Synthesis of Acryl Group-Modified Adsorption Resins and Their Adsorption Properties for Matrine and Oxymatrine in Aqueous Solutions

Tao Sun, Hui Li, Xiaoli Ma, Jianbao Ding, Jianlong Ma, Bolin Gong, and Jin Yang*

ABSTRACT: Three series of resins with different functional groups (PS-EA, PS-MP, and PS-BA) based on D101 copolymer were prepared via the atom transfer radical polymerization method. The adsorption capacities of functionalized resins toward matrine (MT) and oxymatrine (OM) depended on the specific surface area, the surface chemistry, and the good polarity match between the target compound and porous material. It is noted that the accumulation of functional groups uploaded on the surface of resins increased the adsorption affinity difference between the MT-functionalized resin system and OM-modified copolymer system. The selectivity of modified resins to MT and OM would attribute to polarity matching. The results could provide a possible strategy for the design of efficient adsorbents applied for the isolation the bioactive compound from complex natural products.

1. INTRODUCTION

Macroporous adsorption resins (MARs) are a type of highly cross-linked, non-ionic chromatographic materials that can separate chemicals based on their molecular weights and polarities. The polymeric adsorbents have been applied in enrichment and purification the bioactive compounds from natural products due to the simple procedure, low cost, easy regeneration, and small amounts of unwanted chemical residues in the product. Generally, the adsorption affinities of target constituents onto commercial MARs in aqueous solutions are attributed to hydrophobic interaction, van der Waals force, π−π interaction, and hydrogen bond. In the view of low contents and approximate structural characteristics of components in natural product extracts, it is difficult to obtain high-resolution separations and high degrees of purification of certain biomolecules using the MAR technique. Recently, in order to improve the separation efficiency, the researches on modification of the surface chemistry of MARs have attracted much attention in the academia and industry. Several functional groups had been reported to introduce to commercial poly(styrene-co-divinylbenzene) microsphere or chloromethylated polystyrene, such as amino groups, carboxylic, hydroxyl groups, ionic liquid, and β-cyclodextrin. The modified MARs demonstrated good adsorption performance to (-)-epigallocatechin-3-gallate (EGCG), rutin, rebaudioside, chlorogenic acid, and so on. The adsorption mechanism involved the hydrogen bonding. The results show potential to provide implication for sorbent selectivity and better design of adsorbents with high selectivity and capacity for liquid-phase adsorption according to the chemical structures of polyphenols.

To date, alkaloids exhibit a range of biological and pharmacological activities and are still the potential natural products in drug discovery. Some alkaloids have been successfully enriched and purified from herbal medicines using MARs. The efficiency and selectivity of adsorption processes remained to be increased. Introducing designed functional groups to MARs according to the structural characteristics of alkaloids may be advantageous in the adsorption separation processes. For enhancing the selectivity of the target compound, it is attractive and challenging to study the relationship between the functional group and alkaloids. Liu’s group and Zeng’s group synthesized amino acid- and amino-modified polymeric adsorbents and investigated the adsorption properties in the separation of tabersonine and berberine, respectively. These two well-documented separation processes mainly focused on the chromatographic characteristics, and the study on the relationship between the content of functional groups and adsorption affinity was, to the best of
Our knowledge, rarely reported. We proposed that the accumulation of functional groups uploaded on the surface of resins could increase the difference in adsorption affinity consisting in an adsorbent–adsorbate system, thereby increasing selectivity.

The atom transfer radical polymerization (ATRP) is a controlled radical polymerization technique, where ATRP initiating functionalities were easily grafted to the surface and the terminal groups can serve as a functional group for further reaction to provide a possibility for the increase of active groups on the polymer surface. Various chromatographic stationary phase or separation materials have been prepared via the ATRP technology and applied in the processes of nucleoside/protein detection, solid-phase extraction, and isotope enrichment. By controlling the amount of monomers or the reaction time, the different degrees of grafting adsorbents can be obtained. This strategy would provide an opportunity to analyze the relationship between the content of functional groups and adsorption affinity of the target alkaloid.

Quinolizidine alkaloids, as a kind of active ingredients extracted from the genus Sophora, have been well investigated in the past several decades owing to their various excellent bioactivities, including anti-inflammation, anti-virus, anti-cancer, anti-fibrosis, and anti-arrhythmia regulations. In a previous study, a method was exploited to enrich and separate quinolizidine-type alkaloids from S. alopecuroides using MARs in an industrial scale. In order to improve the adsorption selectivity, based on the structural features of matrine (MT, 1) and oxymatrine (OM, 2, Figure 1), we supposed that MARs containing acyl groups would increase adsorption affinity toward the target alkaloids via some intermolecular interactions in aqueous solutions. Herein, in the present study, MT and OM were selected as matrices. 4-Ethenylphenyl acetate (EA), 4-methylphenylene (MP), and 4-vinylbenzoic acid (BA) were used as monomers and grafted from bromomethylated styrene and divinylbenzene adsorbent (D101 MAR) with the ATRP method. The structure–activity relationship between surface chemistry and adsorption performance was investigated and discussed.

