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ZIF-8 Assisted Polyacrylamide Functionalized Silica Core-Shell Stationary Phase for Hydrophilic Interaction Liquid Chromatography

Tong Zhang [1,2], Yijing Li [1], Xiaofeng Lu [1], Yong Guo [1], Licheng Wang [1,*] and Xiaojing Liang [1,*]

[1] Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: wanglc@licp.cas.cn (L.W.); xjliang@licp.cas.cn (X.L.)

Abstract: A novel ZIF-8 assisted polyacrylamide functionalized silica polar stationary phase was prepared by a facile method of adding ZIF-8 nanoparticles and silica into polyacrylamide (PAM) aqueous solution, and then stirring the mixture until the solution was evaporated absolutely with the help of mechanical agitator. Interestingly, the prepared stationary phase (PAM-Sil@ZIF-8/PAM) showed favorable hydrophilicity, as demonstrated by good separation performance and strong retention ability toward several types of polar compounds, such as amino acids, saccharides, and alkaloids. In addition, PAM-Sil@ZIF-8(50 mg)/PAM showed better separation performance compared with amino-modified silica and Sil/PAM stationary phase due to the addition of ZIF-8. Furthermore, it was demonstrated that the addition of ZIF-8 improved the specific surface area and provided extra interaction sites for the stationary phase and analytes, which is beneficial for the separation of samples. In addition, the column efficiency can reach 7861.9 plates/m for colchicine. Moreover, it exhibited good stability and reproducibility under our operation conditions. In short, a novel stationary phase, which can be used for hydrophilic interaction liquid chromatography, was obtained and proved that the separation performance of polymer modifying silica stationary phase can be greatly improved by the addition of MOF nanoparticles.

Keywords: ZIF-8; polyacrylamide; core-shell stationary phase; hydrophilic interaction liquid chromatography

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1. Introduction

Since chromatography was proposed by Tswett in 1903, it has become one of the most popular and practical techniques in separation science, and was widely used in many fields, such as petrochemical and organic synthesis. As a form of chromatography, high-performance liquid chromatography has the advantages of fast analysis speed, high resolution, and high sensitivity, which is the most important method for analyzing complex samples. Hydrophilic interaction liquid chromatography (HILIC) is a mode of high-performance liquid chromatography, and it uses an organic-rich aqueous as mobile phase in order to separate polar analytes [1,2]. It can make up for the disadvantage that reversed-phase liquid chromatography cannot separate polar compounds using polar stationary phases. Due to the fact that separation performance of HILIC strongly depends on the stationary phase, many efforts have been made to produce new materials for use as the stationary phase of HILIC.

A variety of polar stationary phases have been prepared to achieve different selectivity. Silica-based materials attracted more attention due to their advantages, such as adjustable particle size, high mechanical strength, big surface area, and porous structure. Apart from this, silica gel microspheres are easy to be chemically modified due to the presence of a large number of reactive silanol groups on the surface. Diol [3], amino [4], and amide [5] functionalized silica have been proven to be stationary phases of HILIC with good separation performance of a variety of polar samples. Shen's [5] group prepared a novel amide stationary phase by modifying silica-gel through a click chemistry reaction. Furthermore, it was reported that the stationary phase showed good separation performance for polar compounds, including nucleosides and nucleic acid bases with high column efficiency and good stability. In addition, hydrophilic polymer coated silica has been extensively studied, such as polyvinyl alcohol (PVA) [6] and hydrogel [7] modified silica. Yang's group [8] prepared a PVA-coated silica stationary phase for hydrophilic interaction liquid chromatography by thermal immobilization, and it exhibited excellent separation of polar compounds. Furthermore, our group [7] prepared a double-layer hydrogel-functionalized silica material as stationary phase by combining physical coating and chemical coating for liquid chromatography. Interestingly, since the hydrogen bond between the stationary phase and the analyte changes at different temperatures in the column oven, the retention behavior changes, which indicated that the obtained new stationary phase showed characteristics of temperature response. In addition, the new stationary phase exhibited excellent selectivity for many polar analytes and exhibited high column efficiency.

Metal organic frameworks (MOFs) that can be formed by various combinations of metal ions and various organic ligands, possessing metal sites and regular pore sizes, are widely studied in catalysis [9], gas capture [10], and separation [11]. For example, Wang's group [12] prepared an orderly MOF-assembled hybrid monolithic stationary phase, which possessed hierarchical micro-, meso-, and macropore structure. Its unique pore structure and surface chemistry gives multiplex interactions with molecules, in order that it is able to separate compounds of different sizes. In addition, Li's group [13] designed UiO-67 modified silica core-shell materials as stationary phase for liquid chromatography and the prepared UiO-67@SiO_2 column showed outstanding selectivity for separation of hydrophilic compounds, such as thioureas. Furthermore, our group prepared MOF-808@silica [14] core-shell materials by in situ growth MOF on silica surface with the help of sodium dodecyl benzenesulfonate. It was demonstrated that the obtained materials can be used as stationary phase for hydrophilic interaction liquid chromatography and showed excellent separation performance in terms of alkaloids and nucleosides. In addition, our group prepared 2D MOF-FDM-23@silica [15] core-shell materials used as stationary phase and exhibited good separation performance for many polar analytes, such as sulfonamides and amino acid compounds, etc. It was demonstrated that the novel 2D MOF-FDM-23@silica stationary phase showed better separation performance and stability than most reported MOF-based stationary phases. Apart from this, our group also prepared a series of novel stationary phases by co-modifying the surface of silica with MOFs and polymer [16,17]. For example, Zn-BTC and dual-network hydrogel modifying silica materials were obtained by adding Zn-BTC to the solution, which contained silica and precursor of hydrogel. Thanks to the addition of MOF particles, the shortcomings (such as osmotic pressure caused by hydrogel swelling) were overcome. Furthermore, due to the synergistic effect of MOF and hydrogel polymer, many kinds of analytes (such as organic acids and carbohydrates, etc.) can be selectively separated and high column efficiency (90,300 plates/m for sucrose) was obtained.

