Applied Surface Science 364 (2016) 579–588

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Adsorption characteristics, recognition properties, and preliminary application of nordihydroguaiaretic acid molecularly imprinted polymers prepared by sol–gel surface imprinting technology

Sen Liao, Wen Zhang, Wei Long, Dan Hou, Xuechun Yang, Ni Tan*

School of Chemistry and Chemical Engineering, University of South China, Hengyang 421001, Hunan Province, PR China

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
22 December 2015
Accepted 22 December 2015
Available online 25 December 2015

Keywords:
Nordihydroguaiaretic acid
Surface molecularly imprinted polymers
Sol–gel
Selectivity recognition
Ephedra

ABSTRACT

In this paper, a new core-shell composite of nordihydroguaiaretic acid (NDGA) molecularly imprinted polymers layer-coated silica gel (MIP@SiO_2) was prepared through sol–gel technique and applied as a material for extraction of NDGA from Ephedra. It was synthesized using NDGA as the template molecule, γ-aminopropyltriethoxysilane (APTS) and methyltriethoxysilane (MTEOS) as the functional monomers, tetraethyl orthosilicate (TEOS) as the cross-linker and ethanol as the porogenic solvent in the surface of silica. The non-imprinted polymers layer-coated silica gel (NIP@SiO_2) were prepared with the same procedure, but with the absence of template molecule. In addition, the optimum adsorption affinity occurred when the molar ratio of NDGA:APTS:MTEOS:TEOS was 1:6:2:80. The prepared MIP@SiO_2 and NIP@SiO_2 were analyzed by scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and Fourier transform-infrared spectroscopy (FT-IR). Their affinity properties to NDGA were evaluated through dynamic adsorption, static adsorption, and selective recognition experiments, and the results showed the saturated adsorption capacity of MIP@SiO_2 could reach to 5.90 mg g^{-1}, which was two times more than that of NIP@SiO_2. High performance liquid chromatography (HPLC) was used to evaluate the extraction of NDGA from the medicinal plant ephedra by the above prepared materials, and the results indicated that the MIP@SiO_2 had potential application in separation of the natural active component NDGA from medicinal plants.

1. Introduction

Nordihydroguaiaretic acid (NDGA) (Fig. 1) is a phenolic lignan found in the leaves and twigs of the shrub ephedra, Larrea tridentate [1], and it possesses a number of biological properties potentially useful to human. Modern pharmacological studies indicated that NDGA as a lipoxygenases inhibitor had multiple bioactivities such as free-radical scavenging, antioxidation, antitumor, anti-virus, and so on [2–5]. Recently, NDGA was also found to be able to inhibit dengue virus infection by targeting genome replication and viral assembly [6]. Due to these biological activities, many researches on the separation and purification of NDGA from complex medicinal herbal ingredient have been explored using thin layer chromatography (TLC) and high performance liquid chromatography (HPLC), etc. [7]. However, these techniques were time consuming, laborious, and required large volume of organic solvents. Thus, extraction and purification technologies for NDGA are important to enhance the utilization efficiency.

In recent years, the molecular imprinting technology (MIT) is a versatile and easy method for preparing artificial recognition polymers with high affinity and selectivity toward a particular target molecule [8]. Molecularly imprinted polymers (MIPs) are a kind of synthesized material through MIT, in which a great deal of imprinted cavities which are complementary to the template molecules in shape, size and functionality are designed [9]. Thus, at present, MIPs with specific molecular recognition ability and high affinity for the template molecules have been successfully used to separate and extract some pharmacologically active molecules [10].

