

Preparation of N-methylimidazolium-based Strongly Basic Macroporous Resins and Their Adsorptions Performance towards Aromatic Acids

Guangming Zhong

Jiaxiang Guo

Jing Xiao

Xueyan Lin

Xin Xu

Ke Zhang

Mingze Zhang

Xueying Hou

Yuli Fu

yulifu_tut@163.com

Mancai Xu

Shihua Zhong

Research Article

Keywords: Adsorption, Resin, Aromatic acid

Posted Date: May 11th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9497558/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Journal of Polymer Research on August 29th, 2026. See the published version at <https://doi.org/10.1007/s10965-026-05089-w>.

Abstract

Herein, N-methylimidazolium-based strongly basic macroporous resins were synthesized according to bimolecular nucleophilic substitution (SN_2), and they were applied to adsorb aromatic acids of different molecular weights in aqueous and isopropanol. Using chloromethylated polystyrene (PS) as the matrix and N-methylimidazole as the functional monomer, a bimolecular nucleophilic substitution reaction at 383 K produced the functionalized resin PS-R-X. Subsequently, ion exchange with NaOH, HCl, and HNO_3 was performed respectively to obtain the resin in three distinct ionic forms (PS-R-OH, PS-R-Cl, and PS-R- NO_3). Consistent with the Type I strongly basic anion exchange resin selectivity order ($\text{NO}_3^- > \text{Cl}^- > \text{OH}^-$), PS-R-OH exhibited higher adsorption capacities for naphthol, binaphthol, and benzoic acid than PS-R-Cl and PS-R- NO_3 . Adsorption experiments were conducted on benzoic acid, naphthol and binaphthol, and the adsorption capacity reached 405.90, 511.55, and 453.28 and mg/g at 298K, respectively. PS-R-OH also showed superior adsorption selectivity, good reproducibility, and effective reusability, highlighting its strong potential for aromatic acid adsorption. Mechanistic analysis revealed that the adsorption process was dominated by hydrophobic interactions and desolvation effects, operating in conjunction with π - π interactions and hydrogen bonding.

1. Introduction

The ongoing expansion of industrial production worldwide has led to severe and unavoidable damage to the ecological environment. A wide range of organic pollutants, particularly aromatic compounds such as phenols and benzoic acid, are present in industrial wastewater. These substances are teratogenic, carcinogenic, and bioaccumulative, thereby presenting a serious risk to both human health and ecological security^[1-3]. Benzoic acid, though structurally simple, can acidify water bodies, harm aquatic life, and contribute to photochemical ozone formation in the atmosphere^[4]. Phenolic compounds including phenol, naphthol, and binaphthol are widely used in pesticides, pharmaceuticals, coking, oil refining, metallurgy, and insulation materials, resulting in highly toxic and concentrated wastewater. Naphthol, an important chemical intermediate, generates wastewater that is highly toxic and difficult to degrade. Binaphthol, a precursor in drug synthesis, similarly poses environmental risks. Improper discharge or insufficient treatment of these phenols leads to resource waste, water pollution, and serious ecological damage^[5]. Therefore, the rapid and efficient removal of such organic pollutants has become increasingly significant and has attracted growing research attention in recent years^[6].

Porous polymer adsorbents, owing to their high adsorption capacity, low preparation cost, and good regeneration and reusability, are widely used for the treatment of organic compound in aqueous solutions to achieve their adsorption, separation, and purification^[7, 8]. As a typical representative of porous materials, resins have garnered growing interest from researchers and are developing rapidly. Conventional adsorption resins rely solely on physical pores and hydrophobic interactions to adsorb aromatic compounds, resulting in a relatively simple adsorption mechanism. In contrast, ion exchange resins feature ionizable functional groups such as sulfonic acid groups ($-\text{SO}_3\text{H}$) and carboxyl groups ($-\text{COOH}$)

COOH) bonded to their surface or matrix, thereby endowing them with a richer adsorption mechanism. For organic acid pollutants in aqueous solutions, in addition to traditional hydrogen bonding and π - π interactions, ion exchange resins can more importantly utilize their charged functional groups to undergo electrostatic interactions or even specific ion exchange with organic acid anions. This chemical bonding significantly enhances the binding affinity and adsorption selectivity toward organic acids. Benefiting from this stoichiometry-based ion exchange process, ion exchange resins maintain high and stable removal efficiency even under low concentrations of organic acids. Based on this, Zhang et al.^[9] developed a starch-based ion exchange resin (SIR) through the copolymerization of raw starch with styrene (ST) and sodium methallyl sulfonate (SMAS). According to the introduction of SMAS and ST, strong acidic groups ($-\text{SO}_3^-$) were incorporated to endow ion exchange functionality, while ST enhanced both the physicochemical stability and mechanical robustness of the SIR. This consequently increased its adsorption capacity for dyestuffs and limited the swelling of the starch matrix. Sareena Mhadmhan et al.^[10] proposed an alternative process for reducing the acidity of refined palm oil by adsorbing free fatty acids (FFAs) using an anion exchange resin (AER). The findings revealed that the quaternary ammonium groups within the resin exhibit a strong tendency to dissociate for anion exchange, and the gel-type resin allowed easy access for FFA molecules. The type of functional group had a greater impact than the resin architecture. The dominant adsorption mechanism was governed by ion exchange equilibrium, not by hydrogen bonding complexes. Weakly basic anion exchange resins are generally prepared by introducing weakly basic functional groups such as primary amine ($-\text{NH}_2$), secondary amine ($-\text{NHR}$), or tertiary amine ($-\text{NR}_2$) groups onto the base resin. James T. M. Amphlett et al.^[11] obtained a series of linear polyamine-functionalized weakly basic anion exchange resins by employing Merrifield resin. The results showed that the synthesized polyamine resins outperformed commercially available ones under industrially relevant uranyl ion concentrations, and their absorption capacity rose as the polyamine chain length increased. Isotherm studies of uranium loading were carried out and modeled using the Langmuir and Dubinin-Radushkevich equations, yielding a maximum observed loading capacity of 269.50 mg/g.

In this work, using chloromethylated polystyrene (PS) as the matrix and N-methylimidazole as the functional monomer, and three functionalized macroporous resins were constructed by SN_2 reaction (Scheme 1). After the characterization of the resin in detail, the influencing factors including temperature, concentration, contact time and ion concentration ($\text{Cl}^- / \text{SO}_4^{2-}$) on the adsorption of three aromatic organic acids by PS-R-OH were investigated. It was found that the modified resin exhibited markedly enhanced capability for adsorbing aromatic organic acids, which was attributed to the increased polarity and the introduction of abundant hydroxyl groups through functionalization. This modification strengthened acid-base interactions, as well as enhanced hydrogen bonding, π - π interactions, and hydrophobic effects during the adsorption process. In addition, PS-R-OH was applied to the extraction of aromatic acids in isopropanol and exhibited excellent adsorption capacity.

