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Molecularly Imprinted Polymers Based on Konjac for Selective Caffeine Adsorption in Aqueous Solution

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Abstract: A number of caffeine extraction methods have been developed, such as microwave assisted extraction and ultrasonic-assisted extraction. The disadvantages of these methods are low selectivity, inconvenience, and inefficiency. Among the existing technologies, molecularly imprinted polymers (MIPs) are one of the most efficient and economical methods for the removal of caffeine contaminants. In this study, the objective was to prepare MIPs for the removal of complicated samples. The obtained materials were used as a sorbent for the extraction of caffeine from coffee brewed in an espresso. The MIPs were prepared using konjac/acrylic acid as a functional monomer, N, N′-methylenebisacrylamide as a cross-linker, and caffeine as a template. The chemical structures of MIPs were characterized by Fourier transform infrared spectroscopy. MIPs exhibited a higher maximum adsorption capacity (87.72 mg/g). The equilibrium adsorption data fit well with the Langmuir adsorption isotherm models, which confirm the monolayer adsorption behaviour of caffeine molecules on the surfaces of the MIPs samples. According to the experimental results of the adsorption capacity of caffeine from aqueous solution, the MIPs showed a higher percentage removal of caffeine (75.66%). Our findings suggest that MIPs are useful adsorbents for the decaffeination of coffee brewed in an espresso.

Keywords: adsorption, molecularly imprinted polymer, konjac, caffeine, sorbent

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1. INTRODUCTION

Caffeine (1,3,7-trimethylxanthine) is a widely known compound found in numerous plants and beverages such as cocoa, coffee, tea, and cola. Caffeine alleviates fatigue by activating the central nervous system and stimulating metabolism. However, consumption for an extended period or in large quantities results in unpleasant effects, including addiction, neuroticism, muscular twitching, and anxiety (1, 2). Limiting caffeine intake from coffee is recommended, depending on the time zone and other conditions. Decaffeinated coffee was first advocated in the early 1900s; by the early 2000s, decaffeinated coffee accounted for approximately 10% of the entire coffee consumption (3). Coffee beans were heavily decaffeinated before roasting. Organic solvents such as chloroform, dichloromethane (4), supercritical carbon dioxide (5, 6), and water were utilized in the initial part of the decaffeination process (7). Following the extraction procedure, further decaffeination was performed. This method of adsorbing caffeine from coffee extracts utilizes adsorbents such as activated carbon (AC) (8), which can reduce the levels of other desirable substances in coffee, such as polyphenols (9, 10).

Molecularly Imprinted Polymers (MIPs) demonstrate a considerably higher affinity towards molecules employed as templates than similar molecules, including closely related isomers. MIPs have

received significant attention in recent years because of their unique benefits, such as predetermined recognition ability, stability, relative ease, low cost of synthesis, and possible application to a wide range of target molecules (11-17). MIPs are distinctly more advantageous than typical solid-phase extraction packing materials in terms of specificity (18). As an adsorbent, caffeine MIP was used to extract caffeine from green tea after four hours of solvent extraction (19). A large quantity of chlorinated solvent is used in the conventional method to obtain caffeine from a sample, which is time-consuming (20). In contrast to traditional sorbents, MIPs are better at concentrating and separating target analytes from mixtures. MIPs are based on synthetic and natural polymers, depending on their primary components. To synthesize MIPs, cross-linking agents, such as N, N′-methylenebisacrylamide and ethylene glycol dimethacrylate, copolymerize functional monomers of acrylic acid (AA) and acrylamide. The resulting copolymers are expensive. Additionally, they exhibit poor biocompatibility and biodegrade slowly in the environment (21, 22). However, MIPs derived from natural polysaccharides, such as cyclodextrin (23,24) and chitosan (25-27), offer the following advantages: they are biocompatible and biodegradable, and particularly well suited for use in biology and medicine. MIPs are cost-effective due to their abundance and biodegradability. Therefore, polysaccharide-based MIPs have gained considerable attention recently. According to Lin et al., MIPs used for protein recognition are based on agarose (28). According to Zhao et al., alginate is used to make MIPs for protein separation (29). Konjac (K), which is a water-soluble polysaccharide with a large molecular mass, is composed of □-1, 4 connected D-glucose and D-mannose units in a 1:1.6 molar ratio. It is prepared from the tubers of the Amorphophallus konjac plant, which is an important crop in mountainous areas. Due to its high water solubility as well as its film and gel properties, konjac has several applications in medicine, biology, chemical engineering, and other fields (30-34). However, research on MIPs based on konjac is limited (35).

MIPs based on konjac were prepared for caffeine extraction using a graft copolymer of konjac and acrylic acid (K-g-PAA) as the functional monomer, N, N′-methylenebisacrylamide as the cross-linker, and caffeine as the template. The adsorption capabilities of the MIPs were tested for caffeine adsorption properties in aqueous solutions. In this study, MIPs were used as sorbents for decaffeinated coffee solutions to find out how well they could remove caffeine from coffee brewed in an espresso.

2. EXPERIMENTAL SECTION

2.1. Chemicals and Materials

Standard caffeine (≥99%), ammonium ceric nitrate (CAN), and acrylic acid (AA) were sourced from Loba Chemie Pvt. Ltd. (India). AA was distilled via CuCl at low pressure prior to use. Theophylline, anhydrous (□99%), and N, N′-methylenebisacrylamide (NMBA, □99%) were purchased from Sigma–Aldrich (USA). Konjac was obtained from Bkkchemi (Thailand) and used as received. Fresh coffee samples were obtained from local markets. All the other reagents were of analytical grade and were used untreated. Deionized water was used throughout the experiments.