2. RESULTS AND DISCUSSION

2.1. Characterization of the Modified Adsorbents. On the basis of the ATRP mechanism, the different degrees of grafting adsorbents can be obtained by manipulating the polymerization time or the concentration of monomers. In the present research, for improving the adsorption performance of MT and OM, EA and MP were used as monomers and grafted from bromomethylated D101 resin via the ATRP technique. PS-BA resins were prepared from PS-MP12 via oxidation reaction (Scheme 1). Since the initial concentrations of monomers were kept the same, the different lengths of polymer chains depended on the polymerization time.

The data of elemental analysis demonstrated that the contents of carbon and proton rapidly diminished after the ATRP reaction and the contents of oxygen increased with the prolonging of reaction time (Table 1), suggesting that functional groups had been introduced on the surface of D101 resin. The PS-MP12 possessed the maximum amount of carbon, thereby was selected to prepare PS-BA resins. According to the measured C or O content, the grafted amounts (GA, μmol·m⁻²) of functionalized groups on D101 resin were estimated with the following equation:

\[
GA = \frac{\%X(10^6)}{\%X_{P(\text{cal})} \times \left(1 - \frac{\%X}{\%X_{P(\text{cal})}}\right) \times M \times A}
\]

where \(\%X\) is the increased C or O percent of polymer units in 1 g of polymer grafted PS-Br resin; \(\%X_{P(\text{cal})}\) is the calculated weight percent of element in functionalized groups; \(M\) is the formula weight of monomer; and \(A\) is the specific surface area of prepared resins measured by the \(\text{N}_2\) adsorption method.

As shown in Table 1, the grafted amounts of monomers in PS-EA and PS-MP resins increased first and reached the peak values at the reaction time of 12 h, and then, they slightly decreased. However, the contents of oxygen on the surface of the modified resins increased according to the results of XPS. X-ray photoelectron spectroscopy (XPS) was also applied to analyze the surface composition and the changes in modified groups of the resins before and after ATRP reactions (Figure 2). The characteristic XPS substrate signals for functionalized MARs at 284.8 eV were attributed to C 1s, and the peaks at 70.9 eV were from Br 3d, which corresponded to bromomethyl. The presence of the O 1s peaks located at 533.2 eV in the spectrum of PS-EA and PS-BA resins indicated that functional groups containing oxygen grafted to the PS-Br via the ATRP reaction. Meantime, the peak areas of O 1s for

![Figure 1. Chemical structures of matrine (MT, 1) and oxymatrine (OM, 2).](image)

![Scheme 1. Reaction Scheme for the Preparation of PS-Br and PS-EA/MP/BA on the Basis of D101 Resin](image)
PS-EA and PS-BA series resins increased with the prolonging of reaction time (Figure 2A,B), which indicated that the contents of oxygen in the surface of functionalized resins were also in the same trend and might affect the adsorption affinity to MT and OM.

Figure S1 exhibits the Fourier transform infrared (FTIR) spectra of D101, PS-Br, PS-EA, PS-MP, and PS-BA. In the spectra of PS-Br and PS-MP, an adsorptive band at 586 cm$^{-1}$ was ascribed to the stretching vibration of the C–Br bond.26 Comparing with the IR spectrum of D101, there was a new adsorptive band at 1264 cm$^{-1}$, which was the in-plane bending vibration adsorption of the unsaturated hydrocarbon bond of the aromatic ring after binary substitution caused by the substitution of hydrogen atoms at the para position of benzene rings by −CH$_2$Br.27 In the spectra of PS-EA and PS-BA, the ketone carbonyl vibrations at 1726 and 1696 cm$^{-1}$ can be observed, respectively, which indicated that ester groups were introduced to the resins.28 The inferences were also supported by the stretching vibrations of C–O–C at 1036 cm$^{-1}$ in the IR spectra of PS-EA. In the spectrum of PS-BA, the broad adsorptive band at 3600–3400 cm$^{-1}$ belonging to the carboxyl group can be observed. The information above displayed that the modified porous materials were successfully synthesized.

The results of nitrogen sorption/desorption analysis are displayed in Table 1 and Figure S2. Comparing with D101 resin, the specific surface areas of modified resins decreased and the average pore diameters increased after the functionalized reaction. The transformations of physical properties would interpret that coiling and rotation of modified group chains were more inclined to happen and then cross-linking reaction may happen to some extent. It would lead to change in pore structures. With the increasing of reaction times, the functional groups would thicken, resulting in the decreasing of specific surface areas and average pore diameters. At the same reaction times, PS-MPs showed a bit larger BET area than PS-EAs; this revealed that the hydroxyl at the terminal of EA would possess steric hindrance.

