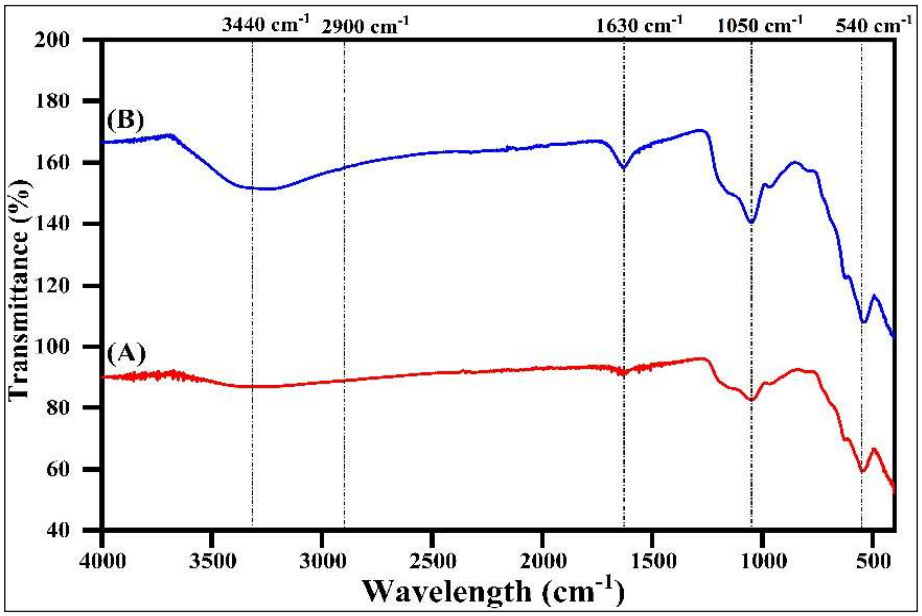


FIGURE 2. FTIR spectrum (A) MMIPs and (B) MNP@TEOS

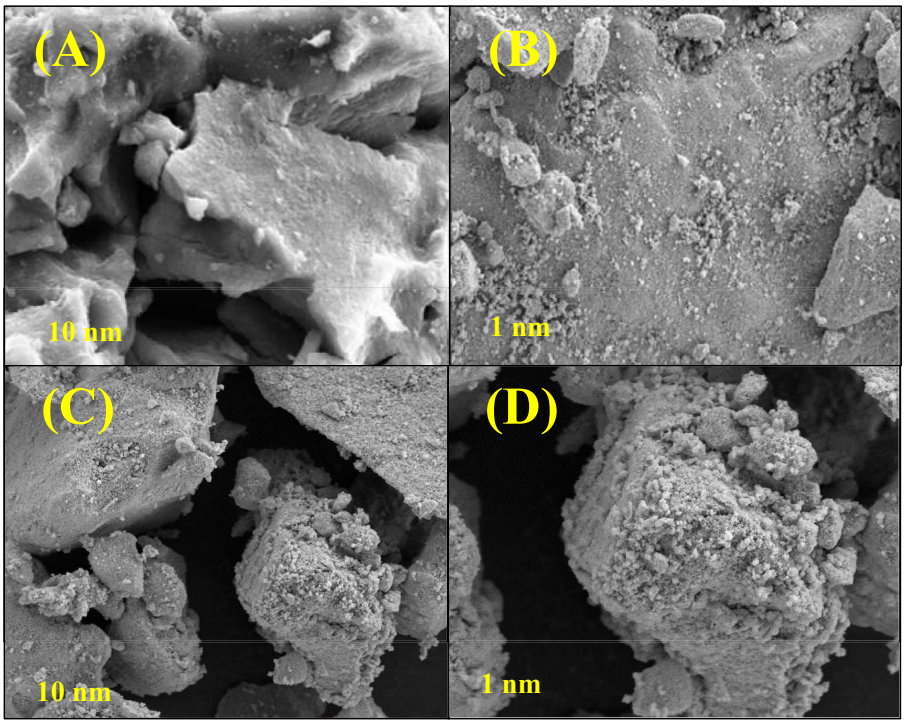


FIGURE 3. FESEM analysis of (A) MNP@TEOS and (B) MMIPs

TABLE 1. BET analysis of adsorbents

Adsorbent	Surface area (m^2/g)	Pore diameter (nm)
MNP@TEOS	28.7	6.0
MMIPs	50.4	13.7