2.2. Preparation of Molecularly Imprinted Polymers (MIPs) and Nonimprinted Polymers (NIPs)

Konjac (1.5 g) in 70 mL of deionized water, 1.0 g of caffeine, and 0.14 g of CAN were added and stirred in a three-necked flask. A solution of 935.9 mL of AA and 15.4 g of NMBA was prepared by dissolving them in deionized water; it was poured into the three-necked flask through a pressure equalizing dropping funnel. The filtrate was washed with deionized water, methanol, and acetic acid/methanol, respectively, until no UV absorption was detected at 275 nm. After removing the acetic acid with methanol, it was dried under vacuum for 24 h to obtain MIPs. NIPs were prepared and processed in a similar manner as MIPs, except that caffeine was not used as a template.

2.3. Fourier Transform Infrared Spectroscopy Analysis (FTIR)

FTIR spectra of the samples were obtained using a Shimadzu (FTIR 8900) at wavenumber range from 4000 to 400 cm^{-1} using the KBr pellet technique.

2.4. Determination of Caffeine in Coffee Samples by UV–vis Spectrophotometry

The absorbance of caffeine was measured at 275 nm using a UV-vis spectrophotometer with double-beam optical system (Agilent Cary 60). A calibration curve was constructed each day before the analysis of the samples. Deionized water was used as a blank. Calibration standards from the caffeine stock solution (2 mg/mL) were prepared by dissolving 200.00 mg of pure caffeine in 100 mL of distilled water. Working solutions of 0.014, 0.020, 0.026, 0.032, and 0.038 mg/mL (14, 20, 26, 32, 38 mg/L) caffeine were prepared by serial dilution of the stock in 25 mL volumetric flasks with deionized water.

2.5. Adsorption Experiment

MIPs or NIPs weighing 0.1 g were added to the solution of caffeine (2 mg /mL, pH 7) in a volume of 5 mL. The concentration of caffeine in the filtrate solution was measured using UV-vis spectrophotometer at a wavelength of 275 nm; the adsorption capacity was calculated, and a plot between the adsorption capacity and time was created. The adsorption capacity (Q, mg/g) was primarily determined by the variance in caffeine concentration, which was computed using the following formula:

$$Q=\frac{(C_0-C_t)}{m\times V} \quad \text{(Eq. 1)}$$

where C_0 (mg/mL) is caffeine's initial concentration, C_t (mg/mL) is the caffeine concentration in filtrate at t min, V (mg/mL) is the starting solution volume, and m (mg) is the mass of the MIPs or NIPs.

2.6. Modelling of Experimental Isotherms

The modeling of the experimental data of the isotherms is used to determine the adsorption capacity of MIPs and NIPs adsorbent materials and to evaluate the mechanisms applied in the adsorption process. The Langmuir and Freundlich isotherm models were applied to fit the experimental data. The Langmuir isotherm model justifies a monolayer and homogeneous adsorption.

$$Q_e=\frac{Q_m\times K_L\times C_e}{1+K_L\times C_e} \quad \text{(Eq. 2)}$$

where Q_m (mg/g) and K_L are the Langmuir maximum adsorption capacity of the adsorbent material and Langmuir's constant; Q_e (mg/g) represents the amount of caffeine adsorbed, and C_e represents the equilibrium concentration (mg/mL). According to the Freundlich isotherm model, the adsorption is multilayer and heterogeneous in nature.

$$logQ_e=\frac{1}{n}logC_e+logK_F \quad \text{(Eq. 3)}$$

where K_F and n are the Freundlich adsorption and exponential coefficients, respectively.

2.7. Selectivity Test of MIPs and NIPs

Theophylline was used as a control molecule to determine the selectivity of the MIPs and NIPs. The adsorption test was performed, as previously described, using 0.1 g of MIPs or NIPs in 5 mL of caffeine or theophylline (0.1 mg/mL, pH 7). The selectivity of the MIPs was demonstrated using static distribution coefficient (K_D), separation factor (α), and relative separation factor (β). The values are determined by the following formulas (25, 36):

$$K_D=\frac{Q_e}{C_0} \quad \text{(Eq. 4)}$$

where C_0 (mg/mL) represents the initial precursor concentration and Q_e (mg/g) is the equilibrium adsorption capacity; K_D represents the binding capacity between the MIPs and the precursor (the higher the K_D, the stronger the rebinding capacity).

$$\alpha=\frac{K_{Di}}{K_{Dj}} \quad \text{(Eq. 5)}$$

where K_{Di} and K_{Dj} are the static distribution coefficients of MIPs and control polymers, respectively; α demonstrates the selectivity of MIPs (the higher of the value of α, the better the selectivity).

$$\beta=\frac{\alpha_M}{\alpha_N} \quad \text{(Eq. 6)}$$

where α_M is the separation factor of MIPs, and α_N is the separation factor for control polymers. β demonstrates the difference between molecular selectivity of MIPs and control polymers.

2.8. Caffeine Adsorption Capability of MIPs in Coffee Brewed in an Espresso

A liquid–liquid decantation using dichloromethane was performed for decaffeinating coffee brewed in espresso solutions (37, 38). The coffee solution (Espresso 2 oz, 60 mL) was mixed with MIPs according to the best conditions obtained from the above study. Next, 2 g of sodium carbonate (Na_2CO_3) and 4 mL of dichloromethane (CH_2Cl_2) were added to the mixed samples in a separating funnel and shaken for 20 min. The residual water was separated from dichloromethane by draining dichloromethane through a separating funnel. The extraction was repeated by adding 4 mL of dichloromethane. The extracted solution was evaporated by heating, and the sample was adjusted to the required volume with deionized water before UV–vis analysis, where the absorbance was measured at a wavelength of 275 nm.