In this work, a novel polyacrylamide and ZIF-8 co-functionalized silica stationary phase was prepared by a facile method. The obtained composite was tested for the HILIC separation of multiple polar compounds, such as nucleosides/bases, alkaloids, saccharides, and amino acid compounds. It was demonstrated that the addition of ZIF-8 improved the separation performance of stationary phase. Compared with NH_2-modified silica column and only PAM modified silica column, the composite showed better peak shape and resolution. Apart from this, the different column's efficiency was compared, as well. It was indicated that the addition of ZIF-8 possessed higher column efficiency. In addition, the composite showed good stability and reproducibility by evaluation of various relative standard deviation (RSD) parameters.

2. Materials and Methods

2.1. Materials and Instruments

Zinc nitrate hexahydrate was obtained from Xilong Scientific Co., Ltd., Chengdu, China. 2-Methylimidazole was purchased from Aladdin Co., Ltd., Shanghai, China. Hydrochloric acid (HCl) was purchased from Chengdu Kelong Chemical Co., Ltd., Chengdu, China. NH_2-modified silica packing (5 μm particle size, 70 Å pore size) and bare porous silica (5 μm particle size, 70 Å pore size) were supplied by the Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences. PAM (MW = 10,000,000, 89.21%) was purchased from Guangya Polymer Chemical Co., Ltd., Nanchong, China; acetonitrile (ACN) and methanol (MeOH) for the mobile phase were purchased from Por Mee. Nucleosides/bases, alkaloids, saccharides, and amino acid compounds were all purchased from Sigma-Aldrich. The chemicals and reagents were used without further purification.

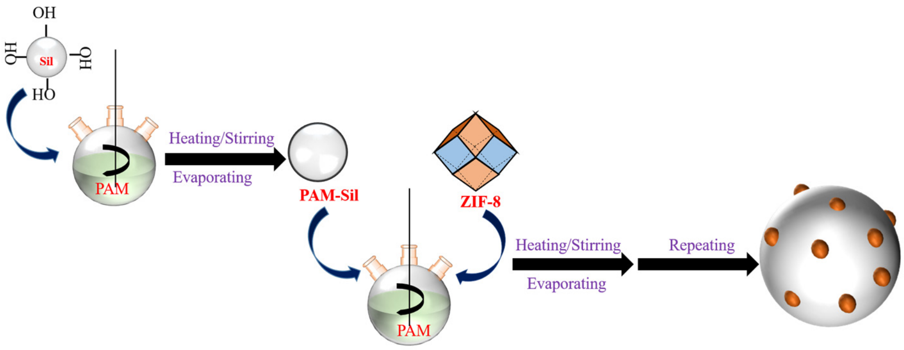
Analytes were conducted on HITACHI Primaide system, which consists of a quaternary pump, a 1430 UV/vis detector, a 1310 column oven, and a 20 μL sample loop (Hitachi, Ltd., Xianggang, China), as well as an Agilent 1100 Series modular HPLC system (Agilent Technologies, Santa Clara, CA, USA) with an evaporative light-scattering detector (ELSD). The detection wavelength was 254 nm. The gas used by the ELS detector is the air produced by the automatic air generator (XWM-III, Tianjin Jinfen Analytical Instrument Co., Ltd., Tianjin, China). In addition, the ELSD was set as follows: Gas flow was 2.5 L/min; evaporative temperature was 90 °C. All columns in the paper are 15 cm long (150 × 4.6 mm i.d.). Scanning electron microscope (SEM) images were obtained from JSM6701F (JEOL, Tokyo, Japan). Energy-dispersive spectrometer (EDS) spectra of SEM were obtained from JSM5600LV (JEOL, Japan), and transmission electron microscopy (TEM) images were obtained from Tecnai G2 TF20 transmission electron microscope (FEI, Portland, OR, USA). X-ray diffractogram (XRD) measurements were carried out on an X'Pert Pro Multipurpose diffractometer (PANalytical, Inc., MA, USA) with Ni-filtered Cu Kα radiation (0.15406 nm) from 5 to 80° operated at 40 kV and 20 mA. N_2 adsorption surface areas were measured by BET technique on a Micrometritics ASPS 2010 analyzer (Micromeritics, Norcross, GA, USA).

