

Photoswitchable Organocatalyst based on a Catalyst-imprinted Polymer Containing Azobenzene

1. Experimental

1.1. Instrumentation and reagents

¹H NMR (300 MHz) was recorded on a Bruker AV-300 or Bruker 600 NMR instrument at ambient temperature. UV-Vis spectra were recorded with an UV-4802 spectrophotometer (UNICO (Shanghai) Instruments Co., Ltd., China). A CEL S-500 Xe light was used as the light source (Au Light Inc., Beijing, China), and 365 and 440 nm light wavelengths were selected using filters, respectively. High performance liquid chromatography (HPLC) analysis was performed with an Agilent HPLC 1200 series system equipped with quaternary pump (G1311A), variable wavelength detector (G1314A), and autosampler (G1313A).

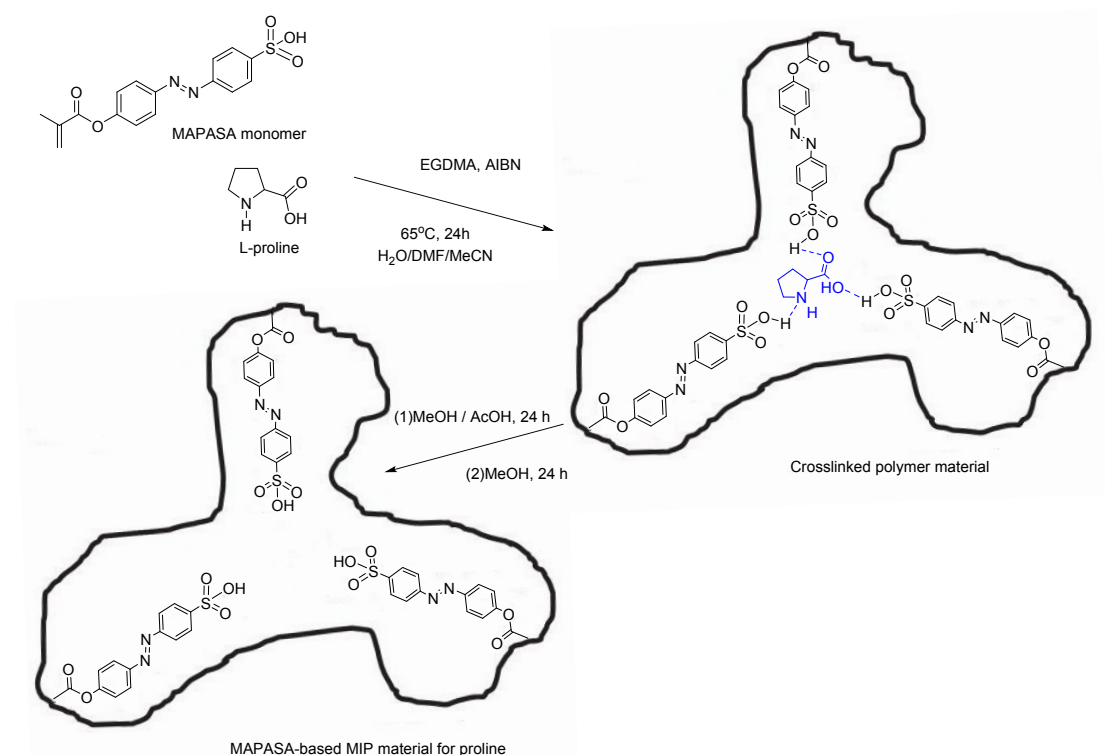
Ethyleneglycol dimethacrylate (EGDMA), L-proline, 4-nitrobenzaldehyde, 2,2-azobisisobutyronitrile (AIBN) were purchased from Shanghai Jing Chun Chemical Co., China. Acetonitrile (MeCN), dimethyl sulphoxide (DMSO), methanol, N,N-dimethylformamide (DMF), and iso-propyl alcohol are all of HPLC grade and were purchased from Kermel Chemical Reagents Development Center (Tianjin, China). AIBN was recrystallized in methanol prior to use.

1.2. Synthesis of MIP

Azobenzene-containing 4-[(4-methacryloyloxy)phenylazo]benzenesulfonic acid (MAPASA) was synthesized according to a previous report¹ and used as the functional monomer.