3. RESULTS AND DISCUSSION

3.1. Preparation of MIPs (K-g-PAA) and NIPs

Figure 1 illustrates the method of producing MIPs using caffeine as a template. Acrylic acid and konjac are initially bound together by hydrogen bonds surrounding caffeine molecules. Graft copolymers are prepared by graft polymerization using NMBA as the cross-linker and ammonium ceric nitrate as an initiator. Noncovalent linkages were used to imprint the caffeine molecules into the cross-linked graft polymer. When caffeine molecules are removed by the eluent, molecular recognition units are formed, which have equivalent structures and sizes to caffeine molecules (35, 39). Subsequently, the MIPs obtained can selectively recognize caffeine molecules. Typical photographs of MIPs are shown in Figure 2. The sample of dry MIPs resembles a flaky white powder.

3.2. FTIR Analysis of the Samples

The spectra of the samples are illustrated in Figure 3. Caffeine, konjac, MIPs before extraction, MIPs

after extraction, and NIPs are represented by Figure 3(a) – 3(e), respectively. The band at 1657 cm^{-1} is attributed to the stretching modes of the C=O group of caffeine, as illustrated in Figure 3(a). The band at 3109 cm^{-1} is the C–H stretching vibration of caffeine's aromatic rings. Additionally, at 748 cm^{-1}, deformation vibrations are observed.

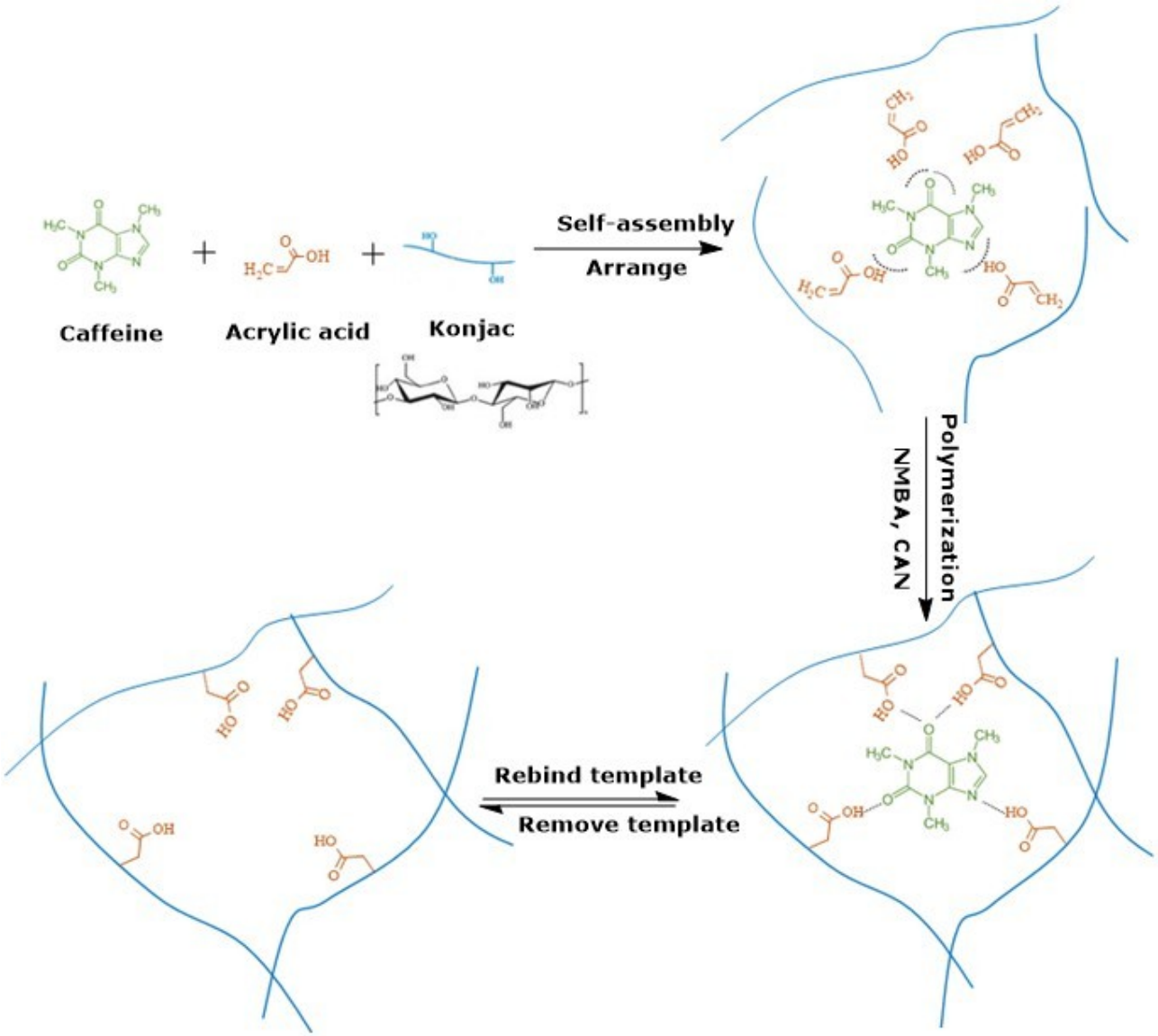

Figure 1: Preparation process of MIPs (K-g-PAA).