2. Results and discussion

2.1 Characterization of the resins

In this work, N-methylimidazole was intended to be chemically grafted onto PS via bimolecular nucleophilic substitution. The FT-IR spectra shown in Fig. 1(a) indicated that the C-Cl stretching vibrations ^[12, 13] observed at 1261 cm⁻¹ and 679 cm⁻¹, were considerably reduced following the reaction. As determined by the Volhard method ^[14], PS-R-OH exhibited a much lower chlorine content (1.86 mmol/g) compared to PS (4.99 mmol/g). Meanwhile, the strong-base exchange capacity of PS-R-OH was measured to be 3.37 mmol/g. Additionally, PS-R-OH, PS-R-Cl, and PS-R-NO₃ all showed strong absorption peaks at 1159 cm⁻¹ and 1666 cm⁻¹, corresponding to the C-H bending mode of the imidazole ring and the C-N stretching mode of the imidazole group, respectively ^[15]. An additional vibration band appeared in the range of 3680–3209 cm⁻¹, attributable to the N-H stretching of N-methylimidazole. The elemental composition of the resin was further examined using XPS analysis. Notably, compared with PS-R-OH and PS-R-Cl, PS-R-NO₃ exhibited a very strong peak at 1352 cm⁻¹, which corresponds to the nitro group of the nitrate-type resin ^[16]. As depicted in Fig. 1(b), the Cl species decreased markedly after substitution, whereas O and N contents appeared, indicating substantial consumption of imidazole groups on the resin. High-resolution C 1s spectra showed that the C-Cl configuration of PS at 285.68 eV declined obviously, while peaks corresponding to C-N and C = N configurations emerged at 286.53 eV and 287.64 eV (Fig. 1(c)) for PS-R-OH. The high-resolution N 1s spectra in Fig. 1(d) further revealed N-C, N⁺=C, and N⁺-C configurations at 401.75 eV, 399.4 eV, and 532.81 eV for PS-R-OH ^[17]. These results further confirm that the modification was successfully achieved.

According to Table 1, PS exhibits an S_{BET} of 84.78 m²/g and a V_{total} of 0.60 cm³/g. After the SN₂ reaction, these two values slightly decreased to 80.15 m²/g and 0.58 cm³/g. This is attributed to the preferential grafting of the bulky N-methylimidazole groups, which partially blocked the entrances of smaller mesopores, reducing the accessibility of nitrogen molecules to these pores at low temperatures, as reflected by the decreases in S_{BET} and V_{total} . Since the pore volume decreased less than the specific surface area, the average pore size showed a slight increase. This demonstrates that the grafting reaction occurs not only on the external surface of the resin but also deep inside the pores, with a more pronounced effect on the smaller pores. As classified by IUPAC, the nitrogen adsorption isotherms follow a Type-II profile (Fig. 1(e)). The steep rise in uptake at relatively high relative pressures ($P/P_0 > 0.9$) suggests that both PS-R-OH and PS are predominantly composed of mesopores and macropores in the range of 20–60 nm ^[18, 19], in agreement with the results presented in Fig. 1(f). This pore size range avoids the excessive mass transfer resistance typical of micropores while providing sufficient specific surface area for site loading, which facilitates rapid diffusion of adsorbate molecules in aqueous phase adsorption.

Notably, the water content of the functionalized resin increased sharply from 51.83% to 71.03%. This synergistic outcome arises from the combination of chemical modification and physical structure, with chemical modification being the dominant factor. The N-methylimidazolium salt introduced by the SN₂ reaction and the subsequently generated hydroxyl groups are strongly hydrophilic, significantly enhancing the affinity between the resin and water molecules through hydrogen bonding, thereby

providing a "water absorption driving force". Meanwhile, the increase in pore size from 27.18 nm to 27.27 nm (Table 1) expands the storage space for water molecules, providing "water storage capacity". The synergy of these two factors endows PS-R-OH with good wettability and swelling ability in aqueous solution. The alcohol hydroxyl content of PS-R-OH was measured to be as high as 62.65%, further confirming the presence of abundant active sites.

Table 1
The structure parameters of the resin

S_{BET} (m ² /g)	PS	PS-R-OH
	84.78	80.15
V_{total} (cm ³ /g)	0.60	0.58
Average pore size (nm)	27.18	27.27
Weak base exchange (mmol/g)	-	3.37
Chlorine content (mmol/g)	4.99	1.86
Water content (wt.%)	51.83	71.03
Alcohol content (wt.%)	-	62.65

Scanning electron microscope (SEM) images of the resin samples are presented in Fig. 2. Both PS and PS-R-OH were observed as regular spherical particles. Notably, the alternating light and dark microstructures clearly indicate that PS-R-OH possesses a larger pore size and a rougher surface, which arises from the modification with polar functional groups. The introduction of these polar groups enables the resin to demonstrate outstanding adsorption performance.

2.2 The adsorption of the aromatic acids on PS-R-OH

The adsorption performance of different resin samples toward naphthol is compared in Fig. 3(a), where PS-R-OH clearly outperforms PS, PS-R-Cl, and PS-R-NO₃. Specifically, at a temperature of 298 K and an equilibrium concentration of 160 mg/L, the equilibrium capacity (q_e) values were determined to be 298.27 mg/g for PS-R-OH, followed by 142.81 mg/g for PS-R-Cl, 128.55 mg/g for PS-R-NO₃, and only 74.68 mg/g for the unmodified PS. Due to the presence of benzene rings in its backbone, PS exhibits a certain level of π - π interaction and hydrophobic affinity toward naphthol, which explains its moderate but still relatively low adsorption capacity. However, after modification, the adsorption capacities of PS-R-Cl, PS-R-NO₃, and PS-R-OH were greatly enhanced. This enhancement is primarily due to the markedly increased polarity of these functionalized resins, along with the enrichment of Cl⁻, NO₃⁻, or OH⁻ ionic species on their surfaces. These changes contribute to the adsorption process in two key ways. On the

one hand, they strengthen acid-base interactions between the resin and the adsorbate. On the other hand, they simultaneously enhance hydrogen bonding, π - π interactions, and hydrophobic effects.

