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Macroporous polymeric sorbents with high selectivity for separation of phenols

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ABSTRACT

A polymeric sorbent with high selectivity and capacity for phenols in aqueous stream was synthesized based on 5-amino-2-methoxyphenol functionalized poly(glycidyl methacrylate-co-trimethylolpropane trimethacrylate), P(GMA-TRIM)-AMP. In addition to sorption, the materials were studied using solid-stated NMR, Fourier transform infrared (FT-IR), elemental analysis, and scanning electron microscopy (SEM). Well-defined internal micrometer-sized spheres of P(GMA-TRIM)-AMP have stable macropore inner structures surrounded by a thin outer shell. The sorbent has functional groups that are similar in chemical structure to 4-propyl-2-methoxyphenol, PMP, and show high selectivity in removal of PMP from glucose- and xylose-containing monosaccharides solutions in bioethanol production without the loss of the saccharides. The sorbent could also be used to separate phenol and 4-chlorophenol from waste water that contained concentrations of phenols in the ppm range. The sorbent is easily regenerated, has good durability and reusability. It was regenerated and reused at least 10 times without loss in sorption behavior.

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1. Introduction

Cellulosic ethanol is a desirable alternative fuel [1–3] that can be obtained by conversion of various lignocellulosic biomass such as woods, herbaceous crops, agricultural residues, waste paper, and other fractions of municipal solid waste [4–8]. Lignocellulosic materials contain cellulose and hemicellulose in a solid matrix with lignin. Both cellulose and hemicellulose are long chain sugar polymers. After pretreatment and hydrolysis the resulting sugar monomers can be converted into ethanol by fermentation [7,9,10]. During hydrolysis, lignin phenol monomers, such as 4-propyl-2-methoxyphenol (PMP), can be created from lignin. Many of these products can inhibit the desired fermentation of monosaccharides into ethanol. Removal of these inhibitors can significantly increase the yield of ethanol. Unfortunately, such selective inhibitor removal is limited by a lack of available separation techniques. Due to its high boiling point, large molecular size, low concentration, and a strong interaction with enzymes, it is difficult to remove PMP from the hydrolysis solution via conventional technologies. Moreover, selectivity is a key need, since removal of PMP shouldn't cause loss of useful components such as sugar, other oligo- and monosaccharides, and ethanol in the hydrolyzed solution [11]. Thus an engineered sorption technology with high selectivity is explored in this research.

Besides the cellulosic ethanol application, phenolic compounds such as phenol, chlorophenol, etc. also exist in many industrial effluents such as those from oil refinering, coal, pharmaceutical, plastics, paint, leather, paper pulp, and steel manufacturing processes [12–18]. These recalcitrant and non-biodegradable organics accumulate in water and contaminate underground sources [19,20]. The continuous consumption of water containing organic contaminants in excess of a few parts per billion (ppb) can lead to serious health problems depending on the type of the pollutant [21]. Phenol is easily absorbed through the lungs, skin, and alimentary canal and is highly toxic [22]. Some substituted phenols such as chlorophenols are carcinogenic [23]. This leads us to believe that improved methods for separation and recovery of phenolic compounds from process waste streams will benefit the environment, industrial safety, and improve process economics.

Adsorption is a convenient and effective technique to remove low concentrations of chemicals from water [13,18,24–27]. A model inhibitor, PMP, is targeted in this work to explore selective removal from saccharide-containing solutions. The sorbent was designed and synthesized based using a variation of the "like dissolves like principle" for solvents. Specifically we used a "like sorbs like" principle. On this basis, porous polymeric sorbents that have

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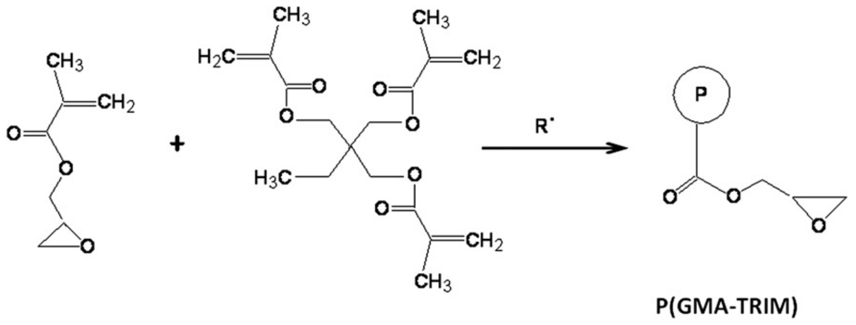


Scheme 1. Synthesis of P(GMA-TRIM) polymer.

a similar chemical structure to PMP were synthesized. Our goal was to create a polymer with the same functional side groups as PMP to promote sorption while avoiding excessive binding of the PMP. Achieving this goal can enable effective sorption affinity while also enabling non-destructive regeneration of the sorbent. Such polymeric sorbents are expected to have good sorption selectivity for compounds of methoxyphenols in the hydrolyzed solution of biomass, and after synthesis, selectivity and capacity for PMP were studied. To our knowledge, no approach based on "like sorbs like" was proposed in developing sorbents before.

2. Experimental

2.1. Materials

Glycidyl methacrylate, GMA (Aldrich, 97%); Trimethylolpropane trimethacrylate, TRIM (Aldrich, technical grade); 2,2′-Azobis(2-methylpropionitrile), AIBN (Aldrich, 98%); poly(vinyl pyrrolidone), PVP (Aldrich, average Mw 1,300,000); 5-Amino-2-methoxyphenol, AMP (Aldrich, 98%); Phenol (Sigma, 99.5%), Chlorophenol (Sigma, 99%), and Toluene (Sigma, 99.9%) were used as obtained.