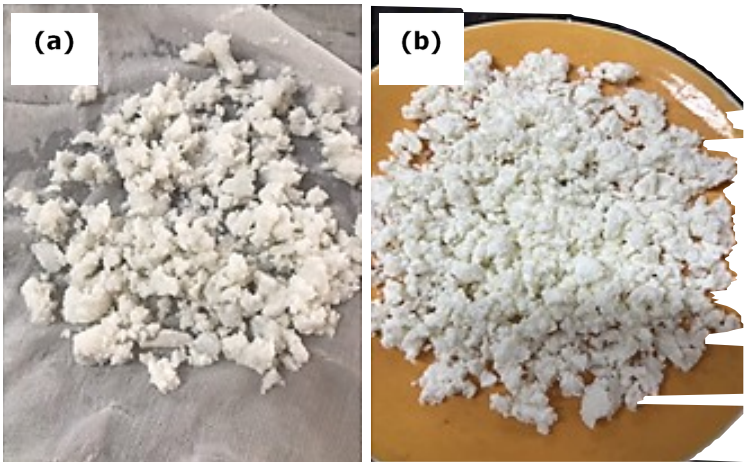

Figure 2: MIPs (K-g-PAA) wet (a) and dry composite (b).

The infrared spectrum of konjac is shown in Figure 3(b). The O–H groups' stretching mode produces a broad band at 3398 cm^{-1}. Sharp bands at 1741 and 1638 cm^{-1} indicated minor C=O groups in konjac and intramolecular hydrogen interactions, respectively. The C–O–C stretching vibrations are attributed to the sharp band at 1020 cm^{-1}. Figure 3(c) illustrates the MIPs' infrared spectrum prior to extraction. In addition to the bands mentioned above for caffeine, there remain the characteristic bands of K-g-PAA. The overlap of O–H groups gives the broad band at 3398 cm^{-1} in both konjac and PAA. The C–O–C stretching and C–H vibrations of konjac are attributed to a sharp band at 1020 cm^{-1} and the band at 2924 cm^{-1}, respectively. For PAA, symmetric and asymmetric stretching of COO^- appear at 1532 and 1407 cm^{-1}, respectively. The carbonyl stretch C=O of a carboxylic acid indicates the presence of a new sharp band at 1659 cm^{-1} . According to the results, caffeine molecules are the template molecules for the graft copolymers (35). The distinctive bands of caffeine disappear in Figure 3(d) (MIPs after extraction), indicating that caffeine had been removed from the MIPs. These differences can be considered as providing evidence that MIPs retained caffeine within their structures, possibly through weak noncovalent interactions like hydrogen bonding. For NIPs, the wave number of 1657 cm^{-1} does not appear in Figure 3(e).

3.3. Adsorption Rate and Adsorption Isotherm of MIPs and NIPs

The adsorption kinetic curves for MIPs and NIPs are shown in Figure 4 (a). Both NIPs and MIPs are capable of adsorbing caffeine. At 80 min, the adsorption capacity increases significantly and gradually decreases until adsorption equilibrium is reached at 120 min. This phenomenon can be explained as follows: In the first stage, adsorption of gels occurs on the surface, resulting in a high adsorption rate. However, as adsorption occurs within the gel network, adsorption equilibrium is subsequently reached on the gels' surfaces. The rate of adsorption is controlled by the rate of caffeine diffusion through the gel network.

Caffeine diffusion into the gels must overcome resistance from the gels' surface and hole wall. As a result, caffeine's diffusion rate is slow, resulting in a slow adsorption rate (40). In addition, the caffeine concentration in the outside solution gradually drops during the adsorption process, but the concentration of caffeine inside the gels rises. Particularly, the concentration gradient between the interior and exterior of the gels reduces, resulting in a low adsorption rate (41). MIPs demonstrate a higher adsorption rate and capacity than NIPs, according to their adsorption curves. This is because template molecules build a large number of recognition units in gel networks during the process, and the adsorption "channels" established by template extraction result in a high adsorption rate.