from 0.05 g to 20 g, as adapted from Li et al. (2018). Increasing the dosage is expected to improve adsorption due to a greater number of active binding sites, though a plateau may occur once saturation is reached. A fixed volume of 10 mL CCA solution (10 ppm) at pH 7 will be used, while stirring at 250 rpm for 20 min.

CONTACT TIME

Contact time affects the rate and extent of metal ion adsorption. This part of the experiment will be conducted with time intervals ranging from 5 to 20 min at room temperature. A constant adsorbent dosage of 0.15 g and 10 ppm metal concentration will be used at pH 7. It is anticipated that adsorption will increase with time due to a high initial concentration gradient and availability of active sites, reaching equilibrium once the adsorbent becomes saturated.

ELUTION SOLVENT

The choice of elution solvent is critical for effective desorption of metal ions from the MMIPs without compromising polymer integrity. Solvents including methanol, ethanol and acetone will be tested. A 10 ppm CCA solution (pH 7) with 0.15 g of MMIPs will be shaken for 20 min. The aqueous phase will then be discarded, and 10 mL of methanol will be used to elute the bound metal ions. This process will be repeated with other solvents to identify the most efficient eluent. Desorption efficiency will be evaluated using atomic absorption spectroscopy (AAS), based on the concentration of metals recovered in solution.

RESULTS AND DISCUSSION

CHARACTERISATION OF MOLECULARLY IMPRINTED POLYMERS (MMIPs)

FOURIER TRANSFORM INFRARED SPECTROSCOPY

In this study, FTIR analysis was employed to verify the successful synthesis and surface functionalization of silica-coated magnetic nanoparticles (MNP@TEOS) into MMIPs by identifying characteristic chemical bonds relevant to heavy metal adsorption. The spectra were recorded in percent transmission (%T) mode, using a resolution of 4 cm^{-1} and averaged over 40 scans. Infrared absorption at specific frequencies corresponds to molecular vibrations, allowing for the identification of surface chemical compositions and functional groups present on the material.

Figure 2 compares the FTIR spectra of MNP@TEOS and MMIPs, illustrating the primary functional groups involved in surface modification and adsorption. A broad band near 3700 cm^{-1} in both spectra corresponds to O–H stretching from surface hydroxyls or adsorbed water (Yuan et al. 2026). The increased sharpness and intensity of this peak in spectrum (A) indicates stronger hydroxyl interactions, likely driven by hydrogen bonding between MNP@TEOS and the target metal ions (Cr, Cu, As), which improves both hydrophilicity and adsorption capacity.

The C–H stretching vibration near 2900 cm^{-1} is present in both spectra, with a slight intensity gain in spectrum (A) confirming the inclusion of alkyl chains from MAA and EGDMA via polymer grafting (Li et al. 2017). Furthermore, a prominent peak at ~1630 cm^{-1} in spectrum (A), attributed to C=O stretching in the ester groups of EGDMA and MAA, confirms successful polymerization on the MNP@TEOS surface (Peng et al. 2018). The weakness or absence of this peak in spectrum (B) further verifies MMIP formation.

Both spectra display strong Si–O–Si asymmetric stretching at ~1050 cm^{-1}, proving that the silica shell remains intact after modification (Xu & Xu 2017). Finally, the Fe–O bending vibration of the Fe_3O_4 core appears at ~540 cm^{-1} in both spectra; its lower intensity in spectrum (A) reflects surface shielding from polymer coating or metal ion complexation (Nur Masyithah et al. 2024). Overall, the FTIR results confirm successful synthesis of a hybrid magnetic–silica–polymer material. The consistent presence of Si–O–Si and Fe–O bands, with no significant foreign peaks, indicates high purity and the absence of residual reagents. Functional groups such as Si–OH and Fe–O enhance the potential for metal ion adsorption through mechanisms like ion exchange and surface complexation.