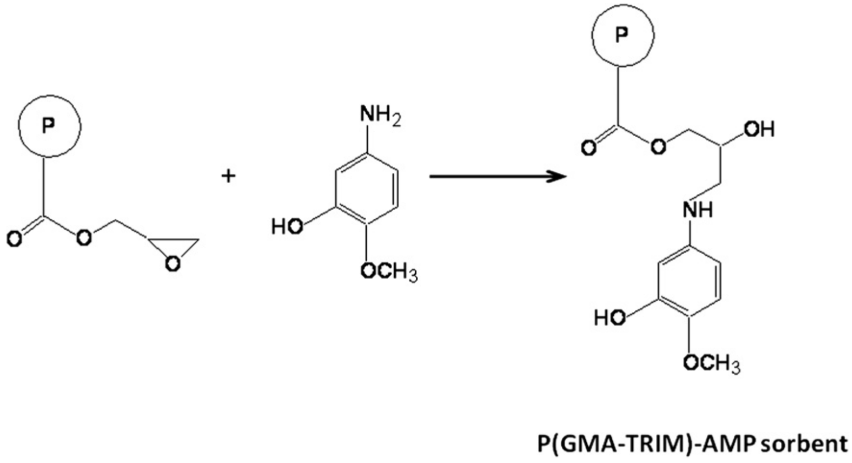
2.2. Preparation of poly(GMA-TRIM)-AMP porous sorbents

The porous copolymer beads were first prepared through suspension polymerization, which was composed of an organic phase and an aqueous phase [28,29]. The ratio of the organic phase to the aqueous phase was 30/70 by volume. The organic phase was composed of GMA and TRIM as monomers, AIBN as initiator, and toluene as a porogen, while the aqueous phase with PVP as a stabilizer dissolved in de-ionized water. The AIBN content was 1% w/v of monomers in organic phase and PVP content was 1% w/v of aqueous phase. The ratio of GMA to TRIM was 5.5/1 (mol). The specific amount of GMA, TRIM, and AIBN were dissolved in toluene to form a transparent organic phase, which was then dropped into the pre-prepared aqueous phase, and kept stirring for 2.5 h in N_2 to form a homogeneous dispersion. The polymerization was carried out at 73–75 °C in N_2 for 15 h, with stirring of 300 rpm, and the de-ionized water was added to the suspension. The system was then cooled to 50 °C and stirring was ceased to enable sedimentation. The supernatant was decanted and the procedure was repeated until a clear supernatant was obtained. The resulting particles were filtered, washed with de-ionized water and acetone, and purified with acetone, filtered and dried at room temperature for 2 days, then dried in vacuo at 70 °C for 4 days. The white P(GMA-TRIM) copolymer beads were obtained.

An excess amount of AMP was dissolved in NMP at 50 °C under N_2 atmosphere, and P(GMA-TRIM) copolymer beads were added and soaked in the AMP solution for 2 days. The reaction was carried out at 80 °C for 15 h, and the resulting product was filtered, washed with NMP, DI water, and acetone. Finally the sample was purified with acetone for 4 days in a Soxhlet extractor and dried under room temperature for 2 days, followed by vacuum at 70 °C for 4 days. The obtained functionalized P(GMA-TRIM)–AMP copolymer beads are a peach color.

2.3. Characterization of the sorbents

Fourier transform infrared (FT-IR) spectra were recorded by means of a Bruker Tensr 27 spectrophotometer using the KBr wafer technique. Solid-state NMR spectra were obtained on a Bruker DSX 400 under CP-MAS conditions. The C, H and N contents of the



Scheme 2. Synthesis of P(GMA-TRIM)-AMP sorbent.

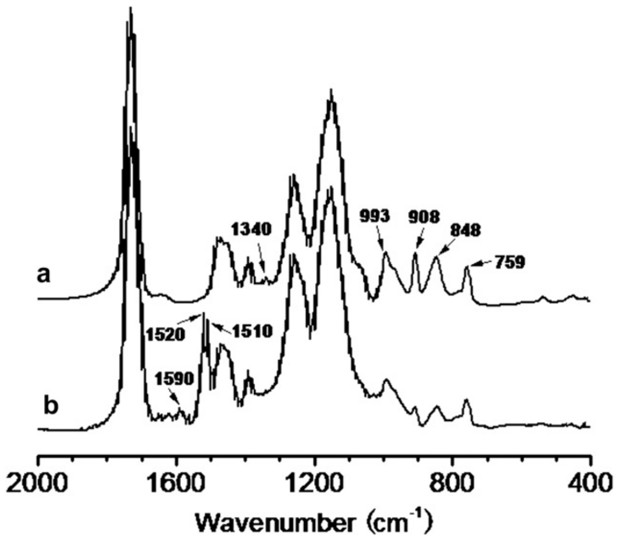


Fig. 1. FT-IR spectra of (a) P(GMA-TRIM), and (b) P(GMA-TRIM)-AMP.

sorbent were determined by elemental analysis using Vario EL III (Elementar Analysensysteme GmbH, Germany). The particle size of the sorbent was determined using sieves with mesh size of 0.355, 0.500, 0.710, 0.850 and 1.0 mm, respectively. Thermo-stabilities of beads were examined with a TGA Q5000 instrument under a flow of nitrogen, heating from about 30 to 650 °C at a rate of 10 °C/min. The overall morphology and the microstructure of the beads were observed on a LEO 1530 thermally-assisted field emission (T-FE) SEM machine at an acceleration voltage of 3.0 kV or 8.0 kV. Samples were used as obtained, crushed, or sectioned using an ultramicrotome, and were surface sputter coated with a thin layer of gold with a thickness ca. 10 nm prior to observation.