2.2. Preparation of the ZIF-8

In a typical synthesis, ZIF-8 was prepared as follows: First, zinc nitrate hexahydrate (1.47 g) and 2-methylimidazole (3.26 g) were dissolved in methanol (100 mL) in a 250 mL beaker, respectively. Then, the prepared solutions were mixed into a separate 250 mL beaker and 30 min of mixing process was applied to the solution with the help of magnetic stirrer. Thereafter, the mixture was allowed to stand at room temperature for 3 h. In addition, the ZIF-8 was collected by centrifugation (11,000 rpm, 2 min) and washed for five times with methanol. Finally, the products were dried at 65 °C in vacuum oven for 12 h.

2.3. Preparation of the ZIF-8 and PAM Co-Functionalized Silica Stationary Phase and Column Packing

The ZIF-8 assisted polyacrylamide functionalized silica core-shell stationary phase was prepared by thermal immobilization, as shown in Scheme 1. In detail, bare silica was treated early by immersion in 37% HCl solution for 48 h, washed by centrifugation to neutrality, and dried at 80 °C in vacuum oven for 12 h. Then, the activated silica (8 g) was added in 400 mL PAM aqueous solution (0.1 mg/mL for PAM) and ultrasonic dispersion for 10 min. Thereafter, the mixture was mechanically stirred (200 rpm) under 80 °C in oil bath until the solution was evaporated completely. In addition, the precipitates were washed with deionized water for two times by centrifugation and dried at 80 °C in vacuum oven for 12 h (denoted as PAM-Sil). The PAM individual modified silica was obtained by repeating the operation process for three times (denoted as Sil/PAM). The ZIF-8 and PAM co-functionalized silica stationary phase was obtained by replacing silica with PAM-Sil and repeating the operation process for two times with the addition of 50 mg ZIF-8 into the mixture solution before placing it in the oil bath (denoted as PAM-Sil@ZIF-8(50 mg)/PAM). Moreover, we prepared PAM-Sil@ZIF-8(10 mg)/PAM and PAM-Sil@ZIF-8(30 mg)/PAM by adjusting the amount of ZIF-8. Finally, the stationary phase was slurry-packed into stainless-steel column (150 × 4.6 mm) with methanol as slurry solvent and propulsion solvent. In detail, the composite (2.2 g) was dispersed in 22 mL of methanol within a 150 mL conical flask by ultrasonication for 10 min. Then, the homogeneous mixture was loaded into a stainless column (150 × 4.6 mm i.d.) with a 40 MPa packaging machine and methanol as a replacement liquid. When the time interval was basically constant, the filling was completed.



Scheme 1. The preparation route of the PAM-Sil@ZIF-8/PAM.

3. Results and Discussion

3.1. Characterization of the Prepared Materials

The obtained products were characterized by SEM, TEM, XRD, and BET. The SEM of ZIF-8, bare silica, and PAM-Sil@ZIF-8(50 mg)/PAM were shown in Figures 1 and 2, respectively. Figure 1 demonstrated that ZIF-8 possessed a rhombic dodecahedron structure and uniform size of about 100 nm. In addition, the SEM of PAM-Sil@ZIF-8(50 mg)/PAM indicated that after co-functionalization by ZIF-8 and PAM, the composites showed a smoother surface compared with bare silica (Figure 2), which demonstrated that the silica were successfully modified. Moreover, the TEM image indicated that the PAM-Sil@ZIF-8(50 mg)/PAM was successfully prepared with a core-shell structure (Figure S1). The XRD patterns of the synthesized ZIF-8 and PAM-Sil@ZIF-8(50 mg)/PAM are shown in Figure 3. The diffraction peaks of prepared ZIF-8 were consistent with standard ZIF-8, which revealed that it was successfully prepared. However, no typical diffraction peaks of ZIF-8 were observed over PAM-Sil@ZIF-8(50 mg)/PAM, owing to the low ZIF-8 addition. Moreover, the EDS mapping of PAM-Sil@ZIF-8(50 mg)/PAM demonstrated that the element of Zn is distributed homogenously, which revealed that ZIF-8 was incorporated into the composite successfully (Figure S2). The specific surface areas and pore structure play an important role in separation. N_2 adsorption-desorption characterization indicated that the BET surface area of the Sil/PAM (312.9 m^2/g) was slightly lower than bare silica (371.5 m^2/g), which may be caused by the pore blocking due to the addition of PAM. Meanwhile, the BET surface area of PAM-Sil@ZIF-8(50 mg)/PAM (354.4 m^2/g) is larger than Sil/PAM due to the high porosity of ZIF-8, as shown in Table S1. Therefore, the addition of ZIF-8 may improve the separation performance of stationary phase.