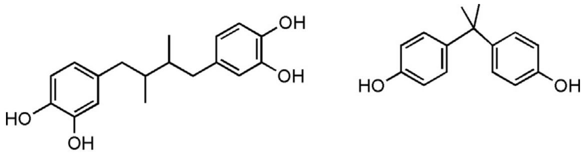
Traditionally, MIPs were prepared by bulk polymerization. However, the obtained MIPs had some common limitations such as low binding capacity, poor sites accessible to target molecules, irregular shape, and heterogeneous binding site distribution [11]. In addition, the template molecules were embedded in the matrices too deeply to be easily diffused and eluted [12]. To avoid the disadvantages mentioned above, surface imprinting technology was developed and gained people more and more attention. A

---

* Corresponding author at: School of Chemistry and Chemical Engineering, University of South China, No. 28, Changsheng Road (West), Zhengxiang District, Hengyang 421001, Hunan Province, PR China.

E-mail address: tannii@21cn.com (N. Tan).

http://dx.doi.org/10.1016/j.apsusc.2015.12.184
0169-4332/© 2015 Elsevier B.V. All rights reserved.



NDGA Bisphenol A (BPA)

Fig. 1. The chemical structure of NDGA and BPA.

fundamental strategy of surface imprinting was to locate the imprinting sites on the surface of silica gel particles, which improved the recognition sensitivity and the elution ability for target molecules [13,14], and the prepared MIPs possessed high stability, chemical inertness and non-swelling properties, and this was just what people expect.

In this paper, a new core-shell composite of nordihydroguaiaretic acid (NDGA) surface molecularly imprinted polymers layer-coated silica gel (MIP@SiO_2) was prepared through sol–gel technique and applied as a material for extraction of NDGA from ephedra, and the obtained polymers were characterized and their adsorption properties for NDGA were also studied in detail. The structures of the template (NDGA) and the related molecule (bisphenol A) were depicted in Fig. 1.

2. Materials and methods

2.1. Reagent and chemicals

Nordihydroguaiaretic acid (97%, NDGA) was purchased from Alfa Aesar Chemicals Reagent Factory (Shanghai, China). Tetraethoxysilane (99%, TEOS), phenyltrimethoxysilane (98%, PTMOS), diethoxydiphenylsilane (98%, DPEOS) 3-aminopropyltriethoxysilane (97%, APTS), methyltriethoxysilane (97%, MTEOS), 2,3-epoxypropoxy propyltrimethoxysilicane (KH-560), and bisphenol A (99%, BPA) were obtained from Aladdin (Shanghai, China). Methanol (HPLC grade), acetic acid (HAc, AR), ethanol (EtOH, AR), ammonium hydroxide solution, hydrochloric acid (HCl, AR), and sodium hydroxide (NaOH) were got from Tianjin Da Mao Chemicals Reagent Factory (Tianjin, China). The mobile phase used for the HPLC experiments was a mixture of methanol and water (65:35, v/v), which was filtered through a 0.45 μm filter prior to use. The medicinal plant ephedra was got from Hengyang Yifeng Pharmacy.

2.2. Apparatus

The infrared spectra were analyzed by using IR Prestige-21 Fourier transform infrared (FTIR) spectrometer of SHIMADZU (Tokyo, Japan). The ultraviolet–visible spectrophotometer was used to detect the UV absorbance (Hitachi U-3900, Japan). The morphological evaluation analysis studies were carried out by using JSM-6610LV scanning electron microscopy (SEM) of JEOL Ltd. (Tokyo, Japan). Thermogravimetric analysis was performed by a NETZSCH STA 409 PC/PG (China).

The extraction experiments were carried out by HPLC-UV system, composed of a P1010 LC liquid delivery pump and a 1000D UV–visible detector (Shandong Lunan Ruihong Chemical Instruments Co., Ltd., Shandong, China), and the analytical column (250 mm × 4.6 mm I.D., C18, 5 μm) was purchased from Dikma Technologies Inc. (Beijing, China). The mobile phase was methanol and water solution (65:35, v/v) at a flow rate of 1 mL min^{-1} with 20 μL injection volumes and the UV detector wavelength was set at 282 nm. The column was rinsed with the mobile phase until a stable baseline was obtained before detecting the samples.