2.4. Sorption and desorption tests

The P(GMA-TRIM)-AMP sorbent was tested for sorption of phenol in batch tests. A small amount of sorbent was added into a plastic-stopper Erlenmeyer flask containing 20 mL phenol solution (the mass of sorbent to the mass of solution was 1/100), and shaken at 25 °C for a specific time period in a shaking water bath (Grand OLS 200L). The sorption capacity (Q_c) of the phenol was calculated using Eq. (1):

$$Q_c = V_o^*(C_o - C_e)/M \tag{1}$$

where Q_c is the equilibrium sorption capacity (mg/g), V_o is the volume of the phenol solution (L), C_o and C_e are the initial and equilibrium concentration of phenol in solution (mg/L), respectively, and M is the mass of sorbent beads used (g).

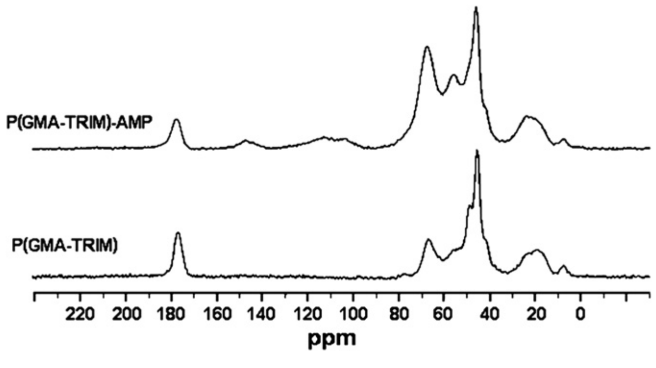


Fig. 2. ^{13}C CP-MAS NMR spectra of P(GMA-TRIM) and functionalized P(GMA-TRIM)-AMP sorbents.

The distribution coefficient K_d, i.e., the ratio of the concentration of adsorbed phenol in sorbent to the equilibrium concentration of phenol in the solution, is expressed as Eq. (2):

$$K_d = C_s/C_e \tag{2}$$

where C_s is the equilibrium concentration of phenol in sorbent, and is calculated with Eq. (3):

$$C_s = (C_o - C_e)^*V_o/V_s \tag{3}$$

where $V_s = M/\rho$, is the volume of sorbent polymer; M is the mass of sorbent, and ρ is the density of the primary submicron particles and shell wall comprising the sorbent polymer. This density was measured as 1.221 ± 0.001 kg/L with a density gradient column at 30 °C (Techne Inc.). The value was determined by allowing more than 20 particles to equilibrate in the column and then using the average of the array of particle position. The range of these positions was fortunately rather small (±1 grid in a column with 70 grids) corresponding to ± 0.001 kg/L.

The phenol saturated sorbent beads were filtered, rinsed with DI water, and dried under room temperature for 12 h. Desorption of phenol was carried out by soaking the saturated beads in ethanol and shaking at 25 °C for varied time from 30 min to 24 h in a shaker unit. The desorbed phenols were the same either in 30 min or in 24 h, about 95 ± 5% phenols can be desorbed in 30 min. Therefore 30 min was used in most desorption experiments, and the mass ratio of saturated sorbent to ethanol was kept at 1/100.

The concentration of phenol was determined with a DU® 720 UV–vis spectrophotometer (Beckman Coulter), using a pre-calibrated curve of UV absorption *vs.* phenol concentration. The concentration of monosaccharide was determined by a Dionex High Performance Anion Exchange Chromatography (HPAEC) with triple pulse amperometry (PAD) detector, and a CarboPac PA10 anion-exchange column.

3. Results and discussion

3.1. Synthesis of porous polymer sorbent

P(GMA-TRIM) copolymer porous beads were synthesized through suspension polymerization using GMA and TRIM as monomers, as shown in Scheme 1. The TRIM works as a crosslinker and yields the resulting polymeric resins mechanical properties, while GMA provides epoxy groups which are effective for introducing the target groups. The resulting P(GMA-TRIM) copolymer beads were then functionalized by a ring–opening reaction of oxirane with the amino groups of AMP, to produce P(GMA-TRIM)–AMP, as shown in Scheme 2, and the AMP functionalized porous polymer beads will be used as selective sorbents to remove phenols from solutions.

The initial monomer ratio of GMA to TRIM was 5.5/1 (mol), thus the theoretical C, H, and O content in polymer is 60.59 wt.%, 7.27 wt.%, and 32.14 wt.%, respectively. The elemental analysis gave the C and H content as 60.27 wt.% and 7.65 wt.%, and by difference, the O content was 32.08 wt.%. These measured elemental fractions in polymer are very close to the corresponding calculations from the initial monomer, indicating that the GMA and TRIM were quantitatively copolymerized to produce P(GMA-TRIM) with the same content of GMA as that in the feed monomers. Therefore, the epoxy group fraction, i.e., the GMA fraction in P(GMA-TRIM) is 85 mol%.

The elemental analysis of the functionalized sorbent, P(GMA-TRIM)–AMP, yielded C, H, and N fraction as 59.44 wt.%, 7.04 wt.%,