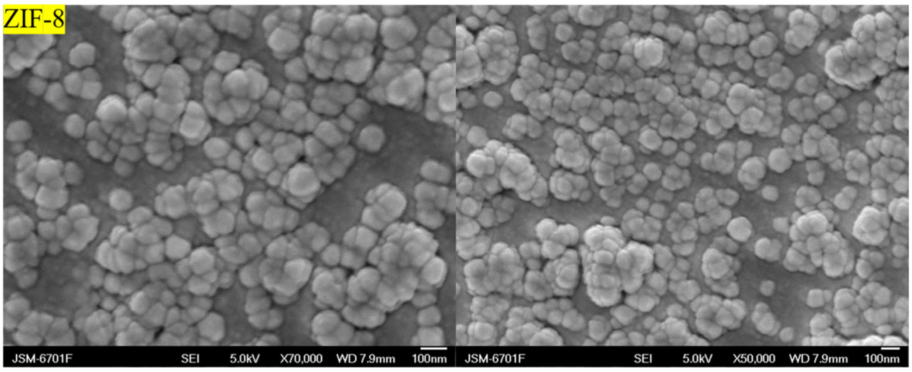


Figure 1. SEM image of prepared ZIF-8.

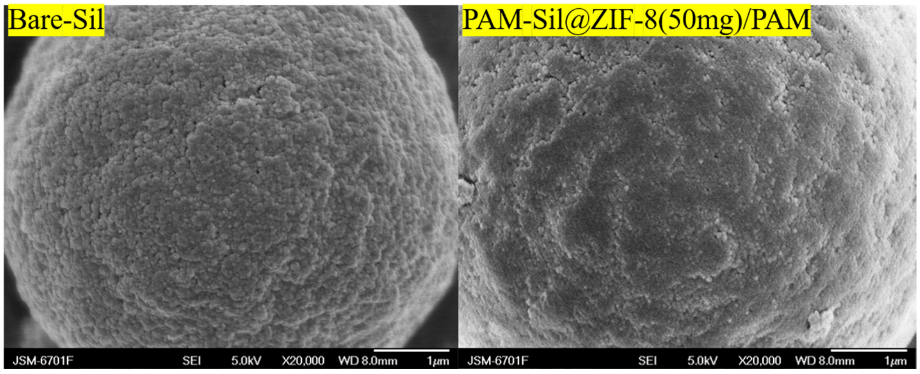


Figure 2. SEM image of bare silica and PAM-Sil@ZIF-8(50 mg)/PAM.

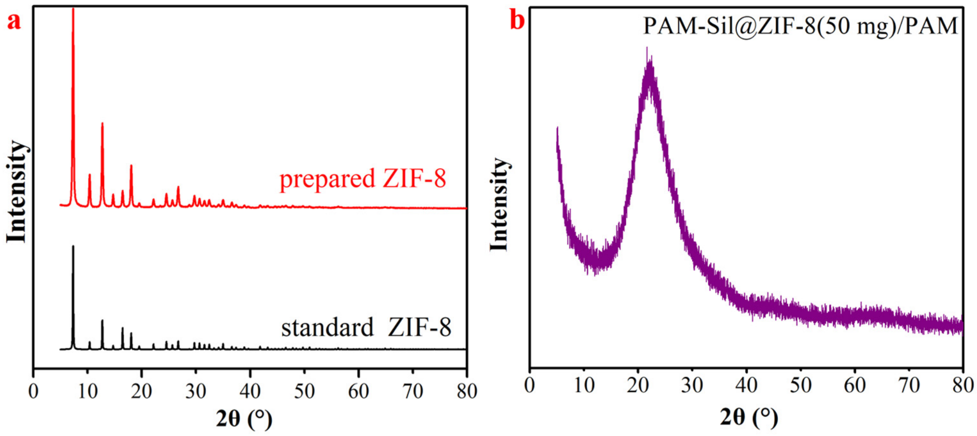


Figure 3. XRD patterns of (**a**) prepared ZIF-8 and (**b**) PAM-Sil@ZIF-8(50 mg)/PAM.

3.2. Effect of ZIF-8 on Chromatographic Separation

Zeolite imidazolate skeleton (ZIF) is composed of metal ions and imidazolate anions. The structure of ZIF is similar to the SiO_2-zeolite and has high thermal stability. As one kind of ZIF, ZIF-8 was obtained by the coordination of zinc ions with dimethylimidazole. To elucidate the effect of ZIF-8 on separation performance, the chromatographic separation performances of Sil/PAM and PAM-Sil@ZIF-8/PAM were compared. As shown in Figure 4a, five nucleosides/bases cannot be separated completely by Sil/PAM, which is the reason why ZIF-8 was not added. It can be seen that the separation performance was improved with the addition of ZIF-8. Interestingly, with the increase in the amount of ZIF-8 from 10 to 50 mg, the separation performance was gradually improved. When the added ZIF-8 amounted to 50 mg, the baseline separation of the five analytes was achieved. Therefore, PAM-Sil@ZIF-8(50 mg)/PAM was chosen for further study. In addition, it can be seen that PAM-Sil@ZIF-8/PAM showed better peaks symmetry compared with Sil/PAM. Furthermore, the separation performance indicated that with the increase in the amount of ZIF-8, the retention times of substances increased, especially for analytes 4 and 5, which demonstrated that ZIF-8 improved the retention ability of stationary phase for nucleosides/bases. Moreover, by comparing amino-modified silica and PAM-Sil@ZIF-8(50 mg)/PAM, the superiority of PAM-Sil@ZIF-8(50 mg)/PAM stationary phase is proved further (Figure 4a,b). The reasons why adding ZIF-8 can improve the separation performance can be explained by the following points: First, it has been reported that ZIF-8 possessed multiple active sites (such as metal sites), which can provide extra sites for the interaction of stationary phase and analytes [18,19]. In addition, the pore structure of ZIF-8 can provide a steric-hinderance effect [20]. Finally, N_2 adsorption-desorption characterization demonstrated that the addition of ZIF-8 increased the BET surface area (by comparing PAM-Sil@ZIF-8(50 mg)/PAM with Sil/PAM), which is beneficial for separation.