The adsorption isotherm of the different temperature was exhibited in Fig. 3(b). Langmuir^[20] and Freundlich^[21] models were employed to describe the adsorption behavior, with the corresponding parameters summarized in Table S1. Based on the R^2 values, the naphthol adsorption onto PS-R-OH followed the Freundlich equation more closely, suggesting a multilayer adsorption process. The estimated maximum adsorption capacities (q_{max}) of PS-R-OH for naphthol at 298, 308, and 318 K were 824.10, 826.89, and 834.48 mg/g, respectively. Fig. S1 and Fig. S2 show the adsorption of binaphthol and benzoic acid on PS-R-OH, and Table S2 and Table S3 summarize the adsorption results. In summary, PS-R-OH demonstrated excellent adsorption performance toward aromatic acids. As shown in Fig. 3(b), Fig. S1, and Fig. S2, raising the temperature enhanced the uptake of naphthol and binaphthol by PS-R-OH, while suppressing that of benzoic acid. This indicates that higher system temperatures are unfavorable for benzoic acid adsorption, implying an exothermic process^[22]. In contrast, the adsorption of naphthol and binaphthol was endothermic. The thermodynamic analysis of PS-R-OH toward the three adsorbates is further presented in Fig. 3(c), Fig. S3, and Fig. S4, all of which exhibited good linear relationships under varying equilibrium concentrations. Consistency with the Freundlich model suggests that the adsorption process follows the Clausius-Clapeyron relation^[23], allowing for the calculation of the adsorption enthalpy (ΔH , kJ/mol).

$$\ln c_e = -\Delta H/RT + C' \quad Eq (1)$$

Based on the equilibrium adsorption isotherm, the Gibbs equation allows the calculation of the Gibbs free energy (ΔG , kJ/mol) using the constant n obtained from the Freundlich model.

$$\Delta G = -nRT \quad Eq (2)$$

The entropy change (ΔS , J/(mol·K)) can then be determined using the Gibbs-Helmholtz equation.

$$\Delta S = (\Delta H - \Delta G)/T \quad Eq (3)$$

As shown in Table S4 and Table S5, the enthalpy values for naphthol and binaphthol were positive, confirming an endothermic adsorption process. In contrast, the ΔH for benzoic acid was negative (Table S6), indicating an exothermic process, which aligns with the observations in Fig. 3(d), Fig. S3, and Fig. S4. The ΔG values were also negative across all three tested temperatures (298, 308, and 318 K), demonstrating that the adsorption of these three aromatic acids occurred spontaneously. The static adsorption performance of PS-R-OH toward benzoic acid, naphthol, and binaphthol at 298 K is presented

in Fig. 3(d). At an initial concentration of 1000 mg/L, the corresponding adsorption capacities were 405.90 mg/g for benzoic acid, 511.55 mg/g for naphthol, and 453.28 mg/g for binaphthol. Compared with data reported in the literature, the adsorption capacities were either comparable or superior, as shown in Table 2.

Generally, industrial wastewater contains a large amount of chloride and sulfate ions. The presence of these ions inevitably interferes with the adsorption of aromatic compounds on resins. Sodium chloride and sodium sulfate were selected as representative inorganic salts to investigate the effect of anions on resin adsorption. As shown in Fig. 3(e), as the inorganic salt concentration increased from 0.00 to 0.05 mol/L, the adsorption capacities of phenol, naphthol, and benzoic acid on PS-R-OH exhibited a trend of first a sharp decrease and then a slow decline. This may be because when the resin adsorbs phenol, naphthol, and benzoic acid in an electrolyte solution, the anions (Cl^- , SO_4^{2-}) dissociated from the salt in the aqueous solution compete with the adsorbates. Therefore, as the anion concentration increases, the competition intensifies, leading to a decrease in the adsorption capacity of the resin for the aromatic compounds. Notably, the adsorption capacity of binaphthol on PS-R-OH did not change significantly. This is because NaOH was added to dissolve binaphthol during solution preparation, resulting in a concentration of OH^- ions far higher than that of the inorganic anions. Consequently, the influence of anions was minimal, and the acid-base interaction was significantly weakened. The adsorption of binaphthol primarily relies on hydrophobic interactions, desolvation effects, and π - π interactions. Comparing the effects of the two inorganic salts on adsorption, it can be observed that Na_2SO_4 has a greater impact. This is because SO_4^{2-} can occupy two active sites on the resin simultaneously, leading to a more pronounced decline in the resin's adsorption capacity upon the addition of Na_2SO_4 . Figure 3(f) shows that the adsorption capacity of PS-R-OH resin for benzoic acid, binaphthol, and naphthol decreased from 360, 356, and 405 mg/g to 331, 337, and 361 mg/g, respectively, with corresponding reuse rates all reaching 90% of the initial adsorption capacity, indicating that the resin exhibits excellent cyclic performance.

Table 2
Adsorption capacity comparison of different adsorbents

Adsorbate	Adsorbents	T (K)	q_{max} (mg•g ⁻¹)	References
PS-R-OH	benzoic acid	298	405.90	This work
	naphthol	298	453.28	
	binaphthol	298	511.55	
Fe ₃ O ₄ @PANI	naphthol	298	28.736	[24]
Polyaniline films	pyromellitic acid	298	175.26	[25]
DES	ferulic acid	room temperature	5.86	[26]
Activated carbon	oleic acid	303	564.00	[27]
MIR resin	4-Hydroxybenzoic acid	303	259.67	[28]
PVG-10%-pc	naphthol	298	381.90	[29]
StAM-Arg	Orange G	298	23.48	[30]

The adsorption performance of the resin toward naphthol, binaphthol, and benzoic acid in isopropanol was examined in Fig. S5, yielding capacities of 107.49, 371.19, and 256.82 mg/g, respectively. These values are substantially lower than those observed for aqueous solution adsorption presented in Fig. 3(d). This reduction can be attributed to the suppression of both hydrophobic interactions between the adsorbates and the resin, as well as hydrogen bonding caused by the presence of isopropanol. Notably, naphthol exhibited the most pronounced decline in uptake, suggesting that hydrophobic interactions play a more dominant role in the adsorption of naphthol onto the resin compared to the other two adsorbates. In addition, the Freundlich model was more suitable for describing the isothermal adsorption process (Table S7), demonstrating that the adsorption process was multi-molecular layer adsorption.

2.3 Adsorption kinetics

Shown in Fig. 4(a) are the adsorption kinetics profiles of naphthol, binaphthol, and benzoic acid onto PS-R-OH at 298 K. The adsorption kinetics of PS-R-OH for the three compounds differed significantly. For naphthol, the adsorption was rapid within the first 200 minutes, reaching 90% of the equilibrium adsorption capacity, and finally reached equilibrium at around 650 minutes. For binaphthol, the fast adsorption stage occurred within 240 minutes, also achieving 90% of the equilibrium capacity, with equilibrium attained at approximately 480 minutes. In contrast, the adsorption of benzoic acid was the fastest: it reached 95% of the equilibrium capacity within just 50 minutes and achieved full adsorption

equilibrium at around 140 minutes. Apparently, the adsorption rate of binaphthol was the slowest, which can be attributed to its largest molecular size and poor solubility in aqueous solution, resulting in the slowest diffusion rate both in the solution and within the resin. Interestingly, naphthol, despite its smaller molecular size, required the longest time to reach adsorption equilibrium. This may be because its molecular size best matches the pore size of the resin, allowing naphthol to continuously and slowly diffuse into the interior for adsorption.