2.2. Results of Adsorption Capacities of Modified Resins toward MT and OM. Generally, the surface chemistry and physical properties of MARs can influence the adsorption capacity.1,2 We synthesized nine modified resins via ATRP and grafted EA, MP, and BA with different amounts on the surface of PS-Br. It appeared that the specific surface area was the decisive factor affecting the adsorption capacities of MT and OM in different resins. As shown in Figure 3 and Table 1, D101 resin had the top adsorption capacities because of its largest BET area. This observation was consistent with the sorption capacities of PS-EA12, PS-MP12, and PS-BA12, which possessed a relatively larger specific surface area when compared to other resins grafted to the same functional

| type of resins | C (%) | H (%) | O (%) | Br (%) | GA (μmol·m$^{-2}$) | specific surface area (m$^2$·g$^{-1}$) | pore volume (m$^3$·g$^{-1}$) | pore size (nm) |
|----------------|-------|-------|-------|--------|-------------------|-------------------------------------|-----------------------------|----------------|
| D101           | 91.27 | 8.73  |       |        |                   | 664.6013                           | 1.0495                      | 9.2023         |
| PS-Br          | 64.78 | 6.68  |       | 27.54  |                   | 397.7341                           | 0.6551                      | 10.8538        |
| PS-EA6         | 68.81 | 6.64  | 7.23  | 17.12  | 14.26             | 395.5552                           | 1.0673                      | 10.9991        |
| PS-EA12        | 71.66 | 7.45  | 7.91  | 12.58  | 15.45             | 432.4967                           | 1.3821                      | 11.4059        |
| PS-EA18        | 71.41 | 6.90  | 7.52  | 16.07  | 14.78             | 411.8038                           | 1.1390                      | 11.1221        |
| PS-MP6         | 67.09 | 6.94  | 25.17 | 2.87   |                   | 417.4301                           | 1.2199                      | 11.8616        |
| PS-MP12        | 69.22 | 7.11  | 23.16 | 5.39   |                   | 437.2636                           | 1.3219                      | 12.2771        |
| PS-MP18        | 69.02 | 7.03  | 22.95 | 5.16   |                   | 429.1491                           | 1.3797                      | 11.7264        |
| PS-BA6         | 59.46 | 5.82  | 18.54 | 15.98  | 28.05             | 411.3111                           | 1.0735                      | 11.1847        |
| PS-BA12        | 59.31 | 5.43  | 21.85 | 15.11  | 31.05             | 431.4420                           | 1.2945                      | 12.4376        |
| PS-BA18        | 59.35 | 5.64  | 19.45 | 15.86  | 28.93             | 434.3121                           | 1.2693                      | 12.1195        |
resin. The chemical features of adsorbates would also in
fluence the adsorption processes.2 Thereby, PS-
BA12 resin acquired similar adsorption capacities to D101
resins of PS-EA. It was observed in the experi-
ments. Such a behavior would attribute that N-
attribute that the deposition of functional groups on the
surface could support more adsorption active sites to alkaloids and,
and consequently, improve the opportunities of contact be-
tween alkaloids and adsorbents. However, the increasing of the steric
hindrance and the hydrophilicity, due to the thickening
functionalized groups, would not be advantageous to the
adsorption process. Comparing with the k1 of MT and OM on
porous agents with a similar modified group, the former was
smaller than the latter, suggesting that the average adsorption
rates of OM on the adsorbents were faster than those of MT
and reached the equilibrium first. This observation would
attribute that the deposition of functional groups on the
polymer surface during the ATRP reaction increased the
surface wettability, leading to pore expansion and improved
access of alkaloids to adsorption sites in porous materials.31
Additionally, the higher temperature made the rate constants
k2 greater, indicating that the increasing temperature can speed
up the adsorption rate. However, the equilibrium adsorption
capacity qe decreased with the increasing of temperature,
indicating more efficient sorption at lower temperatures.

2.4. Adsorption Isotherms. For performing further
characterization of the adsorption behavior of model alkaloids
on functionalized resins, the equilibrium adsorption isotherms
at different temperatures were obtained. The Langmuir and the
Freundlich adsorption models are the best known and most
frequently applied isotherms. The linear equations32 of
mentioned models were given by the following equations:
Langmuir equation:
\[
\frac{1}{q_e} = \frac{1}{q_m} + \frac{1}{K_q q_m} \cdot \frac{1}{C_e}
\]  
(4)
Freundlich equation:
\[
\log q_e = \log K_f + \frac{1}{n} \log C_e
\]  
(5)
where qm (mg·g⁻¹) is the theoretical maximum adsorption
capacity, Kq and Kf are the adsorption constants of Langmuir
and Freundlich models, respectively, and n is an empirical

groups. Thus, an appropriate BET area is necessary for
designing a sorbent.