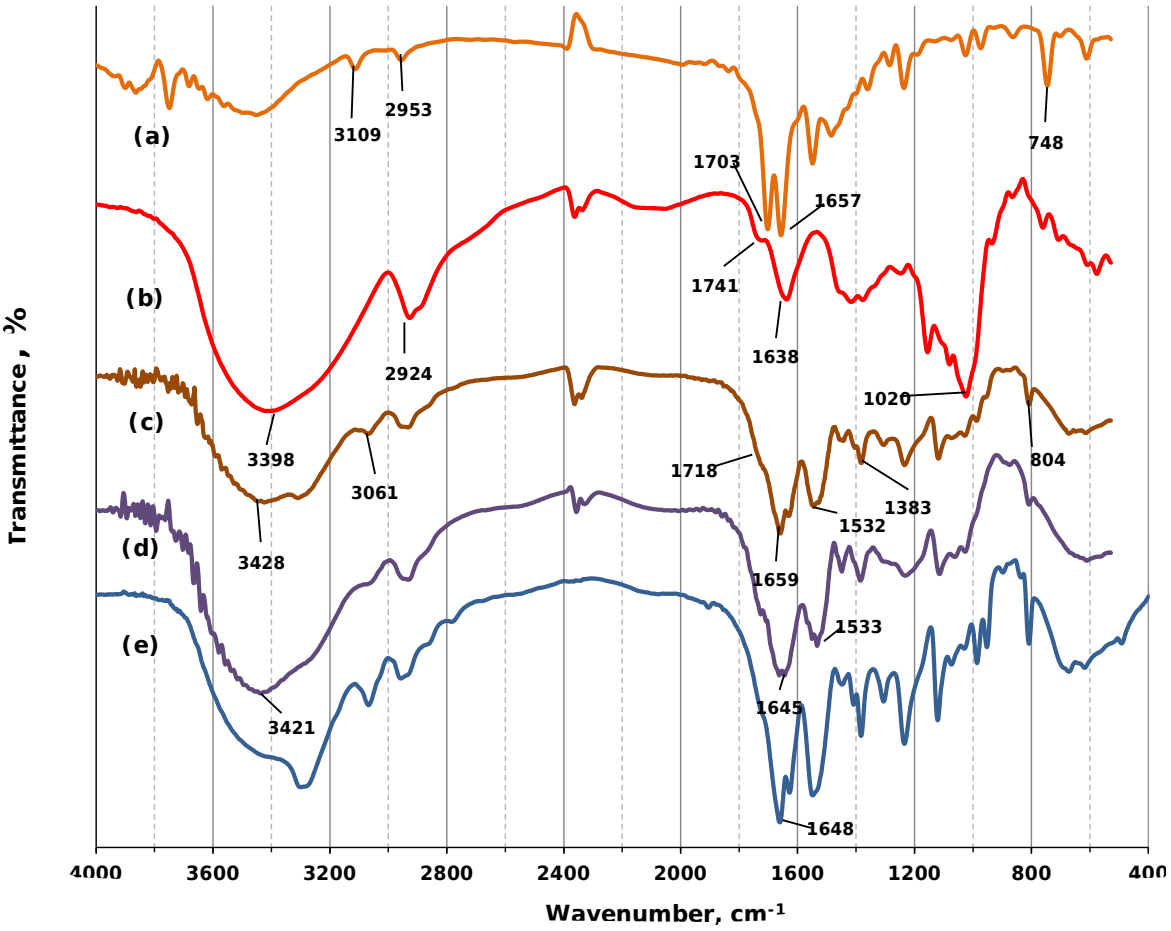

Figure 3: FTIR spectra of MIPs and NIPs ((a), caffeine; (b), Konjac; (c), MIPs before extraction; (d), MIPs after extraction (e) NIPs.)

The adsorption isotherm models for the MIP and NIPs at various caffeine concentrations are depicted in Figure 4 (b). The equilibrium adsorption capacities of both MIPs and NIPs increase with increasing caffeine concentration and then stabilize at a certain level of caffeine concentration. When the interaction between recognition units and caffeine approaches saturation, the gel networks keep a constant number of recognition units, and the adsorption capacity does not increase with increasing caffeine concentration (42). The adsorption isotherms are fitted by Langmuir and Freundlich equations to understand the behaviour of adsorption (26, 43). Figure 5 shows the fitted straight lines for the Langmuir (a) and Freundlich (b) equations, where Q_m of the Langmuir equation and n of the Freundlich equation are calculated from the corresponding slopes; K_L of the Langmuir equation and K_F of the Freundlich equation are calculated from the corresponding intercepts, respectively (Table 1). With the Langmuir model, the linear correlation coefficients for MIPs and NIPs are 0.9978 and 0.9950, respectively. They are greater than the correlation coefficients for MIPs and NIPs with the Freundlich model, which are 0.9757 and 0.9646, respectively. Therefore, the adsorption behaviour of both MIPs and NIPs for caffeine can be expressed in terms of the Langmuir equation; the adsorption behaviour indicates monolayer adsorption (1). Based on the intercept, the Q_m values of MIPs and NIPs are 87.72 and 70.92 mg/g, respectively; the K_L values are 5.18 and 4.02, respectively. Higher Q_m values result in higher adsorption capacities. Similarly, higher K_F values result in higher adsorption rates.

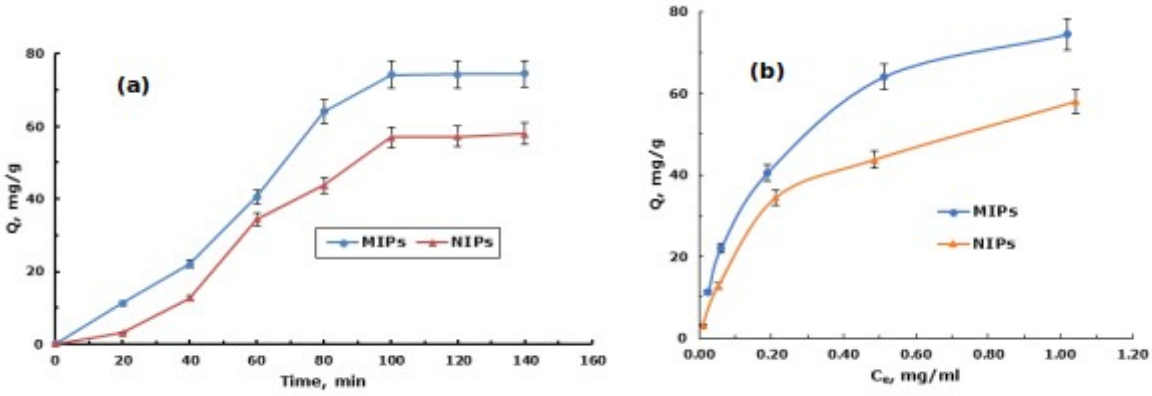

Figure 4: Adsorption kinetics (a) and adsorption isotherms (b) of caffeine on MIPs and NIPs.

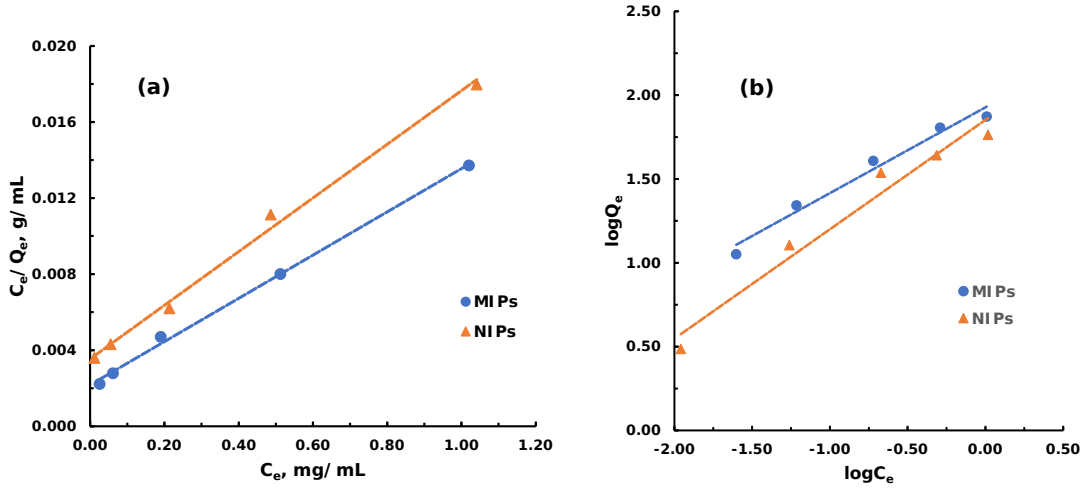

Figure 5: Langmuir isotherms (a) and Freundlich isotherms (b) for caffeine adsorption on MIPs and NIPs.