L-proline-imprinted polymers were fabricated by precipitation polymerization using EGDMA as the cross-linker and L-proline as the template (S.Fig. 1). MAPASA (0.139 g, 0.4 mmol), L-proline (11.5 mg, 0.1 mmol), and EGDMA (0.60 g, 3.0 mmol) were dissolved in 15 mL mixed solution of water–DMF–MeCN (1 : 1 : 1, v/v) in a conical flask, forming an orange solution. The mixture was sonicated for 30 min and stirred in the dark at room temperature for 12 h to facilitate the template-monomer

complex formation. AIBN (100 mg) was then added and the resultant mixture was degassed with nitrogen for at least 20 min before being sealed under nitrogen by a rubber cap. The mixture was then placed in a 70 °C oil bath for 12 h. The solid obtained was filtered and washed with deionized water and methanol and dried at 40 °C for 24 h under vacuum. The template (L-proline) in the polymer material was removed by Soxhlet extraction with 200 mL of a methanol–acetic acid mixture (9 : 1 v/v) for 24 h followed by 200 mL of methanol for 24 h in the dark. The resultant MIP was dried to constant weight at 40 °C for 24 h under vacuum. Control molecularly imprinted polymer (CMIP) was prepared in an identical fashion to the imprinted polymer, with the only difference being that no L-proline was used in the polymerization procedure. Both the MIP and CMIP were stored at room temperature in the dark.



S.Fig. 1 Fabrication of the MAPASA-based MIP material using L-proline as a template.

1.3. Spectroscopic characterization and photoisomerization studies

Spectroscopic characterization of the azobenzene monomer and the subsequent MIP was performed in DMSO using a 1.0 cm path length quartz cuvette at room temperature. Suspension of the MIP was maintained with the help of a magnetic

stirrer and irradiated with a 365 nm light beam and then with a 440 nm visible light beam. The suspension of the MIP and control materials in the solvent media was maintained with the help of a magnetic stirrer. All photoisomerization studies were performed with 1.0 mg of MIP or control material in 3.0 mL of DMSO

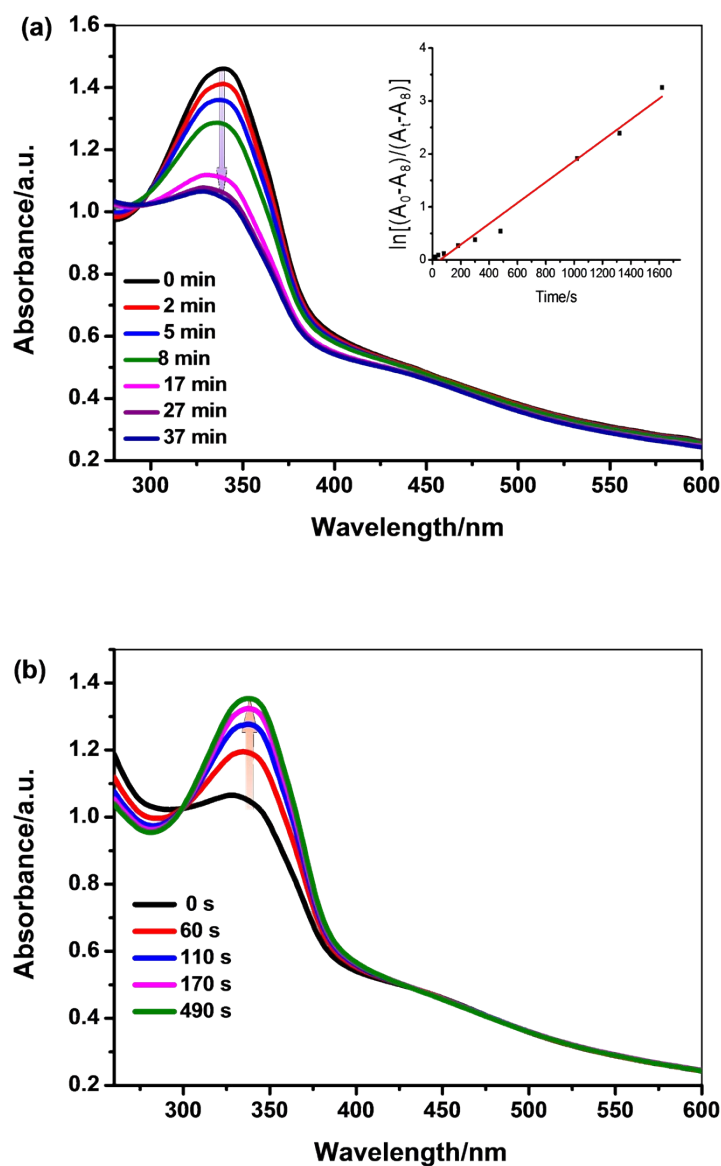
1.4. Photo-regulated uptake and release studies