On the condition that the adsorbents had a similar BET
area, the surface chemistry would impact the sorption behavior.
The intermolecular hydrogen bond and electrostatic inter-
action formed between the carbonyl group on the surface of
PS-BA resins and the nitrogen in the target alkaloids would
play a positive role in adsorption processes.2 Thereby, PS-
BA12 resin acquired similar adsorption capacities to D101
resin. The chemical features of adsorbates would also influence
the adsorption affinity. For D101 resin and PS-MP resins, the
amount of MT was larger than OM, which would interpret that
MT showed better hydrophobicity than OM. OM, a more
polar molecular than MT, will strengthen the adsorption
interaction between the carbonyl group and the nitrogen in the
target alkaloids.

Interestingly, as far as the adsorption capacity on function-
alized porogenic agents was concerned, the differences
between MT and OM were increasing within the accumulation
of functional groups uploaded on the surface of adsorbents,
exactly as we supposed. This discovery would provide a
possibility for separating OM or MT from aqueous solutions.

2.3. Adsorption Kinetics. To understand the different
adsorption capacities of these separation agents, the static
adsorption kinetic curves for MT and OM were investigated at
293.15, 303.15, and 313.15 K (Figure S3). As can be seen from
the figure, the adsorption capacities of functionalized resins
toward target alkaloids increased with the extension of
adsorption time and reached equilibrium around 6 h.

In order to better illustrate the adsorption mechanisms,
pseudo-first-order and pseudo-second-order kinetic models
were applied to describe adsorption processes. Equations of
these kinetic models were expressed as below:29

Pseudo-first-order kinetic model:
\[
\ln(q_e - q_t) = -\frac{k_1 t}{2.303} + \ln q_e
\]  
(2)

Pseudo-second-order kinetic model:
\[
\frac{t}{q_t} = \frac{1}{k_2q_e^2} + \frac{t}{q_e}
\]  
(3)

where qe and qt (mg·g⁻¹) are the adsorption capacities at
equilibrium and time t, respectively; and k1 (min⁻¹) and k2 (g·
mg⁻¹·min⁻¹) refer to the rate constants of pseudo-first-order
and pseudo-second-order of adsorption processes, respectively.

The parameters of pseudo-first-order and pseudo-second-
order are shown in Tables S2 and S3. In terms of the calculated
linear regression correlation coefficients of kinetic models for
modified adsorbents, the pseudo-second-order kinetic model
was considered to be the best model for describing the
adsorption processes of MT and OM on these sorbents. The
results indicated that the adsorption processing of target
alkaloids on functionalized resins would be explained by
diffusion-based mechanisms.29 For all the porous materials,
the rate constants of pseudo-second-order (k2) showed no obvious
change with the increasing of the thickness of the polymer
layers, but both the theoretical qe calc and experimental qe exp
values exhibited a downward trend. As mentioned above,
the functional group chains grafted on the MARs’ surface could
support more adsorption active sites to alkaloids and,
and consequently, improve the opportunities of contact between
alkaloids and adsorbents. However, the increasing of the steric
hindrance and the hydrophilicity, due to the thickening
functionalized groups, would not be advantageous to the
adsorption process. Comparing with the k1 of MT and OM on
porous agents with a similar modified group, the former was
smaller than the latter, suggesting that the average adsorption
rates of OM on the adsorbents were faster than those of MT
and reached the equilibrium first. This observation would
attribute that the deposition of functional groups on the
polymer surface during the ATRP reaction increased the
surface wettability, leading to pore expansion and improved
access of alkaloids to adsorption sites in porous materials.31

Additionally, the higher temperature made the rate constants
k2 greater, indicating that the increasing temperature can speed
up the adsorption rate. However, the equilibrium adsorption
capacity qe decreased with the increasing of temperature,
indicating more efficient sorption at lower temperatures.

Figure 3. Adsorption capacities of D101 and modified resins at
293.15 K.
constant related to the magnitude of the adsorption driving force. The Langmuir and Freundlich parameters are tabulated in Tables S4 and S5. Shown in the tables, for all modified resins, the correlation coefficients of Freundlich equations and Langmuir equations were rather high, suggesting that both equations fitted well the adsorption processing. The n value of the Freundlich model was a measure of the deviation from an infinite perfect plane homogeneous surface in contact with a well-mixed solution. Reductions in the 1/n value from 1 indicated greater spatial constraint on adsorption. This was a reflection of particle surface 3D morphology and the ability of the adsorbing molecule to access this surface.34 The 1/n value is generally applied to estimate whether the adsorption easily takes place. The adsorption can easily take place when the 1/n value is between 0.1 and 0.5; it is difficult to happen when the 1/n value is between 0.5 and 1.0, and it is unable to occur when the 1/n value is greater than 1.33,34 The present experimental results might indicate that the surfaces of these modified resins were not ideal surfaces for the adsorption of MT and OM except PS-BA resins. This ratiocination would explain the reason that PS-BA resins acquired the best adsorption capacities.