The pseudo-first-order (PFO) ^[31] and pseudo-second-order (PSO) ^[32] kinetic models were employed to analyze the adsorption rate data, with the resulting parameters summarized in Table S8. Based on the R^2 values, the PSO model provided a better description for all three adsorbates, a finding also reflected in Fig. 4(a). Due to differences in molecular dimensions and solubilities among the three compounds, their diffusion rates onto PS-R-OH varied. The corresponding PSO rate constants (k_2) for naphthol, binaphthol, and benzoic acid were 3.70×10^{-5} , 4.30×10^{-5} , and 3.62×10^{-4} g/(mg·min), respectively. A larger k_2 value indicates a faster adsorption rate, and benzoic acid consistently showed the highest uptake rate on PS-R-OH. The kinetic fitting using both models, along with the corresponding parameters and results, is presented in Fig. 4(b) and Fig. 4(c).

The kinetic adsorption behavior of benzoic acid at different initial concentrations is shown in Fig. 4(d), (e), and (f). At an initial concentration of 1000 mg/L, the removal efficiency reached 47.78%. As the initial concentration decreased, the removal performance steadily improved, and complete adsorption was achieved when the initial concentration was lowered to 100 mg/L. These results demonstrate that PS-R-OH enables efficient adsorption at high concentrations while achieving complete removal at low concentrations, underscoring its strong potential for practical applications.

3. Possible adsorption mechanism

From the adsorption results, the modified resin shows significantly improved adsorption performance for the target compounds. This is mainly attributed to the functionalization process, which increases the polarity of the resin and enriches it with abundant hydroxide groups. In terms of the adsorption mechanism, acid-base interaction plays a key chemical role, while physical interactions such as hydrogen bonding, π - π interactions, and hydrophobic effects are also significantly enhanced, indicating that the adsorption process results from the synergistic effect of chemical and physical interactions. For benzoic acid, which contains a single benzene ring, the adsorption process is mainly influenced by acid-base interactions, with hydrophobic effects, desolvation effects, pore structure, π - π interactions, and hydrogen bonding also participating synergistically. This indicates that in the adsorption of small-sized molecules, the chemical properties (e.g., acid-base interaction), physical properties (e.g., hydrophobic effect), pore structure, and intermolecular interactions (e.g., π - π and hydrogen bonding) between the resin and the adsorbate all play important roles. Figure 5 illustrates the possible interactions between the modified resin and benzoic acid. For binaphthol, which has a relatively large molecular size, the

adsorption process is primarily dominated by hydrophobic effects and desolvation effects. Additionally, steric structure, π - π interactions, and hydrogen bonding also synergistically influence the adsorption process. This means that in the adsorption of large-sized molecules, the hydrophobic nature of the resin surface, the spatial configuration of the molecules, and intermolecular interactions (e.g., π - π interactions, hydrogen bonding) play major roles.

The order of adsorption capacity of the resin for the three compounds is naphthol > benzoic acid > binaphthol. The resin exhibits the best adsorption effect for naphthol. This is because the molecular size of naphthol matches the resin's pore size well, resulting in little resistance when entering the resin interior. Additionally, the adsorption process involves an enhanced pore-filling mechanism. For benzoic acid, although its small molecular size allows it to easily enter the resin interior, it also readily leaves, so the increase in adsorption capacity is less significant than that of naphthol. For binaphthol, its large molecular size results in high steric hindrance. Moreover, it requires dissolution in a strong base, existing as sodium binaphtholate in the alkaline environment, which reduces the hydrophobic effect. Consequently, its adsorption efficiency is poorer than that of naphthol.

4. Conclusions

Using a simple route and mild conditions, polar N-methylimidazole was quickly grafted onto PS via a bimolecular nucleophilic substitution reaction. After ion exchange, the strong-base exchange capacity of the resulting product PS-R-OH was measured to be 3.37 mmol/g. Compared with PS, PS-R-OH exhibited only minor variations in pore size (from 27.18 nm to 27.27 nm), S_{BET} (from 84.78 m²/g to 80.15 m²/g), and V_{total} (from 0.60 cm³/g to 0.58 cm³/g), with both resins falling into the category of macroporous resins. In this research, benzoic acid, naphthol, and binaphthol were used as adsorbates in adsorption experiments, and all of them exhibited excellent adsorption performance. After 8 cycles of regeneration, the resin still maintained 90% of its initial adsorption performance. The kinetic experiments of benzoic acid on PS-R-OH revealed a rapid attainment of adsorption equilibrium within approximately 120 minutes. Moreover, at an initial concentration of 100 mg/L, PS-R-OH was capable of completely removing the organic acid. Additionally, the resin showed good adsorption of benzoic acid, naphthol, and binaphthol in isopropanol, with capacities of 256.82, 107.49, and 371.19 mg/g, respectively. These results hold significant implications for guiding industrial wastewater remediation.

Declarations

Authors and Affiliations

College of Chemistry and Chemical Engineering, Open Foundation of National & Local Joint Engineering Laboratory for New Petro-chemical Materials and Fine Utilization of Resources, Key Laboratory of the Assembly and Application of Organic Functional Molecules of Hunan Province, Hunan Normal University, Changsha 410081, China

Guangming Zhong & Jiaxiang Guo & Jing Xiao & Xueying Hou & Mancai Xu & Shihua Zhong

Yiyang Heshan District Emergency Management Bureau, Yiyang 413000, China

Guangming Zhong

School of Materials Science and Engineering, Tianjin University of Technology, Tianjin 300384, China

Xueyan Lin & Xin Xu & Ke Zhang & Mingze Zhang & Yuli Fu

Contributions

Guangming Zhong, Jiaxiang Guo, Jing Xiao and Xueyan Lin: Data curation, writing-original draft, methodology and investigation.

Xin Xu, Ke Zhang, Mingze Zhang and Xueying Hou: Experiments and revised the manuscript.

Shihua Zhong, Yuli Fu and Mancai Xu: Supervision, writing-review and editing.

Corresponding author

Correspondence to Shihua Zhong, Yuli Fu and Mancai Xu.

Competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Funding

Key Laboratory of the Assembly and Application of Organic Functional Molecules of Hunan Province, 2018TP1017, Shihua Zhong, Open Foundation of National & Local Joint Engineering Laboratory for New Petro-chemical Materials and Fine Utilization of Resources, KF201804, Mancai Xu.