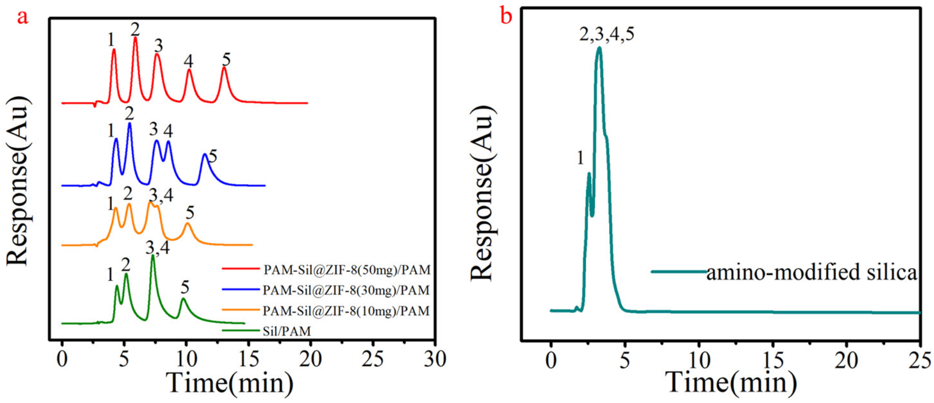


Figure 4. Separation chromatograms of five nucleosides/bases over (**a**) as-prepared stationary phases and (**b**) amino-modified silica. Mobile phase: ACN/100 mM NH_4OAc (85/15, *v/v*). Conditions: Flow rate 1 mL/min, 25 °C, UV detection at 254 nm. Analytes: (1) Uridine, (2) Adenosine, (3) Inosine, (4) Cytosine, (5) Citicoline.

3.3. Adherence to a Quantitative HILIC Retention Model

To further study the chromatographic behaviors of obtained stationary phase, five amino acids were chosen as model analytes to investigate their retention mechanism on PAM-Sil@ZIF-8(50 mg)/PAM by changing the volume fraction of water (20–40%). The HILIC retention mechanism can be expressed by Equation (1) [21,22], which combines the partitioning and adsorption model.

$$\text{Ln } k = a + b \ln \varphi + c\,\varphi, \tag{1}$$

In Equation (1), k is the retention factor of the analytes; φ is the water content in the mobile phase; a, b, and c are constants. The natural logarithm retention factors of five amino acids were plotted against the volume fraction of water in the mobile phase, as shown in Figure 5. It is demonstrated that excellent fits (R^2 0.9771–0.9890, Table S4) for five model analytes were achieved. Therefore, the typical HILIC behaviors of PAM-Sil@ZIF-8(50 mg)/PAM were displayed, in which the retention time of amino acids decreased with the increase in the volume fraction of water in the mobile phase.

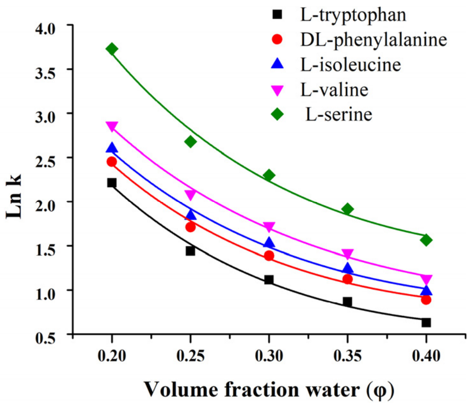


Figure 5. Plots of retention factors (ln k) vs. volume fraction of water for five amino acids on PAM-Sil@ZIF-8(50 mg)/PAM. Mobile phase: ACN/H_2O. Conditions: Flow rate 1 mL/min, 25 °C, ELS detector: Tube temperature 90 °C, gas flow: 2.5 L/min.

3.4. Effect of Column Temperature

To further investigate the chromatographic properties of PAM-Sil@ZIF-8(50 mg)/PAM, the effect of column temperature on the separation of five nucleosides/bases was conducted, as shown in Figure 6. It is reported that the effect of column temperature (15–35 °C) can be explained by the van't Hoff equation [23] (Equation (2)).

$$\text{Ln k} = (\Delta H^\circ)/RT + (\Delta S^\circ)/R + \ln \varphi, \quad (2)$$