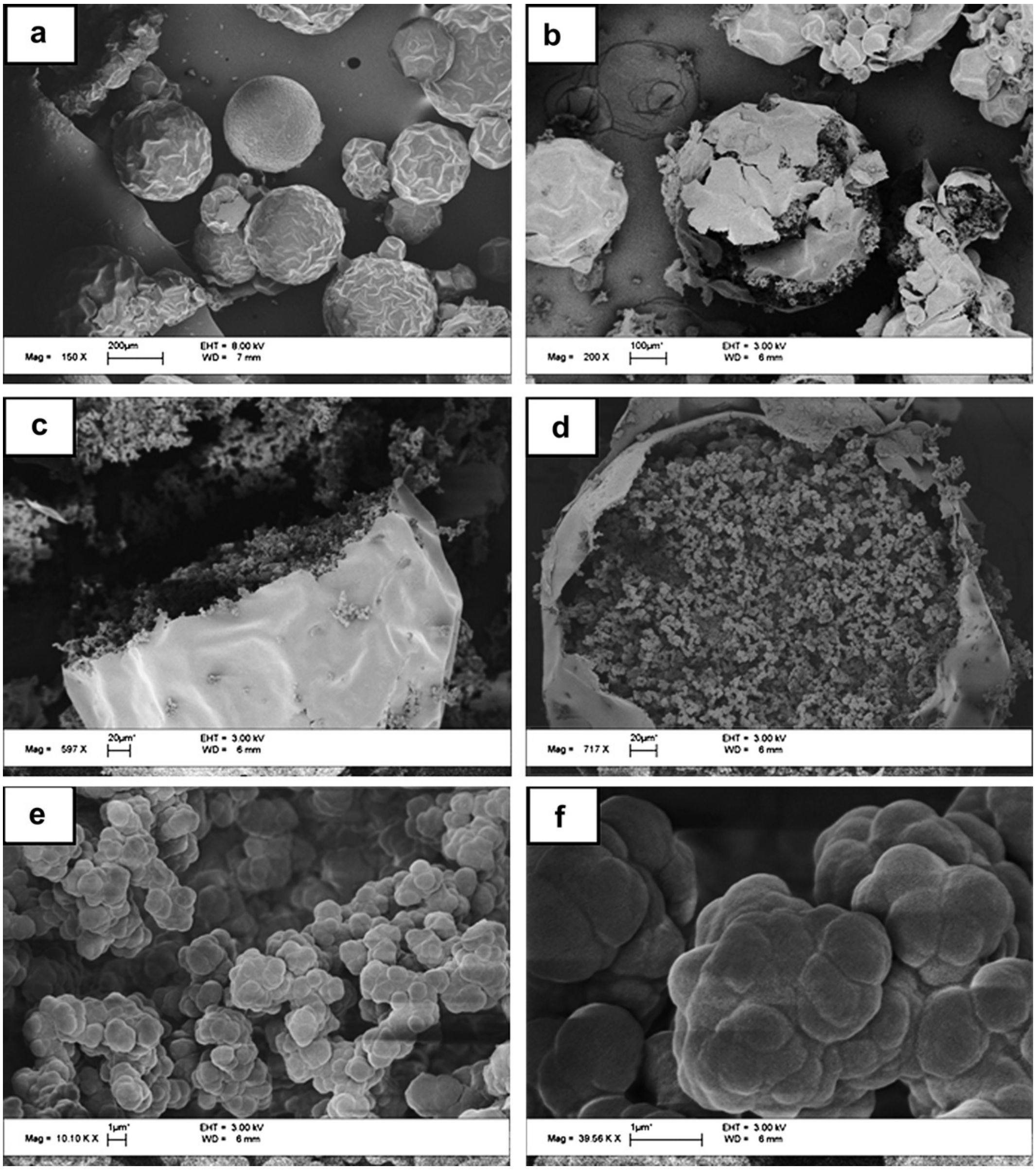


Fig. 3. SEM photographs of (a) beads, (b) crushed beads, (c) and (d) ultramicrotome sectioned sample, (e) and (f) interior structure, (g) a piece of shell, (h) cross section and inner surface of a shell, (i) cross section and out surface of a shell, and (j) cross section of a shell.

and 1.55 wt.%, indicating that AMP fraction is 1.11 mmol/g polymer sorbents. The resulting sorbent was used in the subsequent sorption testing.

As expected, the FT-IR spectra of the copolymer and the sorbent differ considerably from each other, as shown in Fig. 1. Unlike the spectrum of P(GMA-TRIM), the functionalization of P(GMA-co-TRIM) shows the disappearance of the peak at 1340 cm^{-1} and a decrease in absorbance of peaks at the 993, 908, 848 cm^{-1} due to epoxy groups in P(GMA-TRIM), while the new peaks at 1590, 1510, and 1520 cm^{-1} appear due to the benzene groups in P(GMA-TRIM)-AMP, suggesting the successful conversion of the epoxy groups with AMP.

Fig. 2 shows the solid state ^{13}C NMR spectra of P(GMA-TRIM) and P(GMA-TRIM)-AMP. The chemical shift at 166 ppm represents the carbonyl groups conjugated with a double bond, and 176 ppm represents unconjugated ones, i.e. the carbon–carbon double bonds have reacted [30]. No peak at 166 ppm of the unreacted double bonds in P(GMA-co-TRIM) was found, indicating that there are no methacrylate groups left, i.e., the polymerization reaction was carried out thoroughly. Normalizing with respect to that at 176 ppm, the integral at 67.7 ppm in Fig. 2 is 1.32 for P(GMA-TRIM), while it is 6.08 for P(GMA-TRIM)-AMP. The intensity at 67.7 ppm increases after functionalization, indicating that more carbon atoms are attached to hydroxyl groups [31]. The new peaks in the sample of P(GMA-TRIM)-AMP at 100–120 ppm are assigned to the carbon of $-\text{OCH}_3$ groups and carbons in benzene, while the peaks at 140–150 ppm are assigned to the carbon of $-\text{OCH}_3$ groups in AMP. From the results described above, P(GMA-TRIM)-AMP sorbent was successful synthesized.