Acknowledgements

This work was supported by Key Laboratory of the Assembly and Application of Organic Functional Molecules of Hunan Province (NO. 2018TP1017) and Open Foundation of National & Local Joint Engineering Laboratory for New Petro-chemical Materials and Fine Utilization of Resources (NO. KF201804).

References

1. Meng X, Liu Y, Wang S, Ye Y, Song X, Liang Z (2022) Post-crosslinking of conjugated microporous polymers using vinyl polyhedral oligomeric silsesquioxane for enhancing surface areas and organic micropollutants removal performance from water. *J Colloid Interface Sci* 615:697–706
2. Cao Y, Wang Y, Zhou F, Huang J, Xu M (2022) Acylamino-functionalized hyper crosslinked polymers for efficient adsorption removal of phenol in aqueous solution. *Sep Purif Technol* 303:122229
3. Zhang F, Zhang S, Chen L, Liu Z, Qin J (2021) Utilization of bark waste of *Acacia mangium*: The preparation of activated carbon and adsorption of phenolic wastewater. *Ind Crops Prod* 160:113157
4. Ramesh H, Bhuyan A (2024) The food and pharmaceutical additive benzoic acid induces amyloid fibrillation of an intrinsically disordered protein. *Biophys Chem* 306:107172
5. Naguib D, Badawy N (2020) Phenols and polyphenols: promise and peril to human health. *J Environ Chem Eng* 8:103592
6. Yang Y, Ali A, Su J, Chang Q, Xu L, Su L, Qi Z (2022) Phenol and 17 β -estradiol removal by *Zoogloea* sp. MFQ7 and in-situ generated biogenic manganese oxides: Performance, kinetics and mechanism. *J Hazard Mater* 429:128281
7. Sun Y, Gu Y, Yang J (2022) Adsorption of N-heterocyclic compounds from aqueous solutions by sulfonic acid-functionalized hypercrosslinked resins in batch experiments. *Chem Eng J* 428:131163
8. Peng Q, Zhao H, Wang R, Cao X, Liu H, Liu Q (2022) Ferrocene-based hypercrosslinked polymers derived from phenolic polycondensation with unexpected H₂ adsorption capacity. *Mater Today Chem* 24:100854
9. Zhang H, Li Y, Cheng B, Ding C, Zhang Y (2020) Synthesis of a starch-based sulfonic ion exchange resin and adsorption of dyestuffs to the resin. *Int J Biol Macromol* 161:561–572
10. Mhadmhan S, Yoosuk B, Chareonteraboon B, Janetaisong P, Pitakjakpipop P, Henpraserttae S, Udomsap P (2023) Elimination of free fatty acid from palm oil by adsorption process using a strong base anion exchange resin. *Sep Purif Technol* 310:123211
11. James T, Mark D, Richard I, Syna N, Soldenhoff K, Sharrad C (2018) Polyamine functionalised ion exchange resins: Synthesis, characterisation and uranyl uptake. *Chem Eng J* 334:1361–1370
12. Liao H, Fu Y, Hu H, Zhu M, Xu M, Zhong S (2022) Boron Removal from Water and Wastewater using New Polystyrene-Based Resin Grafted with Trometamol and 3-Amino-1, 2-propanediol. *J Chem Soc Pak* 44:33–39
13. Fu Y, Huang X, Zhong S, Yi W, Li L (2019) A new chloromethylation method based on polystyrene-divinylbenzene. *Chem Pap* 73:2183–2188
14. Caldwell J, Moyer H (1935) Determination of chloride: a modification of the Volhard method. *Ind Eng Chem Res* 7:38–39
15. Ni J, Hu M, Liu D, Xie H, Xiang X, Wang L (2016) Synthesis and properties of highly branched polybenzimidazoles as proton exchange membranes for high-temperature fuel cells. *Journal of Materials Chemistry* 2016: 4814–4821

16. Bakhsh I, Solangi, Memon S, Bhanger M (2009) Synthesis and application of a highly efficient tetraester calix[4]arene based resin for the removal of Pb^{2+} from aqueous environment. *Anal Chim Acta* 638:146–153
17. Wang P, Xiong L, He Z, Xu X, Hu J, Chen Q, Zhang R, Pu J, Guo L (2022) Synergistic effect of imidazoline derivative and benzimidazole as corrosion inhibitors for Q235 steel: an electrochemical, XPS, FT-IR and MD study. *Arab J Sci Eng* 47:7123–7134
18. Cao Y, Wang Y, Zhou F, Huang J, Xu M (2022) Acylamino-functionalized hyper-cross-linked polymers for efficient adsorption removal of phenol in aqueous solution. *Sep Purif Technol* 303:122229
19. Peng R, Chen G, Zhou F, Man R, Huang J (2019) Catalyst-free synthesis of triazine-based porous organic polymers for Hg^{2+} adsorptive removal from aqueous solution. *Chem Eng J* 371:260–266
20. Langmuir I (1916) The constitution and fundamental properties of solids and liquids. *Journal of the American chemical society*, Part I. *Solids* 38:2221–2295
21. Freundlich H (1906) Over the adsorption in solution. *J Phys Chem* 57:1100–1107
22. Zhang X, Xue Y, Gao J, He C, Ji Y, Dou Y (2020) Comparison of adsorption mechanisms for cadmium removal by modified zeolites and sands coated with Zn-layered double hydroxides. *Chem Eng J* 380:122578
23. Sun S, Zhao J, Yu D (2018) Dissociation enthalpy of methane hydrate in salt solution. *Fluid Phase Equilibria* 456:92–97
24. Zhou Q, Wang Y, Xiao J, Fan H (2016) Adsorption and removal of bisphenol A, α -naphthol and β -naphthol from aqueous solution by Fe_3O_4 @polyaniline core–shell nanomaterials. *Synth Met* 212:113–122
25. Laabd M, Chafai H, Aarab N, Jaouhari A, Bazzaoui M, Kabli H, Eljazouli H, Albourine A (2016) Polyaniline films for efficient removal of aromatic acids from water. *Environ Chem Lett* 14:395–400
26. Li G, Zhu T, Row K (2017) Isolation of ferulic acid from wheat bran with a deep eutectic solvent and modified silica Gel. *Anal Lett* 4:32719
27. Busto M, Carlos R (2019) Deacidification of vegetable oil by extraction with solvent recovery. *Adsorption* 25:1397–1407
28. Sun Y, Zheng W (2020) Surface molecular imprinting on polystyrene resin for selective adsorption of 4-hydroxybenzoic acid. *Chemosphere* 20:12786
29. Shao L, Li Y, Zhang T, Liu M, Huang J (2017) Controllable synthesis of polar modified hyper-cross-linked resins and their adsorption of 2-naphthol and 4-hydroxybenzoic acid from aqueous solution. *Ind Eng Chem Res* 56:2984–2992
30. Zhang H, Wang P, Zhang Y, Cheng B, Zhu R, Li F (2020) Synthesis of a novel arginine-modified starch resin and its adsorption of dye wastewater. *RSC Adv* 10:41251–41263
31. Lagergren S (1898) About the theory of so-called adsorption of soluble substances. *Sven Vetenskapsakad Handlingar* 24:1–39
32. Ho Y (2006) Review of second-order models for adsorption systems. *J Hazard Mater* 136:681–689

Schemes

Scheme 1 is available in the Supplementary Files section.