The change in enthalpy (ΔH, kJ·mol⁻¹) of the adsorption processes of MT and OM onto modified resins was calculated according to the van’t Hoff thermodynamic equation:35

\[ \ln K_e = -\Delta H / RT + \ln K_0 \]  

where \( K_e \) is the equilibrium constant in the Langmuir model (L·mol⁻¹), \( R \) is the universal gas constant (8.314 J·mol⁻¹·K⁻¹), \( T \) is the absolute temperature (K), and \( K_0 \) is a constant.

The values of ΔH are listed in Tables S4 and S5. As shown in the tables, the values of ΔH were lower than 40 kJ·mol⁻¹, suggesting the physisorption and spontaneous processes for target alkaloids onto all modified resins.36 The values of ΔH also indicated that the driven force would be the hydrogen bond between the alkaloids and modified resins.37 The system of alkaloids-PS-BA12 resin had the greatest absolute ΔH among functionalized adsorbents, indicating that MT and OM would be preferentially adsorbed from aqueous solutions by PS-BA12 resin, resulting in the largest adsorption capacities to MT and OM.38

2.5. Binary Static Adsorption and Breakthrough Curves. Due to the good polarity match and the ideal surface for the adsorption process, PS-BA12 holds the largest adsorption capacities toward two alkaloids. However, the differences in \( Q_e \) between MT and OM were less than those of PS-BA18, indicating that this modified resin had poor selectivity to the target alkaloids. To further understand the adsorption affinities of MT and OM to modified resins, the binary static adsorption experiments were carried out with the mixture solution of equal initial concentration (\( c_{MT} = c_{OM} = 0.3 \) mg·mL⁻¹) at 293.15 K. The binary data of MT and OM on PS-EA18, PS-MP18, and PS-BA18 resins are shown in Figure 4.

As expected, the competitive adsorption between MT and OM on modified resins can be observed, indicating that the adsorption affinity of MT onto three resins was stronger than OM. The result was in good agreement with the relative minor values of ΔH of the MT-modified resin system. The reason could interpret that OM was displaced by more competitive alkaid (MT) when the adsorption sites were not enough.39 Thereby, the ratio of MT and OM can be calculated with the equilibrium adsorption capacity according to the binary adsorption curves (Table 2).6 PS-MP18 exhibited the highest selective adsorption to MT among the three modified resins. Literature researches showed that the oil–water partition coefficients for MT and OM were 1.18 and 0.2 in the neutral aqueous solution, respectively.40,41 The values of log \( P \) for phenyl acetate, toluene, and benzoic acid are 1.62, 2.52, and 1.67, respectively, according to ChemBioDrew Ultra software. The selectivity of modified resins to MT and OM was consistent with polarity matching.

Figure 5 presents the adsorption breakthrough curves of MT and OM mixture on modified resins. Regardless, for PS-EA18, PS-MP18, or PS-BA18 resin, it showed that OM was the first breakthrough alkaid compared to MT. Meantime, the phenomenon of roll-up (\( C/C_0 > 1 \) for OM) was observed in the breakthrough curves, indicating that the selected adsorbents would preferentially sorb MT.39

2.6. Dynamic Desorption Experiments of MT and OM onto Modified Resins. Gradient elution with ethanol solution on the mixture alkaloid-loaded columns was carried out to investigate the separation performances of functionalized resins to MT and OM (Figure 6). The dynamic desorption curves suggested that OM loaded on PS-EA18 and PS-MP18 resins can be desorbed at 10% aqueous alcohol solutions. MT can be obtained at 20% EtOH column fractions.

| Table 2. Selective Adsorption of Absorbents toward MT and OM from the Binary Solution with Equal Initial Concentration at 293.15 K |
|---------------------------------------------------------------|
| type of resins      | \( Q_e \) (mg·g⁻¹) | ratio of MT and OM |
|---------------------|---------------------|--------------------|
| PS-EA18             | 36.87               | 10.67              | 3.64               |
| PS-MP18             | 38.68               | 8.68               | 4.46               |
| PS-BA18             | 77.97               | 25.94              | 3.01               |

Figure 4. Binary adsorption equilibrium of MT and OM mixture on (A) PS-EA, (B) PS-MP, and (C) PS-BA resins at 293.15 K.
These two modified resins exhibited good separation property. Unfortunately, PS-BA18 resin did not display great separation selectivity to MT, which should have been expected according to the results of the static and dynamic sorption tests. We speculated that the adsorption affinity of MT/OM resin involved the electrostatic interaction and ethanol solution cannot weaken this intermolecular force. The observation was consistent with the lower desorption ratio of MT and OM on PS-BA18.