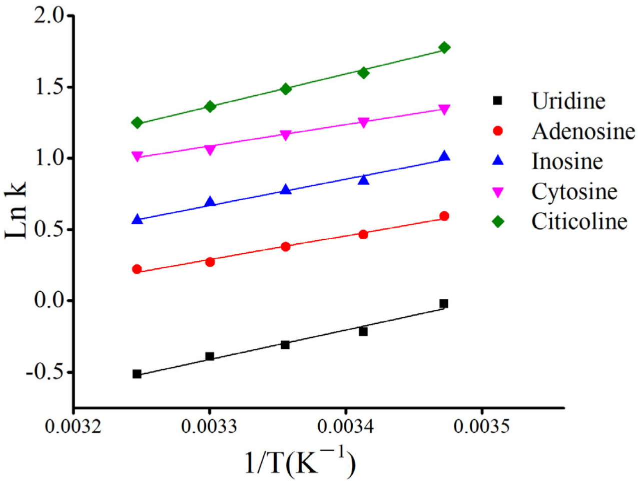


Figure 6. Effect of column temperature on the retention of five nucleosides/bases. Conditions: Flow rate 1 mL/min, 25 °C, UV detection at 254 nm. Mobile phase: ACN/100 mM NH_4OAc (85/15, *v/v*).

ΔH° and ΔS° are the standard molar enthalpy and entropy change between the stationary/mobile phase and analyte; k is the retention factor; R is the universal gas constant; T is column temperature in Kelvin; φ is the phase ratio, respectively. It can be seen that with the increase in temperature, the retention time of analytes decreased. In addition, the excellent linearity between ln k and 1/T (Figure 6 and Table S5) revealed that the separation mechanism has not changed.

3.5. Separation Performance of Alkaloids

Alkaloid is a special compound with physiological activity in plants and a few animals. Its molecular structure is mainly composed of carbon, hydrogen, and nitrogen molecules and can be used as medicine in clinic. To further investigate the separation performance of PAM-Sil@ZIF-8(50 mg)/PAM in HILIC model, five alkaloids were chosen as analytes to separate the prepared stationary phase. As shown in Figure 7, the baseline separation was achieved on PAM-Sil@ZIF-8(50 mg)/PAM with better selectivity and symmetric peak shape. Compared with amino-modified silica and Sil/PAM, PAM-Sil@ZIF-8(50 mg)/PAM stationary showed excellent separation performance, which benefits by the addition of ZIF-8 particles. In addition, the resolution of five alkaloids over different columns were compared. As shown in Table S1, PAM-Sil@ZIF-8(50 mg)/PAM possessed the largest resolution value, which further indicated the superiority of the addition of ZIF-8 nanoparticles. Furthermore, the column efficiency of five analytes were obtained (colchicine was 7861.9 plates/m) as shown in Table S2.

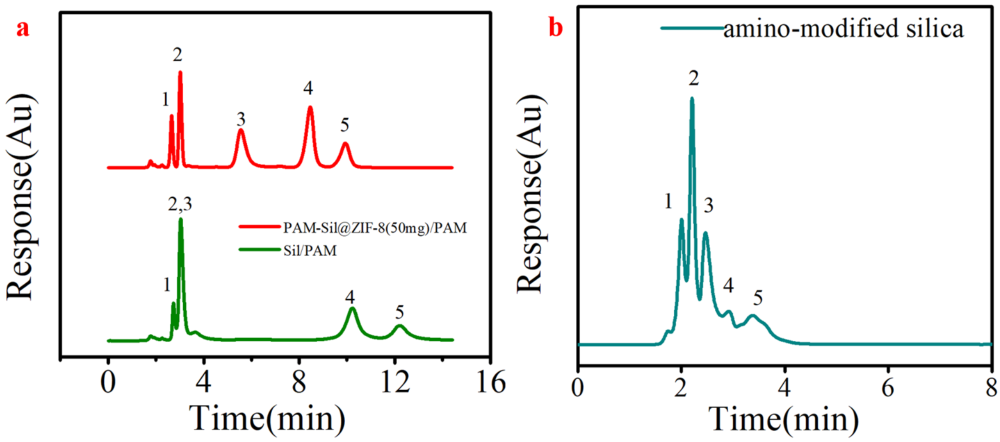


Figure 7. Separation chromatograms of five alkaloids over (**a**) as-prepared stationary phases and (**b**) amino-modified silica. Mobile phase: ACN/100 mM NH_4OAc (90/10, *v*/*v*). Conditions: Flow rate 1 mL/min, 25 °C, UV detection at 254 nm. Analytes: (1) Caffeine, (2) Colchicine, (3) Theophylline, (4) Berberine, (5) Coptisine.