The FESEM images (Figure 3(A)-3(B)) show the surface morphology of the silica-coated magnetic nanoparticles, showing irregular, block-like aggregated structures with coarse surfaces. The silica layer encapsulates the MNPs, creating uneven matrix clusters alongside fine, dispersed spherical nanoparticles anchored across the rough, fractured surfaces, confirming successful silica shell formation onto the magnetic core. However, FESEM images of the MMIPs depict highly irregular, porous aggregate structures with pronounced surface roughness (Figure 3(C)-3(D)). Dense clusters of small, spherical polymer nanoparticles uniformly coat the larger core surfaces, forming a heavily textured, sponge-like network that confirms successful surface molecular imprinting and provides enhanced surface area for target binding.

Table 1 shows the BET analysis of MNP@TEOS and MMIPs. The nitrogen adsorption-desorption analysis showed significant changes in surface area and porosity following molecular imprinting. The BET surface area of the MNP@TEOS precursor was found to be 28.7 m^2/g, with a pore diameter of 6.0 nm. Following surface modification, the resulting MMIPs exhibited a substantial increase in both parameters, achieving a surface area of 50.4 m^2/g and an average pore diameter of 13.7 nm. This notable increase in surface area and pore

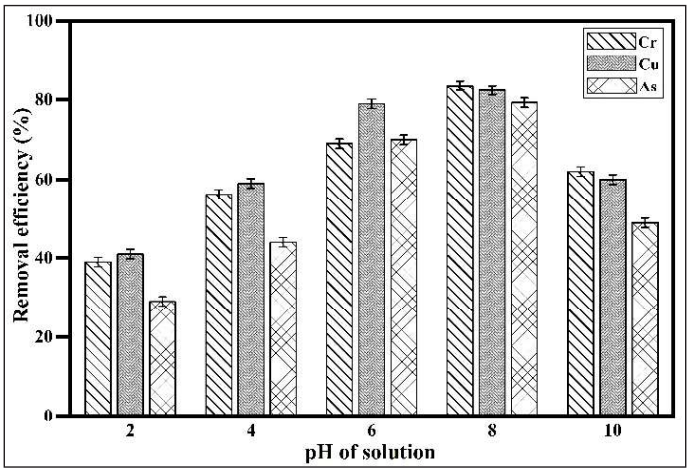


FIGURE 4. Effects of pH on the adsorption of CCA in synthetic wastewater

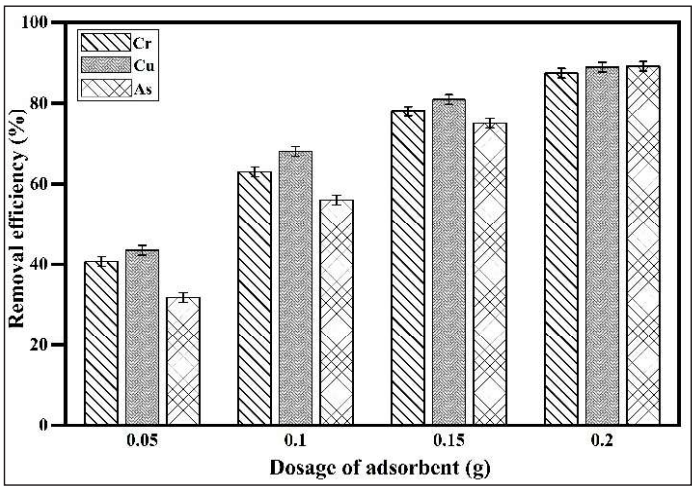


FIGURE 5. Effects of adsorbent dosages on the adsorption of CCA in synthetic wastewater