3.2. Characteristics of the beads

The particle size of the polymer beads was measured with sieves. It was found that more than 95 wt.% of the polymer beads had particle sizes of less than 850 μm, 70 wt.% particles are less than 500 μm, and 45 wt.% are smaller than 355 μm. The overall

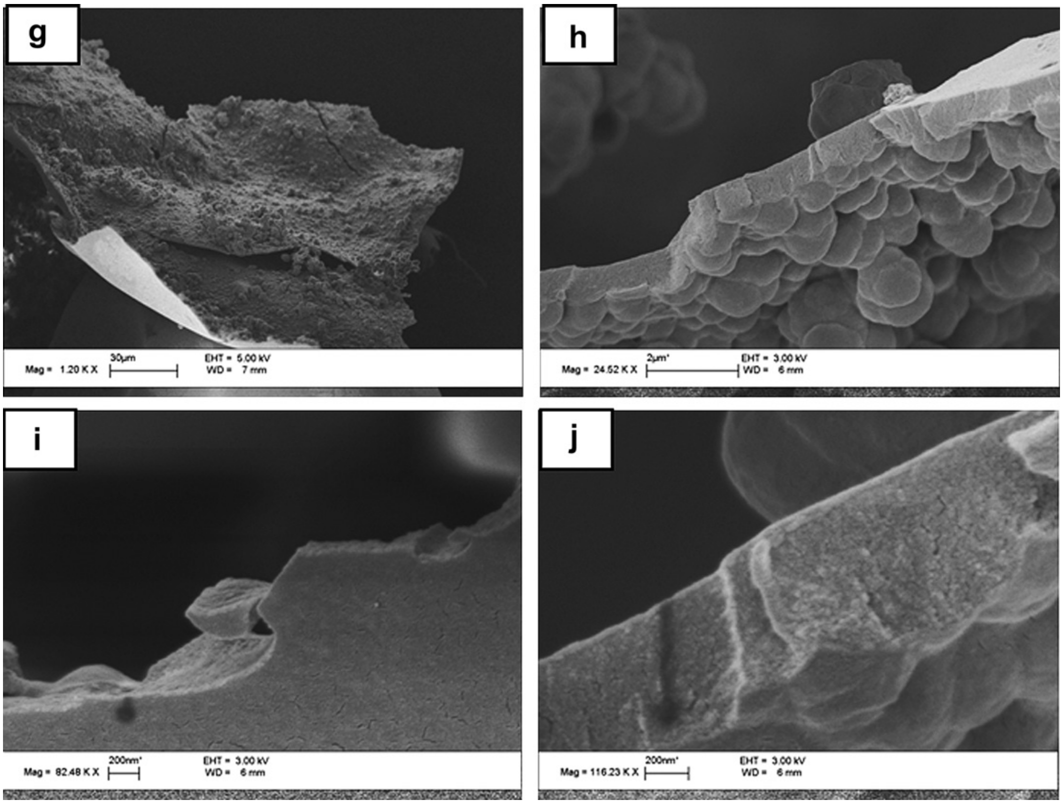


Fig. 3. (*continued*).

morphology and microstructure of the beads were investigated with scanning electron microscopy (SEM), and shown in Fig. 3. The beads are composed of spherical particles with diameters of a few hundred microns (Fig. 3a), and the beads have a shell with porous interior, as shown in Fig. 3 b–d, irrespective of the particle size (Fig. 3b). The small spheres (nodules) within the shells have a diameter of ca.1 μm agglomerated to large entities with diameter of ca. 3.5 μm to form the porous inner structure with a pore size from ∼1 μm to ca. 20 μm (Fig. 3 e–f). The borderline of the shell and the interior is obvious (Fig. 3g–h), and the shell is comprised connected small spheres ca. 1 μm (Fig. 3h). As shown in Fig. 3 h–j, the shell appears to be solid with a thickness of ca. 500–850 nm. The very small nodules of ca. 20–50 nm in Fig. 3j might be composed of polymer, or possibly might also be gold particles from sputter coating, however, no matter what the composition of nodules is, Fig. 3h–j show a dense characteristic of the shell. We conclude that the sorbent has a macroporous inner structure that is sealed by a thin dense outer shell, which might cause a delay of solute to reach the porous interior. This is confirmed by the sorption kinetics and will be discussed later.

The thermal stability of the polymer beads is shown in Fig. 4. P(GMA-TRIM) beads start to decompose around 230 °C. The thermal stability of the polymer increases with the introduction of the functional groups, such that the P(GMA-TRIM)-AMP shows a higher initial decomposition temperature near 300 °C.

3.3. Selective sorption of 4-propyl-2-methoxyphenol, PMP

The P(GMA-TRIM)-AMP sorbent was designed based on "like sorbs like" principle to selectively remove 2-Methoxy-4-

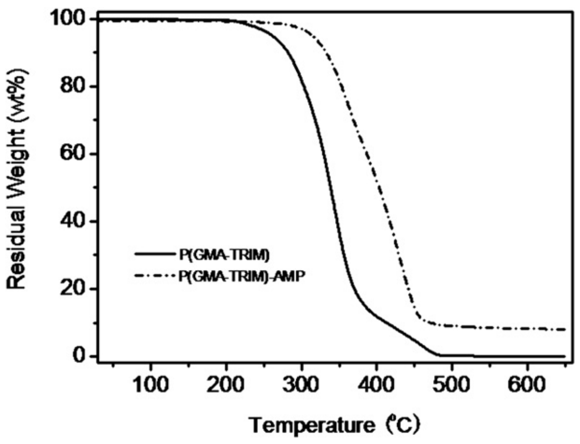


Fig. 4. TGA analysis of P(GMA-TRIM) and functionalized P(GMA-TRIM)-AMP sorbents.

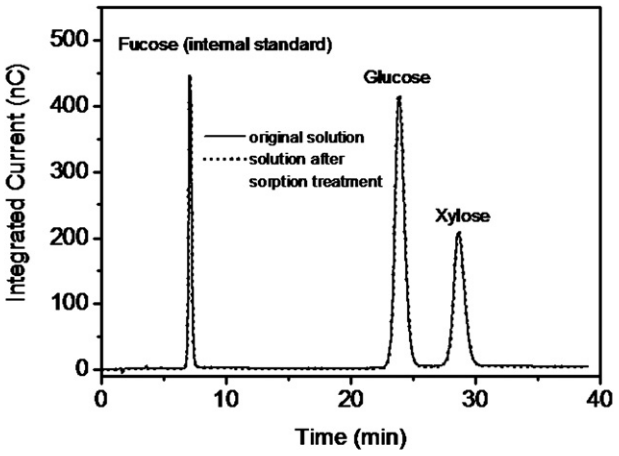


Fig. 5. HPAEC analysis of the sorption of P(GMA-TRIM)-AMP on monosaccharides.