2.3. Preparation of MIP@SiO_2

According to the previous reported literature [15], the procedure to obtain the silicon dioxide particles using the sol–gel method was established as follows with some modifications: 25 mL of ethanol and 10 mL of distilled water were added into a 250 mL three-necked flask and thoroughly mixed in water bath of 40 °C, and then 2 mL of ammonium hydroxide solution (28%, weight percent) was added. Then, 7.5 mL TEOS was added dropwise within 1 h, and the resultant mixture was stirred vigorously for 4 h at 40 °C. Through centrifugalized, washed repeatedly with ethanol till the neutral pH (7.0), and dried in the vacuum drying oven for 24 h, the silicon dioxide particles (SiO_2) for further use were finally obtained.

Then the silicon dioxide particles were activated by adding the mixture of 5 g of the silica gel and 50 mL of 6 mol L^{-1} HCl into a 250 mL three-neck flask. The resultant mixture was refluxed under stirring for 10 h. The solid product was filtered and washed repeatedly with water to neutrality and dried at 110 °C for 12 h [16].

The MIP@SiO_2 was prepared by surface-imprinted polymerization, and the procedure was as follows: NDGA (0.05 mmol) was dissolved in ethanol with stirring, then APTS (0.3 mmol) and MTEOS (0.1 mmol) were added into the mixture. After the above mixture stirring for 30 min, the fixed amount of TEOS and activated silica was added to the mixture. The resultant solution was stirred for another 1 h, then 1 mL of 0.01 mol L^{-1} HAc was added, and the polymerization was performed at room temperature for 24 h. The solid product was collected by centrifuging at 4000 r min^{-1} for 15 min. At this point, the activated silica surface was grafted with the molecularly imprinted polymers. To remove the template, the NDGA-imprinted silica was washed by Soxhlet-extracting method using a mixture of methanol-acetic acid (7:3, v/v) for 24 h, and then washed by methanol until no NDGA molecule was detected. Finally, the particles were dried under vacuum, at the moment, NDGA-MIP@SiO_2 was prepared. The NIP@SiO_2 was also prepared with the same method as MIP@SiO_2 without the addition of the template molecule NDGA.

2.4. SEM, FTIR, TGA and nitrogen adsorption–desorption analysis

The surface characteristics of MIP@SiO_2 and NIP@SiO_2 were analyzed using scanning electron microscopy (SEM). Firstly, C tape was adhered on sample stage. Then, MIP@SiO_2 and NIP@SiO_2 were spread on C tape, and loose powders were blown off. Finally, the samples were air-dried and sputter-coated with 4 nm of gold particles before using.

Fourier transformed infrared (FTIR) spectrometry were used to probe the functional groups in materials. Sample disks were made by mixing 1 mg of dry SiO_2, NDGA-MIP@SiO_2, MIP@SiO_2, or NIP@SiO_2 with 150 mg of KBr, respectively. Data analyses were focused on the 400~4000 cm^{-1} region.

Thermogravimetric analyses were processed respectively by adding 10 mg SiO_2, NIP@SiO_2, or NDGA-MIP@SiO_2 into sample disk on 15~750 °C region.

Nitrogen adsorption–desorption experiments were carried out on a Micromeritics TriStar II 3020 with a bath temperature of 77 K. Surface areas were determined using the Brunauer–Emmett–Teller (BET) theory, and pore size distributions were calculated using the Barrett–Joyner–Halenda (BJH) theory from the adsorption branch.

2.5. Binding experiments of MIP@SiO_2 and NIP@SiO_2

2.5.1. Optimization of the solid-to-liquid ratio

5 mg, 10 mg, 15 mg, 20 mg MIP@SiO_2 and NIP@SiO_2 were added into 10 mL 0.03 mg mL^{-1} ethanol solution of NDGA respectively, and the mixtures were vibrated for 8 h at room temperature. Then the mixtures were separated through centrifugation, and the