3.6. Separation Performance of Amino Acids and Saccharides

Amino acids are organic compounds containing basic amino groups and acidic carboxyl groups and their separation is of great significance to the healthy life of human beings. To further evaluate the ability of PAM-Sil@ZIF-8(50 mg)/PAM for the separation of polar analytes, amino acids and saccharides were selected as model analytes. Five amino acids were completely separated by PAM-Sil@ZIF-8(50 mg)/PAM, as shown in Figure 8a. Compared with Sil/PAM and amino-modified silica, the addition of ZIF-8 improved the ability to retain amino acids, which may be caused by the increased specific surface area and extra interaction sites. This further indicated that the addition of MOF particles to polymer modified silica was a good strategy for improving the separation performance of stationary phase. In addition, we investigated the effect of the volume fraction of water in the mobile phase on the separation chromatograms of five amino acids, as shown in Figure 9. This indicated that the retention time of five amino acids decreases with the increasing proportion of water in the mobile phase. When the volume fraction of water is 35%, the five amino acids cannot be separated completely. Moreover, saccharides, the product of photosynthesis in green plants, are one of the most basic and inexpensive sources of energy for humans and most animals. They are not only nutrients, but some of them also have special physiological activities. However, as hydrophilic compounds, they face great challenges in separation. The separation of five saccharides was achieved on PAM-Sil@ZIF-8(50 mg)/PAM, as shown in Figure 10. In addition, the separation of amino acids and saccharides was detected by an evaporative light scattering detector. The stable baseline indicates that ZIF-8 and PAM is not leached significantly from the stationary phase, which indicated that the stationary phase possessed good stability.

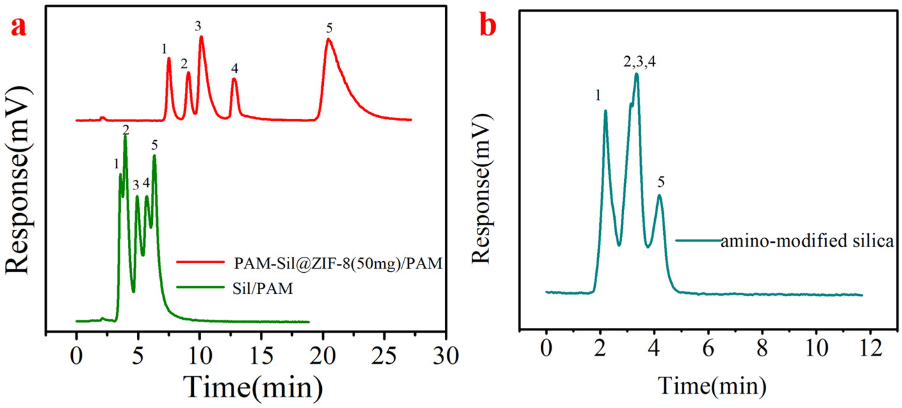


Figure 8. Separation chromatograms of five amino acids over (**a**) as-prepared stationary phases and (**b**) amino-modified silica. Mobile phase: ACN/H_2O (75/25, *v/v*). Conditions: Flow rate 1 mL/min, 25 °C, ELS detector: Tube temperature 90 °C, gas flow: 2.5 L/min. Analytes: (1) L-tryptophan, (2) DL-phenylalanine, (3) L-isoleucine, (4) L-valine, (5) L-serine.

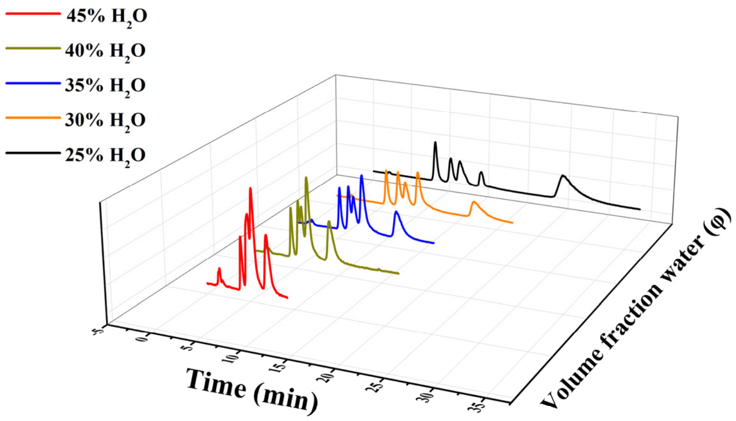


Figure 9. Effect of the mobile phase composition on the separation of five amino acids on PAM−Sil@ZIF−8(50 mg)/PAM column. Mobile phase: CAN/H_2O. Conditions: Flow rate 1 mL/min, 25 °C, ELS detector: Tube temperature 90 °C, gas flow: 2.5 L/min.

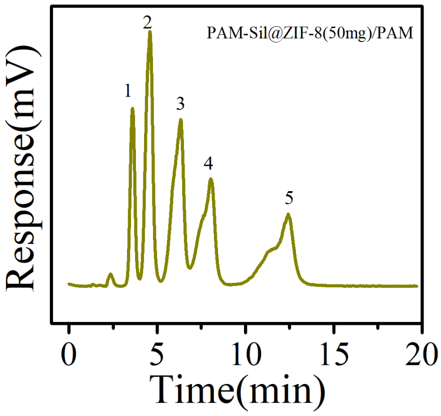


Figure 10. Separation chromatograms of five saccharides over PAM−Sil@ZIF−8(50 mg)/PAM. Mobile phase: ACN/H_2O (75/25, *v/v*). Analytes: (1) Xylose, (2) Glucose, (3) Sucrose, (4) Trehalose, (5) Raffinose. Conditions: Flow rate 1 mL/min, 25 °C, ELS detector: Tube temperature 90 °C, gas flow: 2.5 L/min.