3.4. The Effect of pH on MIPs and NIPs Adsorption

The effect of pH on the adsorption capacity of MIPs and NIPs with various pH values is shown in Figure 6. Q_e initially increases and subsequently decreases with increasing pH in the pH range of 4–7. The highest value of Q_e is obtained at pH 6, but compared to pH 7, there is a slight difference, which gave the experimental results some similarity to those of Da-Ting et al. (35), and also made pH control easy. Therefore, pH 7 was chosen for further study. The following explanations are possible for this occurrence: The structures of the polymer shrink at low pH because the polymer chains of MIPs and NIPs contain COOH groups, resulting in a low Q_e. However, the structures expand as the pH increases due to reciprocal exclusion of COO– groups, resulting in an increase in Q_e. Furthermore, Q_e is maximized when a suitable hole is produced in the network. However, as the pH rises, the holes in the structure become wider, destroying the gels' selective adsorption capability, and as a result decreasing Q_e. Additionally, MIPs exhibit greater Q_e values than NIPs at all pH values, indicating that unique recognition units for caffeine are formed.

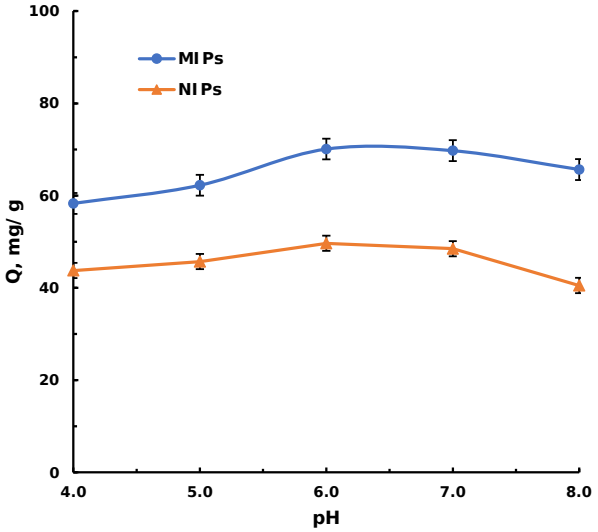

Figure 6: Effect of pH on the adsorption capacity of MIPs and NIPs.

Table 1: Parameters of the equations for the adsorption model of caffeine on MIP and NIP.

Sample	Experimental	Langmuir			Freundlich		
	Q_e (mg/g)	K_L (g/mL)	Q_m (mg/g)	R^2	n	K_F (mg/g)	R^2
MIP	74.40	5.18	87.72	0.9978	1.95	84.43	0.9757
NIP	57.95	4.02	70.92	0.9950	1.53	71.07	0.9646

Table 2: The selectivity of MIPs on caffeine.

Amount of template (mg/L)	K_D (L/g)		α	β
	Caffeine	Theophylline		
0.0	57.95	54.55	1.06	-
0.5	67.84	44.54	1.52	1.43
1.0	74.40	40.21	1.85	1.74

3.5. Selectivity of MIPs

MIPs develop specialized recognition units with certain shapes and sizes when caffeine molecules are cross-linked to the functional monomers of K-g-PAA. These recognition units can be used to selectively adsorb caffeine once the template has been eliminated. Considering the chemical structure of theophylline is similar to that of caffeine, theophylline is used as a competitive molecule to investigate the selectivity of MIPs for caffeine molecules. Table 2 shows the selectivity of MIPs and NIPs in the presence of different templates. K_D, or the static allocation coefficient, is an indicator of the MIPs or NIPs' ability to bind to their target molecules; a high K_D value indicates that MIPs have a high affinity for the target molecules. However, the separation factor and imprinting efficiency measure the selectivity of MIPs or NIPs for target molecules; high values indicate that the MIPs have great selectivity. MIPs have a greater K_D for caffeine than for theophylline. Additionally, as the amount of template increases, the K_D for caffeine increases, whereas the K_D for theophylline slightly decreases, indicating that MIPs have a stronger binding ability for caffeine than theophylline. The variation in adsorption capacity can be attributed to the formation of specific recognition units during the imprinting process. Additionally, as shown in Table 2, both □ and □ exhibit an increasing trend as the amount of template increases, indicating that the amount of template affects the recognition performance of MIPs. Of course, with the increase in the amount of template, the number of specific recognition units in MIPs is increased, and the affinity of MIPs to caffeine becomes stronger.

The adsorption capacities of other adsorbents for caffeine MIPs reported in previous studies were compared in the present study (Table 3). It is evident that the caffein MIPs based on konjac, which were prepared by using a graft copolymer of konjac and acrylic acid as the functional monomers, and N, N′-methylenebisacrylamide as the cross-linker, showed the highest adsorption capacity.

Table 3: Adsorption capacities of different MIPs for caffeine.