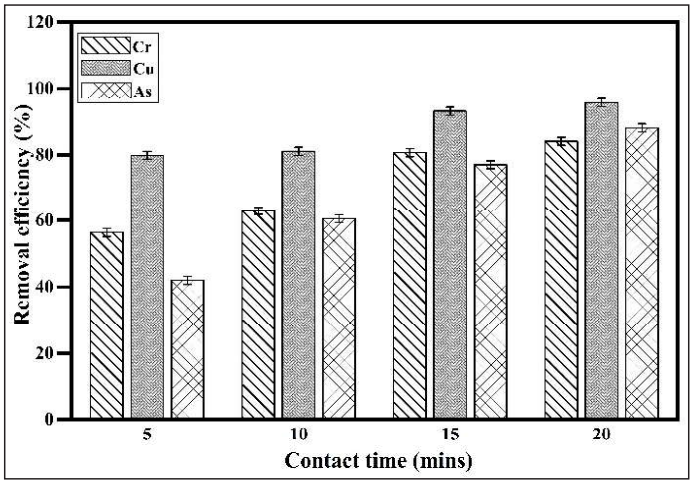


FIGURE 6. Effects of contact time on the adsorption of CCA in synthetic wastewater

size confirms the successful formation of the porous molecularly imprinted polymer layer. The larger surface area and expanded pore dimensions in MMIPs facilitate better accessibility to imprinted cavity sites, which enhances mass transfer and optimises the material's adsorption capacity for target analytes.

OPTIMISATION OF PARAMETERS FOR CHROMIUM, COPPER, AND ARSENIC ADSORPTION

SAMPLE pH

Figure 4 presents the concentrations of synthetic wastewater before and after adsorption at varying pH levels (2, 4, 6, 8, 10), using a fixed initial CCA concentration of 10 ppm, 0.15 g of adsorbent, and 20 min of contact time at 250 rpm. Chromium showed the highest removal at pH 8 (82.5%), likely due to favourable interaction between Cr(VI) and functional groups (–COOH, –OH) on MMIPs in near-neutral conditions. At lower pH (pH 2 and 4), excess protons compete with Cr ions for active sites, reducing adsorption efficiency.

A similar trend was observed for copper, with maximum removal (83.7%) also at pH 8, where Cu^{2+} readily forms coordination bonds with surface functional groups. At pH 10, the formation of $Cu(OH)_2$ may hinder adsorption. Arsenic removal peaked at 79.3% at pH 8. As(V), present as anions, is best adsorbed via electrostatic interactions under near-neutral to slightly alkaline conditions. Reduced performance at pH 10 may be due to competition from excess OH^- ions.

ADSORBENT DOSAGE

Figure 5 summarizes the effect of varying dosages (0.05 g, 0.10 g, 0.15 g, and 0.20 g) on CCA removal from the artificial wastewater. The experiments were conducted with an initial metal concentration of 10 ppm at pH 7, using a contact time of 20 min. The results show a clear increase in removal efficiency with higher adsorbent dosages. For chromium, the removal rose from 40.7% at 0.05 g to 87.5% at 0.20 g, indicating a greater availability of active binding sites. Similarly, copper removal improved to 89.0% at the highest dosage, suggesting enhanced interaction between Cu^{2+} ions and functional groups (–COOH, –OH) on the MMIPs surface.

Arsenic removal also increased markedly from 31.8% to 89.2%, reflecting improved adsorption of As(V) anions through electrostatic interactions and hydrogen bonding as more positively charged surfaces became available. While saturation may eventually occur at higher dosages, the tested range confirms that MMIPs maintain high adsorption capacity across all tested metals.

CONTACT TIME

For contact time, varying contact times (5, 10, 15, and 20 min) will be conducted to observe the effects of contact time on the adsorption process. The initial metal concentration was 10 ppm, at pH 7, using 0.15 g of adsorbent. The results in Figure 6 indicate that removal efficiency increased significantly with longer contact time. For chromium, adsorption rose from 51.5% at 5 min to 84.0% at 20 min, suggesting that equilibrium was nearly reached within this time frame. Copper showed a more rapid uptake, with removal increasing from 77.4% to 95.6%, indicating strong interactions between Cu^{2+} ions and MMIPs functional groups, and high adsorption efficiency within a short time. Arsenic removal also improved from 45.0% to 88.0% as contact time increased.