Figures

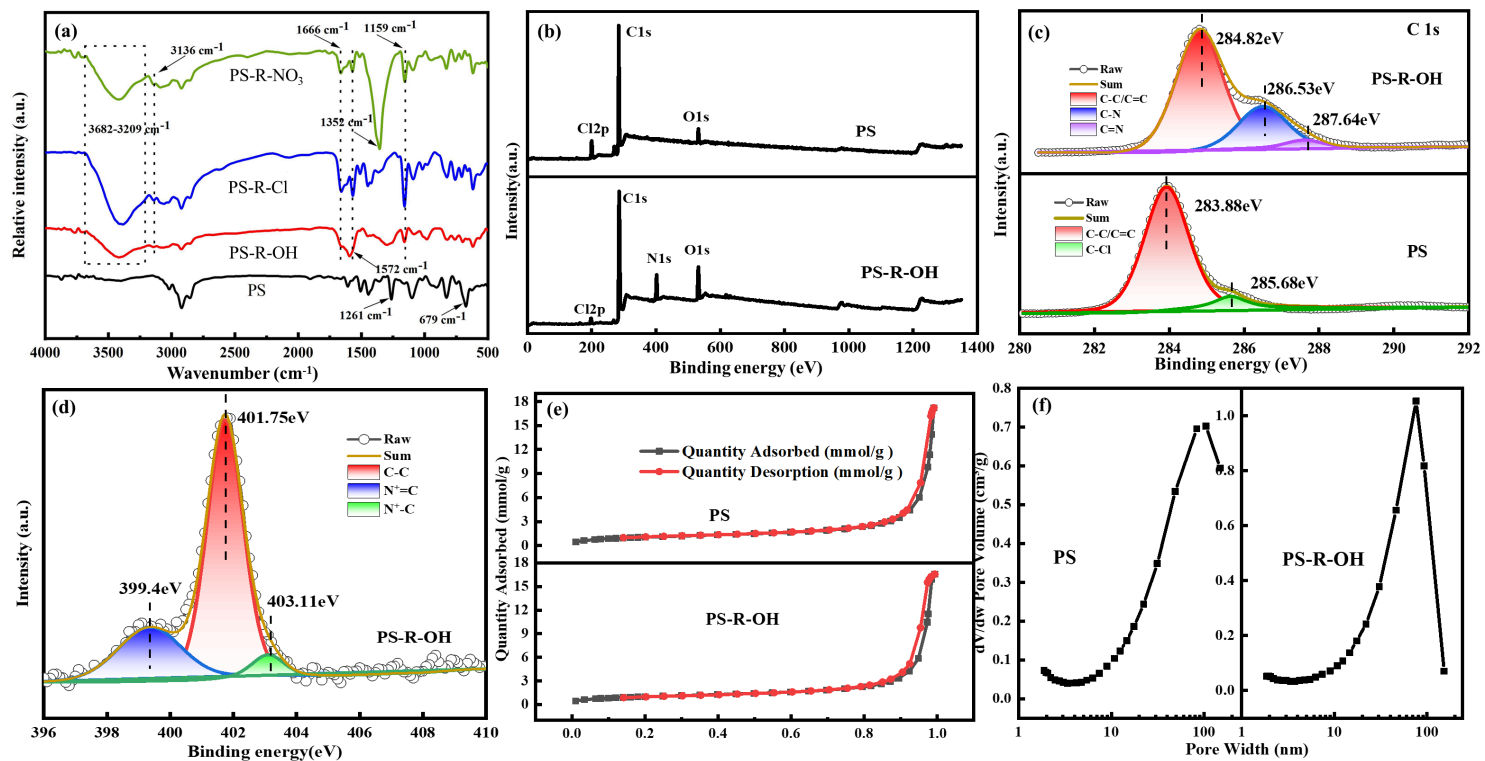


Figure 1

FTIR spectra (a) of PS, PS-R-Cl, PS-R-OH, and PS-R-NO₃; XPS spectra of (b) survey spectrum, (c) C 1s, (d) N 1s of PS and PS-R-OH; (e) N₂ isotherms and (f) The pore size distribution curves of PS and PS-R-OH