Preparation of caffeine MIPs	Q_m	Reference
Functional monomer: methacrylic acid Cross-linker: ethylene glycol dimethacrylate	28.10	44
Functional monomer: methacrylic acid Cross-linker: ethylene glycol dimethacrylate	39.65	45
Functional monomer: konjac glucomannan/acrylic acid Cross-linker: N, N′-methylenebisacrylamide	62.97	35
Functional monomer: konjac/acrylic acid Cross-linker: N, N′-methylenebisacrylamide	87.72	This study

3.6. Caffeine Adsorption Capability of MIPs in Coffee Brewed in an Espresso

In terms of the adsorption capacity of caffeine from coffee brewed in an espresso, MIPs demonstrate a higher percentage removal of caffeine (75.66%). Therefore, MIPs have the potential to be applied in future work.

4. CONCLUSION

In this study, MIPs demonstrated a high capacity for caffeine adsorption. The Langmuir equation is suited to describing the adsorption behaviour of molecularly imprinted polymers for caffeine; the maximum adsorption of caffeine was 87.72 mg/g, which occurred near pH 7 within 120 min. The Langmuir adsorption isotherm model displayed the monolayer adsorption of caffeine molecules on the MIPs. Caffeine extraction from aqueous solution was more efficient using MIPs because they exhibit significantly higher affinity and selectivity for the caffeine used as the template than for similar molecules. Therefore, it can be potentially used for the extraction and separation of caffeine from coffee brewed in an espresso.

5. CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. James JE. Caffeine and cognitive performance: persistent methodological challenges in caffeine research. Pharmacol Biochem Behav. 2014;124:117-122. Available from: <DOI>

2. Rodriguez RS, Haugen R, Rueber A, Huang CC. Reversible neuronal and muscular toxicity of caffeine in developing vertebrates. Comp Biochem Physiol C. Pharmacol Toxicol. 2014;163:47-54. Available from: <DOI>

3. Silvarolla MB, Mazzafera P, Fazuoli LC. Plant biochemistry: a naturally decaffeinated arabica coffee. Nature. 2004;429:826-826. Available from: <DOI>

4. Bichsel B. Diffusion phenomena during the decaffeination of coffee beans. Food Chemistry. 1979;4(1):53-62. Available from: <DOI>

5. Zosel K. Separation with supercritical gases: practical applications, Angewandte Chemie International Edition in English. 1978;17(10):702-709. Available from: <DOI>

6. Udaya sankar K, Manohar B, Chokkalingam AA. A note on supercritical carbon dioxide decaffeination of coffee. J Food Sci Technol. 1986;23(6):326-328. Available from: <DOI>

7. Ramalakshmi K, Raghavan B. Caffeine in coffee: its removal Why and how. Crit Rev Food Sci Nutr. 1999;39(5):441-456. Available from: <DOI>

8. Birtigh A, Liu K, Johannsen M. Regeneration methods for caffeine-loaded CO_2. Sep Sci Technol. 1995;30(17):3265-3286. Available from: <DOI>

9. Farah A, Paulis T, Moreira D. P. Chlorogenic acids and lactones in regular and water-decaffeinated arabica coffees. J Agric Food Chem. 2006;54(2):374-381. Available from: <DOI>

10. Machmudah S, Kitada K, Sasaki M. Simultaneous extraction and separation process for coffee beans with supercritical CO_2 and water. Ind Eng Chem Res. 2011;50(4):2227-2235. Available from: <DOI>

11. He CY, Liu F, Li KA, Liu HW. Molecularly imprinted polymer film grafted from porous silica for selective recognition of testosterone. Anal Lett. 2006;39(2):275-286. Available from: <DOI>

12. Yang HH, Zhang SQ, Tan F, Zhuang ZX, Wang XR. Surface molecularly imprinted nanowires for biorecognition. J Am Chem Soc. 2005;127(5):1378-1379. Available from: <DOI>

13. Sun Y. Molecularly imprinted polymer for 2, 4-dichlorophenoxyacetic acid prepared by a sol-gel method. J Chem Sci. 2014;126(4):1005-1011. Available from: <DOI>

14. Tadi KK, Motghare RV. Computational and experimental studies on oxalic acid imprinted polymer. J Chem Sci. 2013;125(2):413-418. Available from: <DOI>

15. Sellergren B. Molecularly Imprinted Polymers, Man made mimics of antibodies and their applications in analytical chemistry, Techniques and Instrumentation in Analytical Chemistry. Elsevier Publishers. 2001;23.

16. Kupai J, Razali M, Büyüktiryaki S, Keçili R, Szekely G. Long-term stability and reusability of molecularly imprinted polymers. Polym Chem. 2017;8:666-673. Available from: <DOI>

17. Suravajhala R, Burri H R, Malik B. Development of highly specific and selectively recognizing caffeine imprinted polymer nanomaterials with EGDMA crosslinker. Current Nanomaterials, 2022;7(1):65-72. Available from: <DOI>

18. Theodoridis G, Manesiotis P. Selective solid-phase extraction sorbent for caffeine made by molecular imprinting. J Chromatogr A. 2002;948(1-2):163-169. Available from: <DOI>

19. Farrington K, Magnerb E, Regan F. Predicting the performance of molecularly imprinted polymers: Selective extraction of caffeine by molecularly imprinted solid phase extraction. Anal Chim Acta. 2006;566:60-68. Available from: <DOI>

20. He C, Long Y, Pan J, Li K, Liu F. Application of molecularly imprinted polymers to solid-phase extraction of analytes from real samples. J Biochem Biophys. Methods. 2007;70(2):133-150. Available from: <DOI>

21. Saloni J, Lipkowski P, Dasary SSR, Anjaneyulu Y, Yu H, Hill GJr. Theoretical study of molecular interactions of TNT, acrylic acid, and ethylene glycol dimethacrylate-elements of molecularly imprinted polymer modelling process. Polymer. 2011;52(4):1206-1216. Available from: <DOI>