ELUTION SOLVENT

Elution solvents are essential for desorbing metal ions from adsorbents, either for regeneration or further analysis. In this study, methanol, ethanol, and acetone were tested using 10 ppm metal solutions at pH 7, with 0.15 g of adsorbent and a 20-min contact time. Figure 7 shows that methanol is the most effective solvent, achieving desorption efficiencies of 99.2% for chromium, 92% for copper, and 84.1% for arsenic. Its high polarity and small molecular size likely enhanced its ability to penetrate the adsorbent pores and dissolve bound metal ions. Acetone showed moderate performance, while ethanol had the lowest efficiency, possibly due to weaker interactions with metal ions. These results suggest methanol is the most suitable solvent for metal recovery and MMIPs reuse.

VALIDATION OF CHROMIUM, COPPER, AND ARSENIC ANALYSIS METHOD USING ACTUAL WASTEWATER SAMPLES

To ensure the reliability of the adsorption results, method validation was conducted using real wastewater samples obtained from the Forest Research Institute of Malaysia (FRIM). The sample contained 4% CCA (Chromated Copper Arsenate), a wood preservative with chromium, copper, and arsenic as active components. Testing with real samples provides a more accurate assessment of MMIPs performance under complex, real-world conditions. Testing with actual industrial wastewater is essential to validate MMIP performance amidst matrix interferences, such as ionic strength variations and dissolved organic matter. While ideal model solutions (10 ppm) demonstrate baseline adsorption behavior, validating these results against real samples confirms the adsorbent's practical utility for CCA wastewater treatment (Melliti et al. 2023). Comparable studies in the literature have similarly reported that magnetic molecularly imprinted polymers retain superior selectivity and removal efficiency (>90%) in real matrix evaluations due to pre-organized cavity recognition (Nur Masyithah et al. 2024).

Five real wastewater samples (S1-S5) containing CCA were analyzed to evaluate the performance of MMIPs

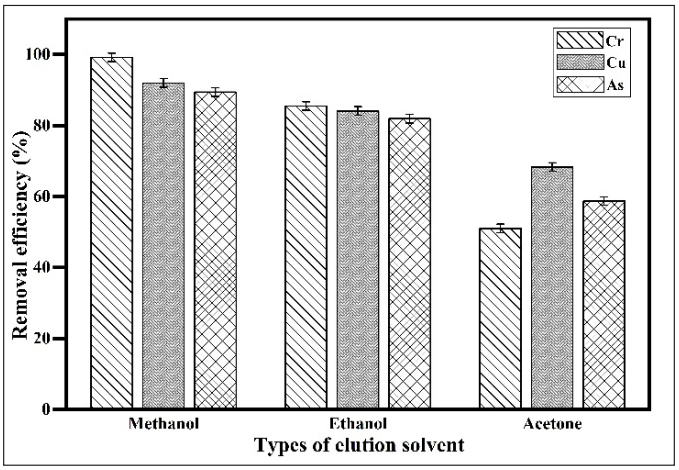


FIGURE 7. Effects of elution solvent on the desorption of CCA in synthetic wastewater