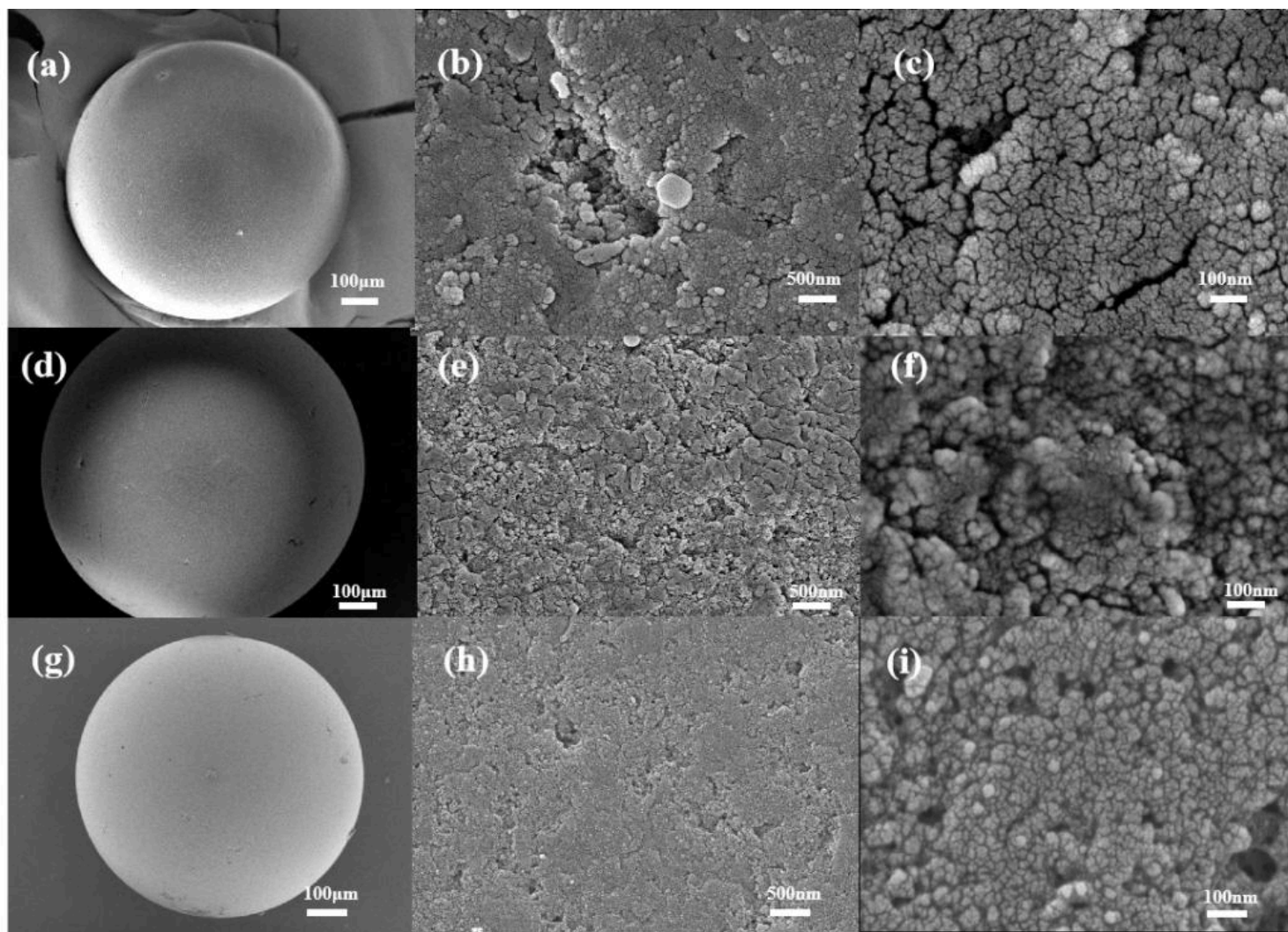


Figure 2

SEM of (a-c) PS and (d-f) PS-R-OH

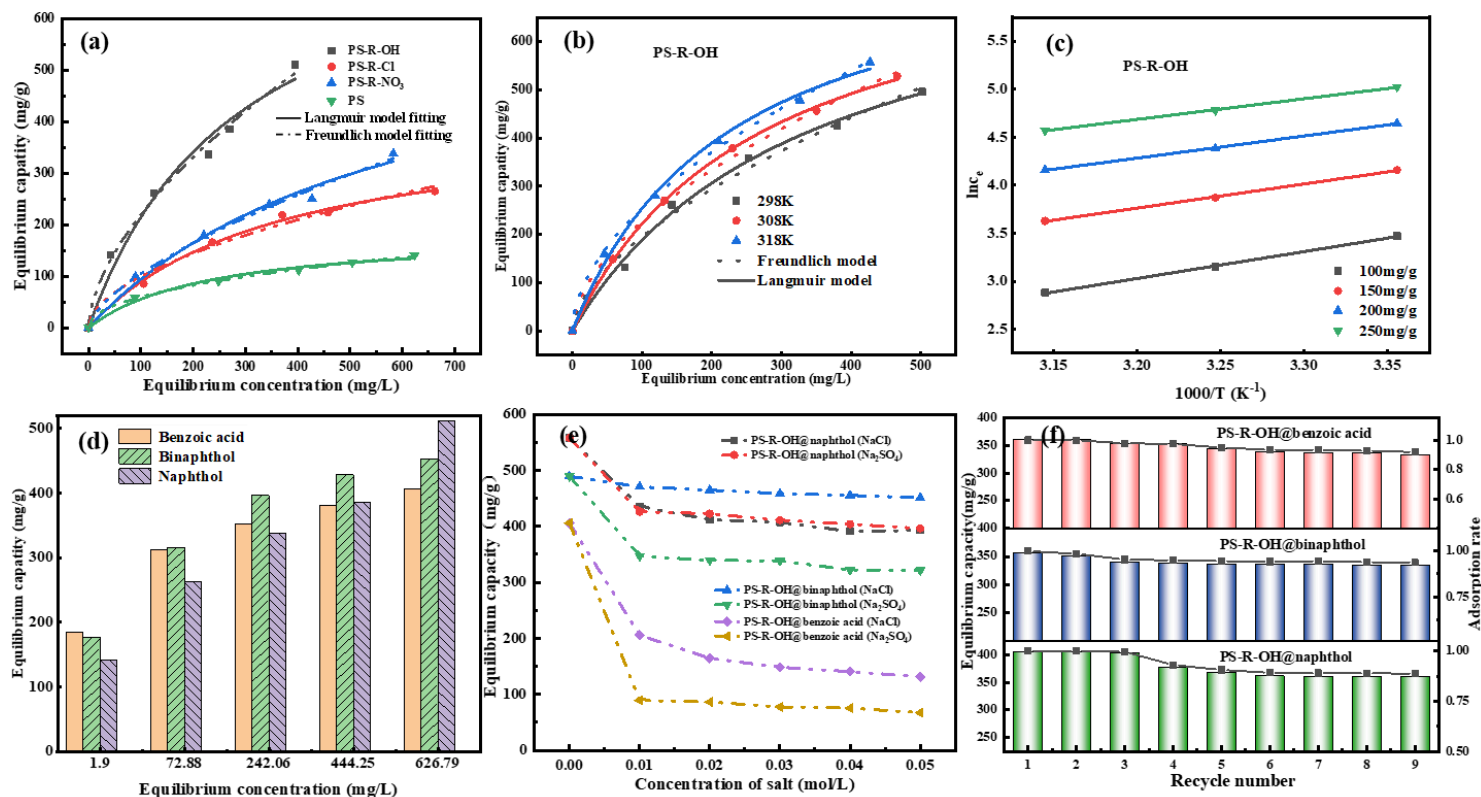


Figure 3

(a) Adsorption isotherms of naphthol on PS, PS-R-OH, PS-R-Cl, PS-R-NO₃ and PS-R-OH; (b) Equilibrium capacity and (c) $\ln C_e$ versus $1/T$ of naphthol adsorption in aqueous solution on PS-R-OH; (d) Adsorption of benzoic acid, naphthol, and binaphthol on PS-R-OH; (e) Effect of coexisting ions on adsorption; (f) Reuse performance