In all experiments, 10.0 mg of MIP and 3.0 mL of L-proline solution in DMSO (1.0×10^{-4} mol/L) were placed in a quartz tube of 1.0 cm optical path length fitted with a magnetic stir bar. The tube was then screw-capped to ensure airtightness and was placed in the stirring table. The suspension was stirred in the dark for 12 h. For the photo-regulated release of proline, the mixture was stirred and irradiated at 365 nm for 60 min. The stirring was then stopped and the mixture was centrifuged at 10 000 rpm for 3 min, and 2.0 mL of the clear supernatant was taken out for ninhydrin reaction, and the level of freely dissolved proline was analyzed by UV spectrophotometer. Each round of irradiation was 60 min, and substrate concentration was measured at the end of each irradiation round. For the photoregulated uptake of proline, irradiation at 440 nm was adopted.

2. Characterization

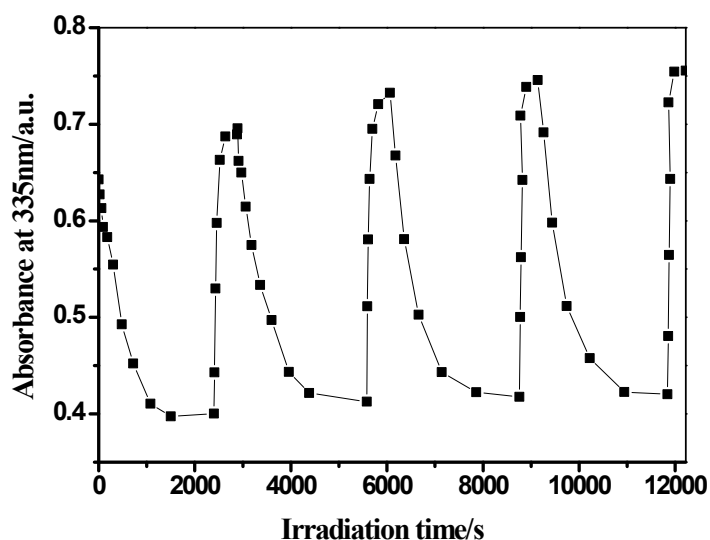
2.1. Photoisomerization properties of MAPASA and MIP

S.Fig. 2 shows the UV-Vis spectra and spectral changes of MAPASA upon irradiation at 365 (S.Fig. 2a) and 440 nm (S.Fig. 2b) in DMSO. The UV-Vis spectra exhibit a strong absorption band around 335 nm, which is typical for the azobenzene compounds and can be ascribed to the $\pi \rightarrow \pi^*$ electron transitions of the N=N bond. Rate constants for the trans \rightarrow cis and cis \rightarrow trans photoisomerization are measured to $(2.37 \pm 0.091) \times 10^{-3}$ /s and $(10.77 \pm 1.01) \times 10^{-3}$ /s, respectively.



S.Fig. 2 UV-Vis spectra and spectral changes of MAPASA (1.0×10^{-5} mol/L) in DMSO upon (a) irradiation at 365 nm for 2, 5, 8, 17, 27, and 37 min, and then upon (b) irradiation at 440 nm for 60, 110, 170, and 490 s. Insets: the kinetics of the photoisomerization of MAPASA.

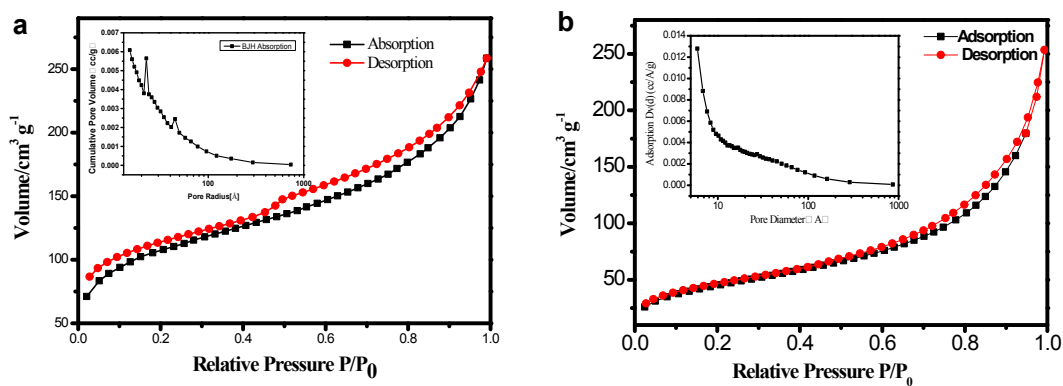
Reversibility of photoisomerization of the azobenzene chromophores within MIP was also investigated. S.Fig. 3 shows the modulation of the absorbance of a MIP suspension upon alternate irradiation at 365 and 440 nm. MAPASA groups in the imprinted MIP are able to undergo reversible photoisomerization and still maintain isomerization properties.