3. CONCLUSIONS

In the present study, three series of functional resins with 4-ethenylphenyl acetate (EA), 4-methylphenylene (MP), and 4-vinylbenzoic acid (BA) were grafted to bromomethylated styrene and divinylbenzene adsorbent (D101 MAR) with the ATRP method. MT and OM were selected as matrices, and the structure–activity relationship between surface chemistry and adsorption performance was investigated and discussed. The results indicated that the specific surface area would be the main factor affecting the adsorption capacities. This observation was consistent with the sorption capacities of PS-EA12, PS-MP12, and PS-BA12, which possessed a relatively larger specific surface area when compared to other resins grafted to the same functional groups. On the condition that the adsorbents had a similar BET area, the surface chemistry would play a positive role in adsorption processes. Thereby, PS-BA12 resin acquired similar adsorption capacities to D101 resin. The chemical features of adsorbates would also influence the adsorption affinity. A good polarity match of OM and PS-EA resins led to the relatively better sorption performance. Meantime, N−O in OM’s structure held back the formation of the electrostatic interaction between the carbonyl group and the nitrogen in the target alkaloids, resulted in the decreasing of the adsorption capacity of OM toward PS-BA resins. These observations were consistent with the equilibrium adsorption isotherms and the thermodynamics. The Langmuir constant $K_L$ suggested that the adsorption processes were favorable at operation conditions studies. However, the $n$ value of the Freundlich model indicated that the surfaces of these modified resins were not ideal surfaces for the adsorption of MT and OM except PS-BA resins. The system of alkaloids-PS-BA12 resin had the greatest absolute $\Delta H$ among the functionalized adsorbents, which would explain the reason that PS-BA resins acquired the best adsorption capacities.

More importantly, the accumulation of functional groups uploaded on the surface of materials increased the adsorption affinity difference between the MT-functionalized resin system and OM-modified copolymer system, exactly as we supposed. However, the kinetic study implied that the increasing of the steric hindrance and the hydrophilicity, due to the thickening functionalized groups, would be not advantageous to the sorption process. Binary static adsorption observed the competitive adsorption between MT and OM on modified resins. The selectivity of modified resins to MT and OM was consistent with polarity matching.

Overall, based on the chemical features of target adsorbates, the specific surface area and the adsorption capacities of functionalized resins depended on the specific surface area, the surface chemistry, and the good polarity match between the target compound and porous material during selective adsorption processing. The results could provide a possible strategy for the design of efficient adsorbents applied for the isolation the bioactive compound from complex natural products.

4. EXPERIMENTAL SECTION

4.1. Materials and Reagents. Anhydrous zinc chloride, paraformaldehyde, $N,N$-dimethylformamide (DMF), anhydrous ethanol, concentrated sulfuric acid, concentrated nitric acid, acetone, acetic acid, triethylamine, and disodium
ethylendiaminetetraacetate (EDTA-Na) were purchased from Tianjin Damao Chemical Reagents Co. (Tianjin, China). 2,2′-Dipyridine and cuprous bromide were bought from Shanghai Dibai Chemical Reagents Co. (Shanghai, China). Hydrogen bromide (33% in acetic acid), 4-ethenylphenyl acetate (EA, >97%), and 4-methylphenylene (MP, >99.99%) were obtained from Shanghai Macklin Biochemical Co. Ltd. (Shanghai, China). All of the reagents abovementioned were of analytical grade. Nitrogen (>99.9%) was purchased from Ningxia Guangli Trading Co. (Ningxia, China). HPLC grade methanol was bought from Burdick & Jackson Chemical Company. Distilled water and deionized water were used in the study.

Matrine and oxymatrine used in this investigation were kindly provided by Ningxia Doushun Biotechnology Co. Ltd. (Ningxia, China), and their purities were determined as more than 98.0% by HPLC analysis based on the peak area normalization method.

D101 MAR, a nonpolar styrene co-divinylbenzene copolymer with no functional groups, was purchased from Anhui Sanxing Resin Technology Co. Ltd. (Anhui, China). Before the experiments, the resins were soaked with ethanol overnight followed by deionized water and then was dried at 60 °C under reduced pressure until the mass did not change any more.

4.2. Synthesis Functional Adsorbents. The reaction scheme for the preparation of resins with bromomethylated groups (PS-Br) and MARs with different functional groups (PS-EA and PS-BA) on the basis of D101 copolymer is shown in Figure 2.