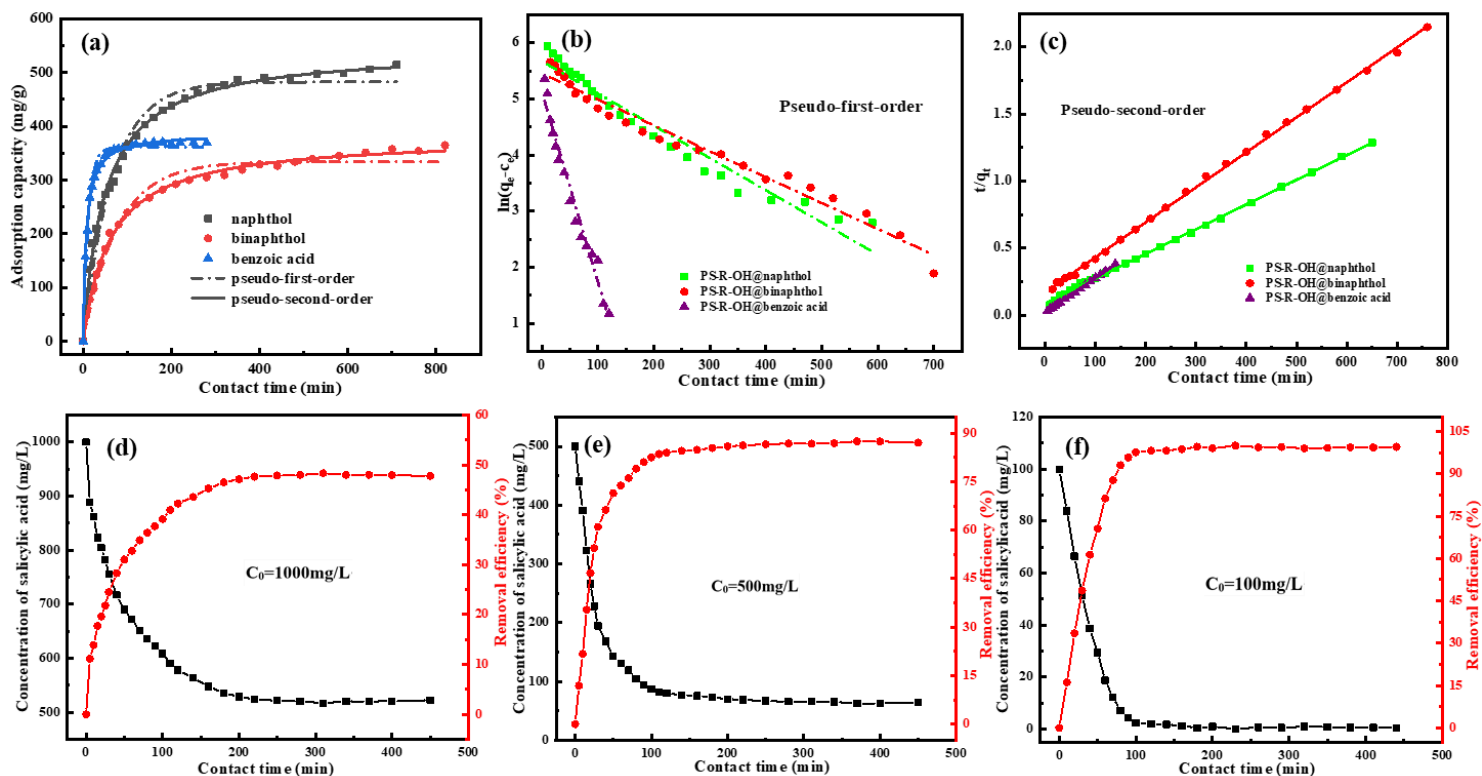


Figure 4

(a) Kinetic curves, (b) PFO and (c) PSO of benzoic acid, naphthol, and binaphthol on PS-R-OH; (d) $C_0=1000$ mg/L, (e) $C_0=500$ mg/L, (f) $C_0=100$ mg/L of kinetic adsorption benzoic acid on PS-R-OH

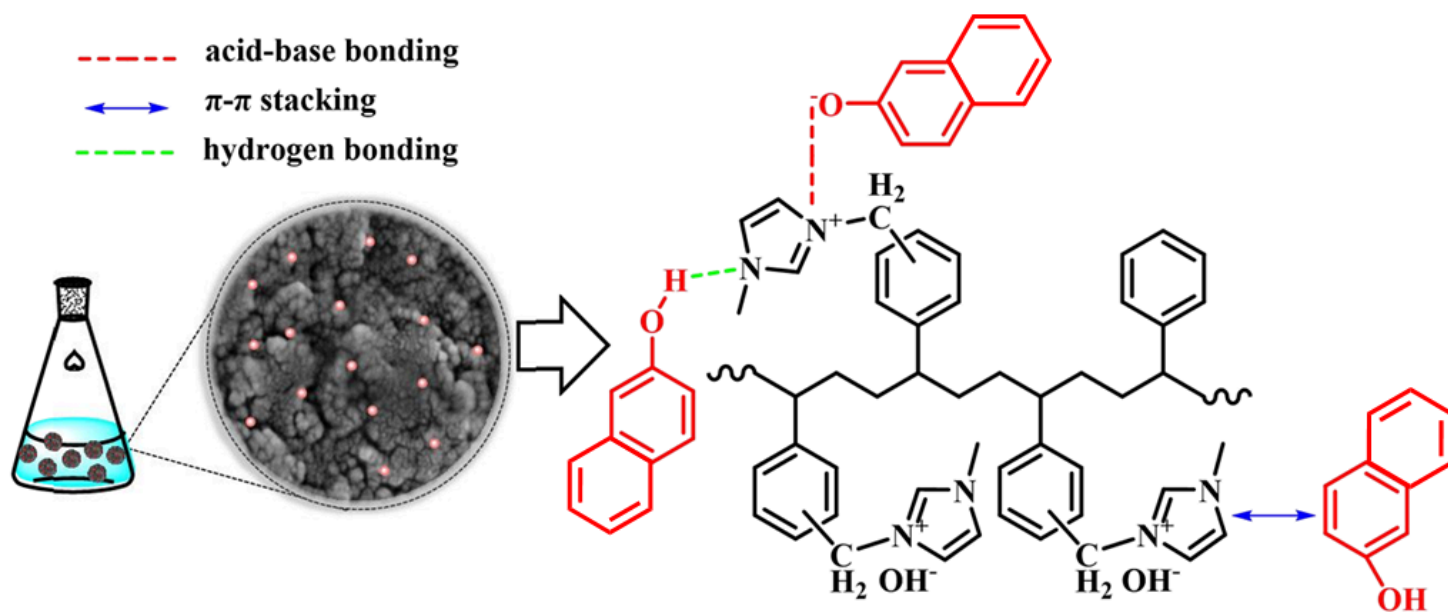


Figure 5

Possible adsorption mechanism between adsorbate and the resins

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SC1.png](#)
- [Authorstatement.docx](#)
- [DeclarationofInterestStatement.docx](#)
- [Highlights.docx](#)
- [Supportinginformation.docx](#)