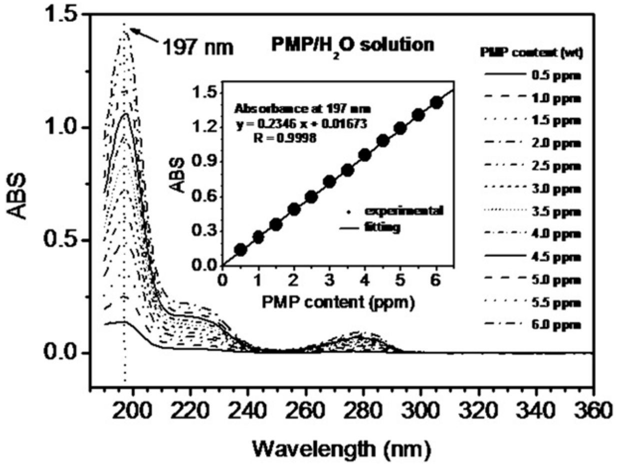


Fig. 6. UV-spectrum analysis of PMP in water solution.

propylphenol, PMP, from the hydrolysis solution of a biomass which contains glucose and xylose. The selective sorption performance of P(GMA-TRIM)-AMP sorbent is shown in Fig. 5. P(GMA-TRIM)-AMP yields no measurable sorption of glucose and xylose, either in the saccharides solutions or in PMP-containing saccharide solutions. The HPAEC curves of the saccharides in the original solutions are identical with that in the solution following sorption studies at 25 °C for 24 h experiment thereby indicating that both glucose and xylose concentration remained unchanged after the sorption experiment. Meanwhile the P(GMA-TRIM)-AMP yields good sorption performance of PMP in solutions with/without saccharides, as will be discussed later. The results indicate that P (GMA-TRIM)-AMP sorbent has good inherent selective affinity to PMP, and can be used as a sorbent to selectively remove phenols from biomass fermentation broths without loss of saccharides. These results support the idea of making sorbents based on the "like sorbs like" principle for selective separation of a specific component from a mixture. To pursue such an approach, a sorbent should have moieties with chemical structures similar to those of the solute which would be selectively removed.

3.4. Sorption and desorption of phenols

PMP has a maximum absorption at 197 nm in UV-spectrum, as shown in Fig. 6. The intensity of the absorption increases with an increase in PMP concentration. Good linearity ($R^2 = 0.9998$) is apparent between the absorbance and PMP concentration up to a PMP concentration of 6 ppm (beyond which phase separation was observed), and this calibration curve was used to calculate the concentration of PMP before and after sorption tests. It was observed that both glucose and xylose had no influence on UV spectra of the PMP solution, i.e., the wavelength and absorbance of PMP did not change with the addition of glucose and xylose.

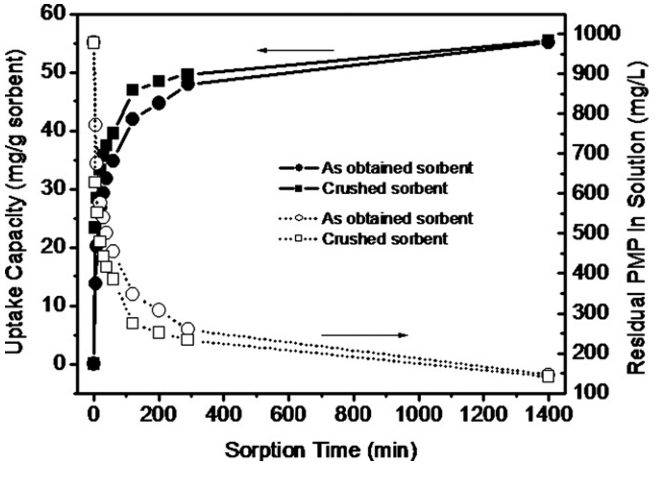


Fig. 7. Time dependence of sorbent uptake capacity (solid line) and residual PMP in solution (dotted line).

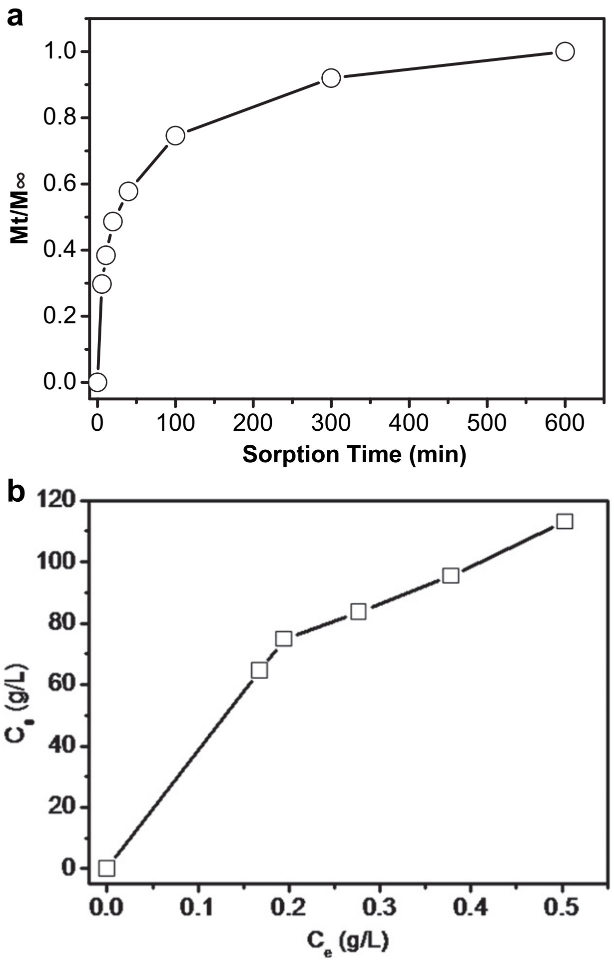


Fig. 8. PMP sorption on P(GMA-TRIM)-AMP sorbent: (a) equilibrum time, and (b) partition coefficient.