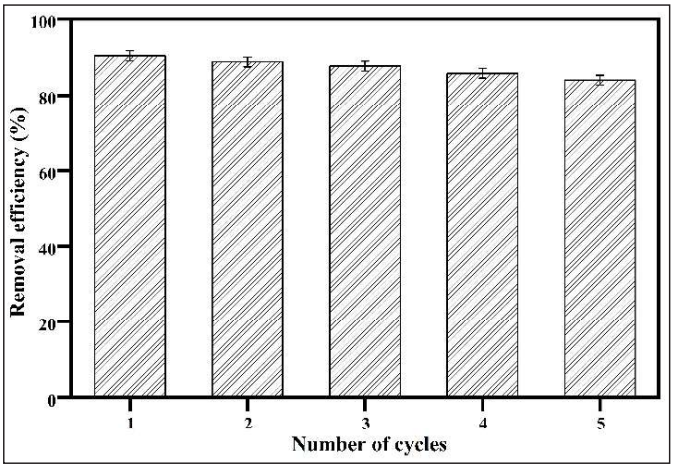


FIGURE 8. Adsorption of CCA from actual wastewater sample

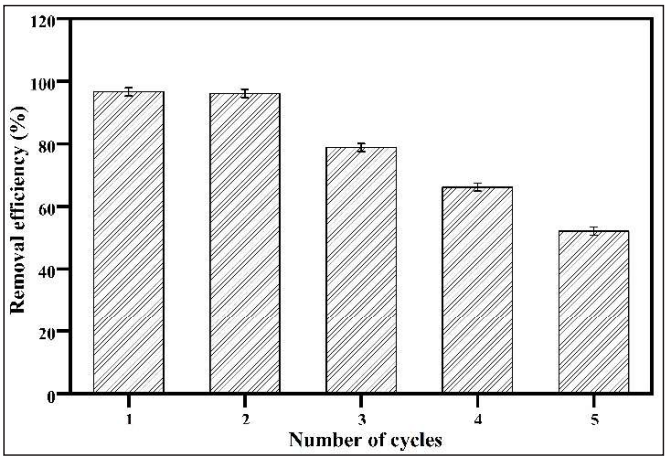


FIGURE 9. Desorption of CCA from actual wastewater sample

under optimal conditions. With an initial concentration of 40 ppm, the final concentrations after 20 min of adsorption were significantly reduced to 3.84 ppm (Cycle 1), 4.50 ppm (Cycle 2), 4.94 ppm (Cycle 3), 5.69 ppm (Cycle 4), and 6.40 ppm (Cycle 5), corresponding to removal efficiencies of 90.40%, 88.75%, 87.65%, 85.78%, and 84.00%, respectively (Figure 8). These results confirm that MMIPs synthesised with MAA and EGDMA on MNP@TEOS surfaces exhibit high efficiency in removing heavy metals from real CCA wastewater, achieving nearly 90% removal within a short contact time.

Figure 9 shows the desorption efficiency of MMIPs over multiple elution cycles using the 4% CCA samples, with the aim of assessing the reusability and regeneration capability of the adsorbent. The desorption process was conducted using methanol as the eluent under optimal conditions. As expected, the desorption efficiency showed a consistent decreasing trend across cycles, as would typically be expected in sequential elution studies. The first cycle exhibited a desorption efficiency of 96.6%, followed closely by 96.07%, 78.76%, 66.21%, and 52.13% in subsequent cycles. These relatively stable values suggest that the MMIPs retains its structural integrity and binding reversibility after each desorption, indicating good potential for reuse.

The lack of a sharp decline in desorption efficiency could be attributed to several factors. It might be due to CCA is bound across sites of non-uniform energy levels, leading to a biphasic release profile during reusability tests. Desorption occurs preferentially from outer, weakly bound sites in early cycles, whereas molecules occupying high-affinity or sterically hindered inner cavity sites are liberated more slowly over extended cycles (Bi et al. 2024; Fu et al. 2026). Moreover, the eluent may gradually penetrate deeper into the polymer structure, accessing binding sites that were initially shielded during the first desorption. Overall trend demonstrates the effective and repeatable desorption performance of MMIPs, supporting its application as a regenerable adsorbent for CCA removal in wastewater treatment.

COMPARISON STUDY

To benchmark the performance of the developed MMIPs against existing technologies, a comparative evaluation of heavy metal adsorbents was conducted. Table 2 summarizes the adsorption capacities, experimental conditions, and performance metrics reported in recent literature alongside the results from this study. The comparison was conducted based on several key criteria, including adsorbent dosage, contact time, initial metal ion concentration, solution pH, type and volume of desorption solvents, and the analytical methods employed. The findings indicate that MMIPs exhibit superior adsorption capabilities relative to conventional adsorbents. This enhanced performance can be attributed to the higher density of accessible active sites and the mesoporous structure of the material, which facilitates efficient metal ion diffusion and binding. The results further affirm that MMIPs are highly effective and reliable for the rapid adsorption of Cr, Cu, and As from aqueous solutions, making them a promising candidate for heavy metal remediation in real-world environmental applications.