Pretreated D101 resin (7.72 g) was immersed in dichloromethane in a 250 mL three-neck round-bottom flask overnight. Subsequently, 13.70 g of anhydrous zinc chloride (0.10 mol), 4.50 g of paraformaldehyde, 10.72 g of hydrogen bromide 33% in acetic acid (0.04 mol), and 20 mL of concentrated sulfuric acid were introduced to the flask. The reaction mixture was stirred (100 rpm) at 363.15 K for 10 h. The synthetic MARs were filtered and washed with deionized water until no precipitate formed, while an aqueous solution of silver nitrate was added to the filtrate and then successively washed with anhydrous ethanol, acetone, and distilled water. The resin functionalized by the bromomethyl group (PS-Br) was obtained and was lyophilized by a freeze dryer (FD-1C-50, Beijing Biocool Co. Ltd., China).

EA and MP were grafted onto the surface of PS-Br via SI-ATRP according to the literature. A 6.00 g solution of PS-Br was put into a 250 mL three-neck round-bottom flask and was swelled in DMF overnight. CuBr (0.35 g, 2.44 mmol) was added in the flask, and the mixture was deoxygenated by purging with high-purity nitrogen at room temperature for 30 min. Then, 1.6 mL of EA (9.0 mmol) or 1.0 mL of MP (9.0 mmol), 0.80 g of 2,2′-bipyridyl (5.10 mmol), and 20 mL of DMF were transferred into the flask using a syringe under a nitrogen atmosphere. The reaction system was incubated at 323.15 K under the protection of N2 for 6, 12, and 18 h. The products were filtrated out from the reaction solutions after the desired reaction times and then successively washed with EDTANa2 aqueous solution (0.1 M), distilled water, acetone, and anhydrous ethanol. The resin functionalized by different modified groups, namely, PS-EA6, PS-EA12, PS-EA18, PS-MP6, PS-MP12, and PS-MP18, were obtained and were lyophilized by a freeze dryer.

PS-BA series resins were produced from PS-MP resins via oxidation reaction. A 5.0 g solution of PS-MP6, PS-MP12, or PS-MP18 resin was oxidized with 100 mL of 25% HNO3 (0.19 mol) for 6 h at 393.15 K. The products, namely, PS-BA12, PS-BA12, and PS-BA18, were washed three times with distilled water and 5% NaOH aqueous solution. Afterward, the modified resins were washed with distilled water until neutral and lyophilized by a freeze dryer.

4.3. Characterization of Prepared Modified Adsorbents. The Fourier transform infrared (FTIR) spectra of the modified adsorbents before and after adsorption were recorded on a Nicolet 380 FTIR Spectrometer (Thermo, USA) in the 4000–400 cm−1 region via the KBr pellet method. The morphologies of adsorbent materials were observed by a scanning electron microscope (JSM-670F, JEOL, Japan). The specific surface area and pore size distribution were determined by N2 adsorption/desorption isotherms at 77.15 K using Brunauer–Emmett–Teller (BET) (ASAP 2010, Micrometrics, USA). The functional groups of adsorbent beads used a Vario EL cube Elemental Analyzer (Elementar Co., Ltd., Germany) and analyzed by X-ray photoelectron spectroscopy (XPS) on an Escalab 250 (Thermo Co., USA) using a Mg Kα radiation at a pass energy of 20 eV. The Volhard titration method was used to determine the bromine content.

4.4. Determination of MT and OM. Chromatographic separation conditions were similar to our previous report. A Waters series HPLC system equipped with a 600 HPLC pump and a 2996 photodiode array detector (DAD) was controlled by an Empower2 chromatography data workstation. During the whole analysis, a YMC-Pack ODS-A column (250 × 4.6 mm, 5 μm) together with a C18 guard column was used and the column temperature was maintained at 303.15 K. The mobile phase consisted of 0.1% acetic acid (pH value was adjusted to 5.5 by triethylamine) and methanol (90:10, v/v), and the flow rate was 1.0 mL·min−1. The detection wavelength was 205 nm, and the injection volume was 20 μL. The chromatographic peaks were identified by comparing their retention time with those of standards. The quantities of MT and OM were performed with an external standard method. All sample solutions were filtered through a 0.45 μm syringe filter prior to injection.

The linear regression equations of each compound are listed in Table S1.

4.5. Adsorption Properties of Modified Adsorbents toward MT and OM. The static adsorption tests were carried out in a water bath mode. Accurately weighed resins (0.1 g), which were pretreated with swelling deionized water for 24 h, were introduced into a 100 mL triangular flask. Aqueous solutions (50.0 mL) of MT and OM with known concentrations were added to each flask. The flasks were kept in the shaking water bath (HZS-H, Harbin Donglian Electronic Technology Co., China) at 160 rpm and presetted temperature until the adsorption reached equilibrium. The concentrations of MT and OM in the residual solutions were analyzed by HPLC. According to this approach, equilibrium isotherms and adsorption kinetics of MT and OM adsorption on the modified adsorbents were measured at 293.15, 303.15, and 313.15 K from aqueous solutions.