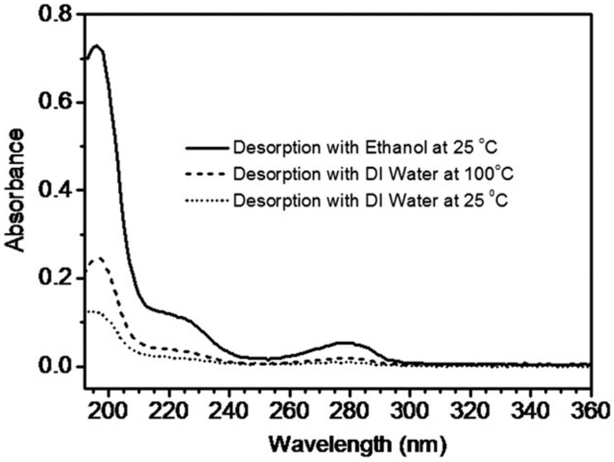


Fig. 9. UV spectra of PMP solution from desorption of the saturate sorbed sorbent.

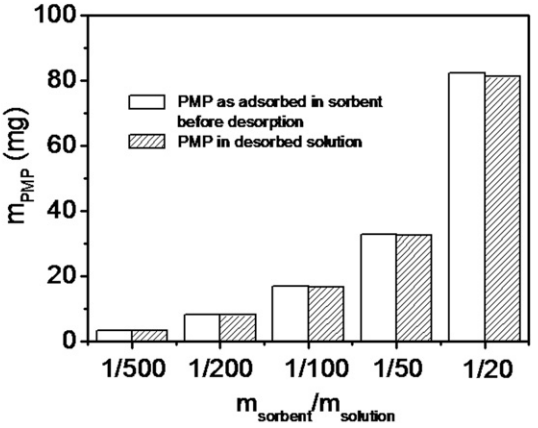


Fig. 10. Desorption efficiency *vs* sorbent concentration in desorption solution.

The typical rate of PMP sorption on P(GMA-TRIM)-AMP sorbent at 25 °C is shown in Fig. 7. The uptake of PMP increases markedly within 120 min, especially in the first 5 min, within which half the amount PMP finally taken up at 120 min was sorbed by the sorbent. Beyond 120 min, the sorption uptakes continuously increase slowly with prolonged sorption time. As a result, the residual PMP in solution decreases quickly in 120 min and then decreases slowly. The shell of the sorbent (see Fig. 3) could delay the sorption rate, particularly in the first 10 min. As can be seen in Fig. 7, the sorption capacity of the crushed sorbent increases more quickly than that of uncrushed sorbent; however, the shell has no effect on the saturated sorption capacities. This implies that a porous sorbent without shell might offer faster kinetics, but it would be more difficult to handle. And as an alternative, making hollow fiber sorbents with porous skins would be more interesting, especially in an industry application.

The kinetic behavior of PMP sorption in P(GMA-TRIM)-AMP sorbent is shown in Fig. 8a, in a plot of the ratio of Mt/M∞ as a function of time, where Mt is the amount of PMP sorbed by the sorbent at the time *t*, and M∞ is the saturated sorption amount of PMP by the sorbent. Under equilibrium conditions, the PMP in sorbent and in residual solution is shown in Fig. 8b, where C_s was the concentration of PMP in the sorbent, and C_e was the concentration of the residual PMP in solution. The calculated partition coefficient, $K_d = C_s/C_e$, is about 390, indicating a high sorption efficiency.

The PMP is easily desorbed from the sorbent by organic solvent, like ethanol or methanol. The PMP saturated P(GMA-TRIM)-AMP sorbent was soaked in DI water or ethanol for 30 min, then the desorbed PMP solution was measured by UV spectra. Fig. 9 compares the desorption efficiency of water and ethanol, and indicates that ethanol is effective to remove PMP from the sorbent. In fact with either ethanol or methanol, 95 ± 5% PMP can be desorbed during desorption period of 30 min. The mass ratio of saturated sorbent to ethanol was also varied from 1/500 to 1/20 to determine the desorption efficiency. As shown in Fig. 10 the efficiency was the same for either 1/500 or 1/20 within experimental error. After desorption, the fractional uptake (Φ) of the solution is given by the expression (4) and (5) [32]:

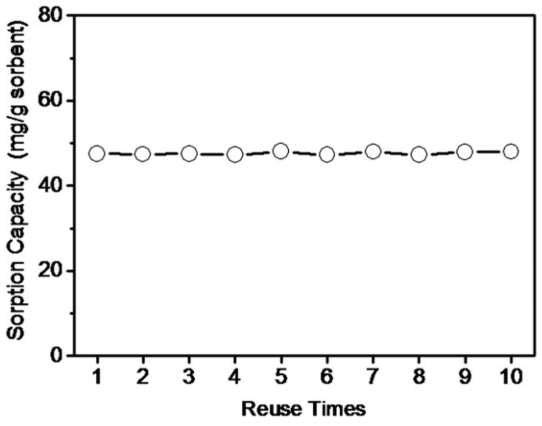


Fig. 11. Sorption capacity of the sorbent as a function of reuse times.