MECHANISM OF THE INTERACTION

The molecular mechanism involved in the adsorption of heavy metals such as copper (Cu^{2+}), arsenic (As), and chromium (Cr^{3+}) by MMIPs is primarily governed by a combination of molecular recognition, coordination bonding, and electrostatic interactions (Figure 10). During the synthesis of MMIPs, specific metal ions are used as templates and are complexed with functional monomers containing groups such as carboxyl (–COOH), amine (–NH_2), hydroxyl (–OH), or thiol (–SH). These

TABLE 2. Comparison of the developed adsorbent with other reported adsorbents

Adsorbent	Dosage of adsorbent (mg)	Contact time (min)	Chromatographic analysis	Percentage recovery (%)	References
MIPs	150	30	AAS	65.6	Wu et al. (2022)
MOFs	100	20	AAS	71.2	Bi et al. (2024)
Activated carbon (AC)	250	30	AAS	35.4	Melliti et al. (2023)
Chitosan Composite	300	40	-	64.8	Patel, Pandey & Uppaluri (2024)
Biochar	200	40	AAS	25.1	Ahuja et al. (2022)
Alginate beads	150	25	-	30.2	Mohammed et al. (2022)
This work	100	25	AAS	90.0	-

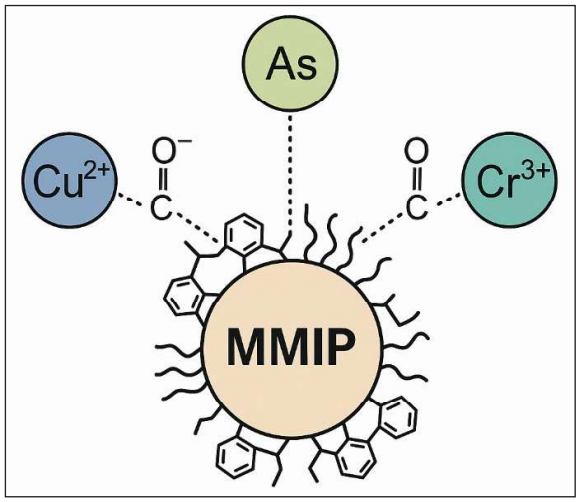


FIGURE 10. Molecular mechanism of adsorption of CCA by the MMIPs

functional monomers form reversible interactions with the metal ions, creating a structured pre-polymer complex. Upon polymerization and subsequent removal of the template ions, selective cavities are formed that are complementary in size, shape, and functional group orientation to the target ions. When exposed to a solution containing Cu^{2+}, Cr^{3+}, or As species, these ions are selectively re-adsorbed into the imprinted cavities through specific interactions. Cu^{2+} and Cr^{3+} typically interact with electron-donating groups via chelation or coordinate covalent bonds, while arsenic, often present as an oxyanion such as arsenate (AsO_4^{3-}), interacts through electrostatic attraction to positively charged sites or via hydrogen bonding. The presence of a magnetic core (Fe_3O_4) facilitates rapid magnetic separation without affecting the adsorption mechanism (Soylak, Konneh & Ahmed 2026). This combination of specificity and magnetic recoverability makes MMIPs highly efficient and reusable for multiple adsorption–desorption cycles, with desorption commonly achieved using acidic or chelating agents to disrupt the metal–ligand interactions (Aziz et al. 2025).

CONCLUSION

This study successfully synthesised MMIPs for efficient removal of chromium, copper, and arsenic from wood treatment wastewater. Under optimised conditions (pH 8, 0.20 g dosage, 20 min contact time), the MMIPs achieved over 90% metal removal efficiency. FTIR analysis confirmed the presence of active functional groups (-COOH, -OH) responsible for metal binding. Application to real wastewater samples validated the material's performance under realistic conditions, highlighting its industrial potential. Compared to conventional methods, this MMIPs system offers selective adsorption, reusability, and environmentally friendly operation. Its magnetic properties also allow easy separation and reduced energy use. Overall, this research contributes valuable insight into advanced materials for sustainable toxic metal remediation.

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