For evaluation of adsorption kinetics, the initial concentrations of MT and OM were 0.3 mg·mL−1 and the concentrations of alkaloids in the samples were analyzed at different times. Different initial concentrations of MT and OM (0.1, 0.2, 0.3, 0.4, and 0.5 mg·mL−1) were used for depicting the equilibrium isotherm.
Dynamic adsorption and desorption experiments were conducted in a plastic chromatography column (Φ 11 × 55 mm). A 0.3 g solution of PS-EA18, PS-MP18, and PS-BA18 resins (dry weight) was pretreated with swelling deionized water overnight and then packed into the column. The bed volumes of adsorbents were 2.5 mL, respectively. The flow of samples in all cases was downward. The mixed solution of MT and OM with equal initial concentration (C_{MT} = C_{OM} = 0.3 mg·mL^{-1}) flowed at a 3 BV·h^{-1} flow rate, and the concentrations of MT and OM in the effluent liquid were monitored by HPLC analysis. After reaching equilibrium, the alkaloid-loaded resins were eluted with two BV deionized water and ethanol–water (20:80, 40:60, 60:40, and 20:80, v/v) solutions successively. Each part of desorption solutions was analyzed by HPLC. The adsorption capacities of individual resins were calculated using the following equation:

\[
Q_e = \frac{(C_0 - C_e)V_o}{W}
\]  

where 

- \( Q_e \) (mg·g^{-1} resin) is the equilibrium adsorption capacity; 
- \( C_0 \) and \( C_e \) (mg·mL^{-1}) are the initial and equilibrium concentration of analytes in the solutions, respectively; 
- \( V_o \) (mL) is the volume of the initial feed; and 
- \( W \) (g) is the weight of dry resin.

**ASSOCIATED CONTENT**

**Supporting Information**
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c03559.

The FTIR spectra and the results of the nitrogen sorption/desorption analysis of D101 and modified resins; kinetic curves of MT on PS-EA, PS-MP, and PS-BA resins and OM on PS-EA, PS-MP, and PS-BA at 293.15 K; the linear regression equations of MT and OM; parameters in pseudo-first-order and pseudo-second-order rate equation for MT and OM onto modified resins; and parameters of Langmuir and Freundlich models and the enthalpy change (\( \Delta H \)) for the adsorption processes of MT and OM on modified resins (PDF)

**AUTHOR INFORMATION**

**Corresponding Author**
Jin Yang — School of Chemistry and Chemical Engineering, North Minzu University, Yinchuan 750021, China; Key Laboratory for Chemical Engineering and Technology, State Ethnic Affairs Commission, Yinchuan 750021, China; Ningxia Engineering Research Center for Natural Medicine, Yinchuan 750021, China; orcid.org/0000-0002-1123-0069; Email: yang_jin@nun.edu.cn

**Authors**
Tao Sun — School of Chemistry and Chemical Engineering, North Minzu University, Yinchuan 750021, China; Key Laboratory for Chemical Engineering and Technology, State Ethnic Affairs Commission, Yinchuan 750021, China
Hui Li — School of Chemistry and Chemical Engineering, North Minzu University, Yinchuan 750021, China; Key Laboratory for Chemical Engineering and Technology, State Ethnic Affairs Commission, Yinchuan 750021, China
Xiaoli Ma — School of Chemistry and Chemical Engineering, North Minzu University, Yinchuan 750021, China; Key Laboratory for Chemical Engineering and Technology, State Ethnic Affairs Commission, Yinchuan 750021, China; Key Laboratory for Chemical Engineering and Technology, State Ethnic Affairs Commission, Yinchuan 750021, China

Laboratory for Chemical Engineering and Technology, State Ethnic Affairs Commission, Yinchuan 750021, China
Jianbao Ding — Ningxia Wuxing Science and Technology Co. Ltd., Yinchuan 750021, China
Jianlong Ma — College of Chemistry and Chemical Engineering, Ningxia University, Yinchuan 750021, China; Ningxia Engineering Research Center for Natural Medicine, Yinchuan 750021, China
Bolin Gong — School of Chemistry and Chemical Engineering, North Minzu University, Yinchuan 750021, China; Key Laboratory for Chemical Engineering and Technology, State Ethnic Affairs Commission, Yinchuan 750021, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c03559

**Notes**
The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**
The authors acknowledge the financial support by Key Scientific Research Projects in 2019 at North Minzu University (2019KJ16), National Natural Science Foundation of China (no. 21565001), Key Research and Development Project of Ningxia Hui Autonomous Region (2019BFH02005), and Innovative Research Team of Ningxia Hui Autonomous Region for Functional Materials and Separation Technology.

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