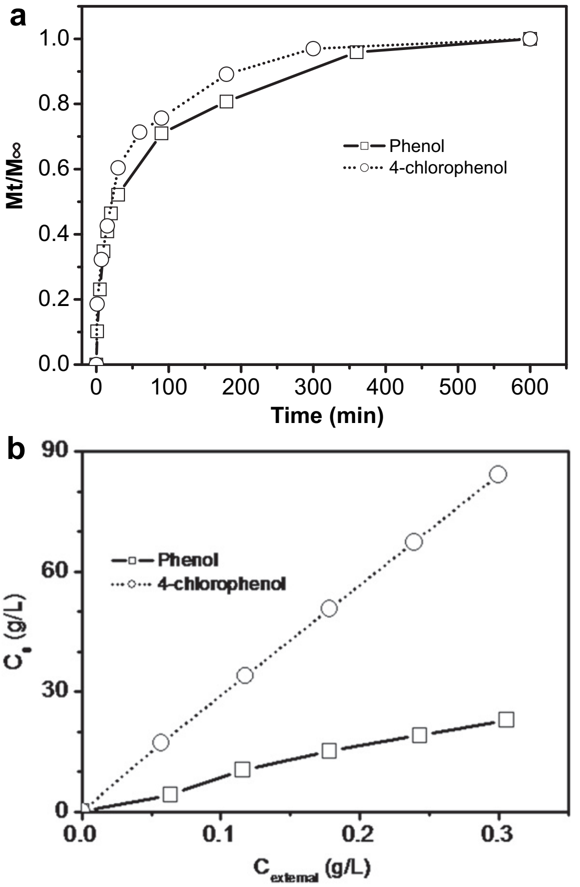


Fig. 12. Phenol and 4-chlorophenol sorption on P(GMA-TRIM)-AMP sorbent: (a) equilibrum time, and (b) partition coefficient.

$$\Phi = \frac{M_{p\ ethanol}}{M_{p\ ethanol} + M_{p\ sorbent}} = \frac{1}{1+\frac{1}{\alpha}} \tag{4}$$

$$\alpha = \frac{V_{Ethanol}}{V_{Sorbent}K'_d} \tag{5}$$

The distribution coefficient K'_d is the ratio of the concentration of phenol in sorbent to the equilibrium concentration of desorbed phenol in ethanol, $M_{pethanol}$ is the mass of PMP desorbed in ethanol, $M_{psorbent}$ is the mass of PMP in sorbents, $V_{ethanol}$ and $V_{sorbent}$ are volumes of ethanol and sorbent, respectively.

Therefore,

$$\Phi = \frac{1}{1+\frac{V_{Sorbent}K'_d}{V_{Ethanol}}} \tag{6}$$

Φ can be calculated from Fig. 10. Thus, K'_d can be obtained when $V_{Sorbent}$ and $V_{Ethanol}$ are known. From Fig. 10, Φ is 99.7% when the mass ratio of sorbent to ethanol is 1/100. K'_d is 0.316, much smaller than K_d (390), indicating the good desorption efficiency of ethanol.

Durability and reusability of the sorbent is an important characteristic in industrial applications. The PMP saturated P(GMA-TRIM)-AMP sorbent was regenerated and reused in separation of PMP, as can be seen in Fig. 11, and it is observed that the sorbent maintained its original sorption capacity even after 10 times of reuse, indicating the feasibility and stability of multiple use of the sorption and desorption of the sorbent in application.

3.5. Sorption and desorption of other phenols

To extend the sorbents to other industry applications, such as waste water treatment, the sorption and desorption of phenol and 4-chlorophenol, which are common pollutants, also were investigated. The UV spectra of phenol shows a maximum absorption at 210 nm, while 4-chlorophenol at 224 nm in water. Like PMP, both phenol and 4-chlorophenol show good linearity between UV absorbance and concentration in the homogeneous solutions. The curve fitting for experimental absorbance of phenol at 210 nm as a function of concentration gave the equation: $y = 0.06032x + 0.01084$ ($R^2 = 0.99981$), while curve fitting for 4-chlorophenol at 224 nm gave the equation of $y = 0.06603x + 0.01166$ ($R^2 = 0.99993$). These fitting curves were used to calculate the concentration of phenol and 4-chlorophenol before and after sorption test.

As can be seen in Fig. 12a, both phenol and 4-chlorophenol were sorbed on the P(GMA-TRIM)-AMP sorbent quickly for the first 120 min after which the sorption rate slows until the sorbent is saturated. Under equilibrium conditions, the distribution of phenols in sorbents and in residual solution is given in Fig. 12b. The calculated partition coefficient is 80 for phenol, and 280 for 4-chlorophenol. These smaller values of the partition coefficients, versus that of PMP, presumably reflect less similarity with chemical structure of functional groups in P(GMA-TRIM)-AMP sorbent.

As with PMP, the sorbents saturated with phenol or 4-chlorophenol could be easily recovered by exchanging with ethanol, and reused.

4. Conclusion

A porous P(GMA-TRIM)-AMP sorbent, designed on the "like sorbs like" principle, was synthesized. The sorbent has functional groups similar to PMP in chemical structure and yields high selectivity in the removal of PMP from glucose- and xylose-containing saccharide solutions. This capability indicates a potential application in cellulosic ethanol production. The resulting sorbent also shows good sorption capacities for other phenols. Overall the results indicate that the idea of making sorbents based on "like sorbs like" is viable for selective separation of specific components from a mixture, resulting in a new method in developing selective sorbents and separation technique. These kinds of sorbents would typically have a chemical structure similar to the solute to be selectively removed. The sorbents even can be synthesized with the target chemical itself. To improve the sorption process, construction of porous hollow fiber sorbents would be interesting.

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