3.7. Stability and Reproducibility of PAM-Sil@ZIF-8(50 mg)/PAM for Separation

The stability and reproducibility of stationary phase is important in practical applications. The reproducibility of PAM-Sil@ZIF-8(50 mg)/PAM for separation was investigated by seven continuous injections of five nucleosides/bases. As shown in Figure 11a and Table S6, the elution time did not change significantly and the relative standard deviation (RSD) of the retention time was within 0.22–0.97% for the analytes. In addition, the stability of PAM-Sil@ZIF-8(50 mg)/PAM was studied by continuous operation for 60 h, as shown in Figure 11b and Table S7. The RSD was within 0.56–1.86%, which indicated that PAM-Sil@ZIF-8(50 mg)/PAM possessed good stability. Therefore, PAM-Sil@ZIF-8(50 mg)/PAM is suitable for use in liquid chromatography.

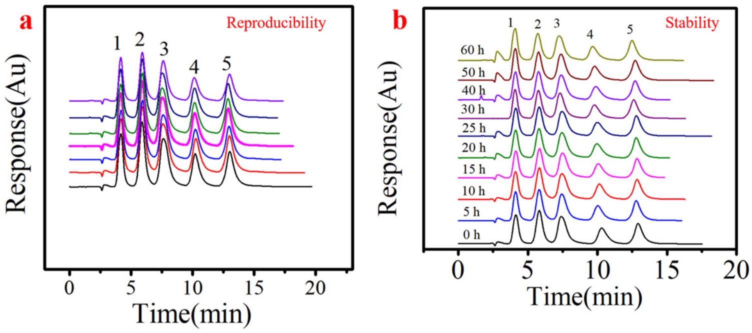


Figure 11. (**a**) Stability and (**b**) reproducibility of PAM-Sil@ZIF-8(50 mg)/PAM for separation. Mobile phase: ACN/100 mM NH_4OAc (85/15, *v/v*). Conditions: Flow rate 1 mL/min, 25 °C, UV detection at 254 nm. Analytes: (1) Uridine, (2) Adenosine, (3) Inosine, (4) Cytosine, (5) Citicoline.

3.8. Comparison with Other Stationary Phases in Literature

The separation performance of PAM-Sil@ZIF-8(50 mg)/PAM was compared with other stationary phases that have been reported in literature. For the separation of nucleosides/bases, PAM-Sil@ZIF-8(50 mg)/PAM exhibited a better peak shape compared with a non-conjugated flexible network modified silica stationary phase (Py-TAC-DMA@SiO_2) [24], which was prepared by a one pot strategy. In addition, PAM-Sil@ZIF-8(50 mg)/PAM has shown better separation performance compared with $(HO)_{12}CB$ [6]-bonded silica [25] stationary phase for the separation of alkaloids.

4. Conclusions

In this study, a PAM-Sil@ZIF-8/PAM HILIC stationary phase was obtained by a simple synthesis process of adding ZIF-8 nanoparticles and silica into polyacrylamide (PAM) aqueous solution, and then stirring the mixture until the solution was evaporated absolutely with the help of mechanical agitator. It was demonstrated that the addition of ZIF-8 nanoparticles can improve the separation performance of stationary phase by improving the specific surface areas and providing extra interaction sites between the stationary phase and analytes. In addition, by changing the addition amounts of ZIF-8 nanoparticles, the novel stationary phase with better separation performances for hydrophilic analytes (such as nucleosides/bases, alkaloids, and amino acids) were obtained. Moreover, compared with amino-modified silica and Sil/PAM stationary phase, PAM-Sil@ZIF-8(50 mg)/PAM showed better separation performance benefit by the addition of ZIF-8, which further indicated that the addition of MOF particles to polymer modified silica was a good strategy for improving the separation performance of stationary phase. Furthermore, the new stationary phase showed good stability and reproducibility, which is suitable for use in LC. The relative standard deviation (RSD) of the retention time for reproducibility with seven replicates of continuous elution was found to range from 0.22% to 97%, and the RSD of the stability for 60 h of continuous operation was found to range from 0.56% to 1.86%. The results indicated that the PAM-Sil@ZIF-8(50 mg)/PAM can be used in HILIC mode of LC.

In short, this strategy proved that the separation performance of polymer modifying silica stationary phase can be greatly improved by the addition of MOF.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/separations10030219/s1. Figure S1: TEM image of PAM-Sil@ZIF-8(50 mg)/PAM; Figure S2: EDS images of PAM-Sil@ZIF-8(50 mg)/PAM and distribution of O, Si, C, and Zn elements; Table S1: BET analysis results of bare silica, PAM/Sil, and PAM-Sil@ZIF-8(50 mg)/PAM; Table S2: The resolution of five alkaloids over different columns; Table S3: Column efficiency of five analytes over different columns; Table S4: The results of regression coefficient of Equation (1) for five amino acids on the PAM-Sil@ZIF-8(50 mg)/PAM; Table S5: Fitting coefficients and corresponding correlation coefficient for Equation (2); Table S6: Reproducibility of PAM-Sil@ZIF-8(50 mg)/PAM; Table S7: Stability of PAM-Sil@ZIF-8(50 mg)/PAM.

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