22. Ge Y, Butler B, Mirza F, Habib-Ullah S, Fei D. Smart molecularly imprinted polymers: Recent developments and applications. Macromol Rapid Commun. 2013;34(11):903-915. Available from: <DOI>

23. Piletsky SA, Andersson HS, Nicholls A. The rational use of hydrophobic effect-based recognition in molecularly imprinted polymers. J Mol Recog. 1998;11(1-6):94-97. Available from: <DOI>

24. Sreenivasan K. Synthesis and evaluation of a Beta cyclodextrinbased molecularly imprinted copolymer. J Appl Polym Sci. 1998;70(1):15-18. Available from: <DOI>

25. Wang Y, Wang E, Wu Z, Li H, Zhu Z, Zhu X, et al. Synthesis of chitosan molecularly imprinted polymers for solid-phase extraction of methandrostenolone. Carbohydr Polym. 2014;101:517-523. Available from: <DOI>

26. Zhang YL, Zhang J, Dai CM, Zhou XF, Liu SG. Sorption of carbamazepine from water by magnetic molecularly imprinted polymers based on chitosan-Fe_3O_4. Carbohydr Polym. 2013;97(2):809-816. Available from: <DOI>

27. Yıldırım A, Acay H, Baran A. Synthesis and characterization of molecularly imprinted composite as a novel adsorbent and competition with non-imprinting composite for removal of dye. J. Turk. Chem. Soc., Sect. A: Chem. 2021;8(2):609-622. Available from: <DOI>

28. Lin Y, Tang SQ, Mao X, Bao LJ. Protein recognition via molecularly imprinted agarose gel membrane. J Biomed Mater Res A. 2008;85(3):573-581. Available from: <DOI>

29. Zhao KY, Cheng GX, Huang JJ, Ying, XG. Rebinding and recognition properties of protein-macromolecularly imprinted calcium phosphate/alginate hybrid polymer microspheres. React Funct Polym. 2008;68(3):732-741. <DOI>

30. Brenner T, Wang Z, Achayuthakan P, Nakajima T, Nishinari K. Rheology and synergy of κ-carrageenan/locust bean gum/konjac glucomannan gels. Carbohydr Polym. 2013;98(1):754-760. <DOI>

31. Ratcliffe I, Williams PA, English RJ, Meadows J. Small stain deformation measurements of konjac glucomannan solutions and influence of borate cross-linking. Carbohydr Polym. 2013;95(1):272-281. Available from: <DOI>

32. Tian DT, Li SR, Liu XP, Wang JS, Hu S, Liu CM. Synthesis and properties of konjac glucomannangraft-poly(acrylic acid-co-trimethylallyl ammonium chloride) as a novel polyampholytic superabsorbent. Adv Polyml Tech. 2013;32(S1):E131-E140. Available from: <DOI>

33. Wu WT, Yang LC, Chen HL. Effects of konjac glucomannan, inulin and cellulose on acute colonic responses to genotoxic azoxymethane. Food Chem. 2014;155:304-310. Available from: <DOI>

34. Zhang C, Chen JD, Yang FQ. Konjac glucomannan, a promising polysaccharide for OCDDS. Carbohydr Polym. 2014;104:175-181. Available from: <DOI>

35. Da-Ting T, Yu-Ch, Z, Ling X, Fang-Ting L. Synthesis and properties of caffeine molecularly imprinted polymers based on konjac glucomannan. Adv Polym Techno. 2017; 36(1):68-76. Available from: <DOI>

36. Tan CJ, Wangrangsimakul S, Bai R, Tong YW. Defining the Interactions between Proteins and Surfactants for Nanoparticle Surface Imprinting through Miniemulsion Polymerization. Chem Mater. 2008;20(1):118-127. Available from: <DOI>

37. Clarke RJ. In Proceedings of the 9th Coll. ASIC. 1980;467-472.

38. Rofti J. In Proceedings of the 5th Coll. ASIC. 1971;179-200.

39. Kai A, Huiting K, Lilei Z, Lianxiong G, Dating T. Preparation and properties of thermosensitive molecularly imprinted polymer based on konjac glucomannan and its controlled recognition and delivery of 5-fluorouracil. J Drug Deliv Sci Technol. 2020;60:101977. Available from: <DOI>

40. Atia AA, Donia AM, Yousif AM. Removal of some hazardous heavy metals from aqueous solution using magnetic chelating resin with iminodiacetate functionality. Sep Purif Technol. 2008;61(3):348-357. Available from: <DOI>

41. Demirel G, Özçetin G, Turan E, Çaykara T. pH/temperature-sensitive imprinted ionic poly (N-tert-butylacrylamide-co-acrylamide/maleic acid) hydrogels for bovine serum albumin. Macromol Biosci. 2005;5(10):1032-1037. Available from: <DOI>

42. Kimhi O, Bianco-Peled H. Study of the interactions between protein-imprinted hydrogels and their templates. Langmuir. 2007;23(11):6329-6335. Available from: <DOI>

43. Li N, Ng TB, Wong JH, Qiao JX, Zhang YN, Zhou R, et al. Separation and purification of the antioxidant compounds, caffeic acid phenethyl ester and caffeic acid

from mushrooms by molecularly imprinted polymer. Food Chem. 2013;139(1-4):1161-1167. Available from: <DOI>

44. Wei S-L, Guo X-J, Wang H-W, Tian Y-X, Yan Z-J. Preparation of caffeine molecularly imprinted polymers and application on solid phase extraction. Chinese J Anal Chem. 2012;40(07):1071-1075. Available from: <DOI>

45. Yinzhe J, Dae-Ki C, Kyung H R. Adsorption isotherms of caffeine on molecular imprinted polymer. Korean J. Chem. Eng. 2008;25(4):816-818. Available from: <DOI>