S.Fig. 3 Reversibility of the photoisomerization process of the azobenzene chromophore of MAPASA in the MIP polymer matrix.

2.2. N₂ adsorption–desorption analysis of MIP and CMIP

The Brunauer–Emmett–Teller (BET) equation was used to measure the surface area (m²/g) of the MIP. The pore volume (cm³/g) and pore diameter (Å) were analyzed by the Barrett–Joyner–Halendal (BJH) model. It was found that the MIP and CMIP has microporous and mesoporous structure (S.Fig. 4). The surface area, pore diameter, and pore volume of MIP and CMIP are listed in Table 1.



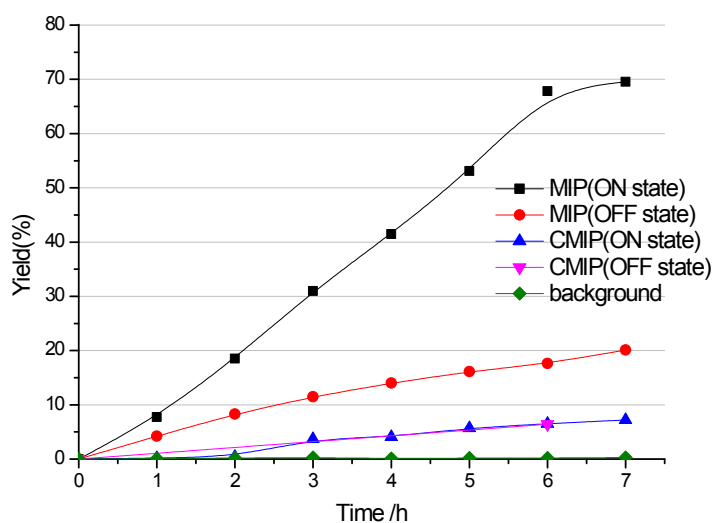
S.Fig. 4 Isotherms and pore distribution of MIP (a) and CMIP (b).

Table 1 The surface area, pore diameter, and pore volume of MIP and CMIP.

content	Surface Area (m ² /g)	Pore Volum (cc/g)	Average Pore Size (Å)
MIP	339.0	0.4012	23.59
CMIP	235.0	0.3896	22.31

2.3. Optimization of experiment conditions for catalysis

The reaction time was firstly optimized. The aldol reaction between 4-nitrobenzaldehyde and acetone catalyzed by L-proline in DMSO was selected as the standard reaction to evaluate the photoswitchable catalyst activity of L-proline-MIP. Utilizing L-proline as the catalyst, the maximum yield of 68% was obtained after reacted for 6 h at 20 °C. Similarly, under irradiation at 365 nm for 6 h at 20 °C, the maximum yield of 67.8% was obtained using the L-proline-MIP as the catalyst (S.Fig. 5).



S.Fig. 5 Yield of aldol reaction versus reaction time

The amount of L-proline was then optimized. As shown in Table 2, higher aldol reaction yield was obtained when higher amount of L-proline was loaded on MIP. However, over-high load of L-proline (50-60 mol% with respect to 4-nitrobenzaldehyde) resulted in the increase of yield in both “NO state” and “OFF state”. The 40 mol% of MIP loaded L-proline performed best, high yield (67.84%)

was obtained in “ON state” and greatest difference in yield between “NO state” and “OFF state” (~50%) was obtained.

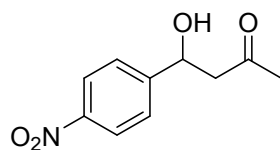
Table 2 The influence of the amount of L-proline loaded on MIP on the aldol reaction of acetone with 4-nitrobenzaldehyde

Entry	L-proline loaded on MIP with respect to 4-nitrobenzaldehyde (mol%)	Yield (%) (ON state) ^a	Yield (%) (OFF state) ^a	ee (%)
1	20%	41.3%	30.3%	32
2	30%	54.2%	23.1%	37
3	40%	67.8%	17.6%	37
4	50%	70.6%	25.8%	33
5	60%	74.1%	35.2%	35

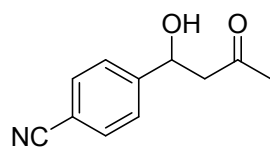
The reaction was performed with 4-nitrobenzaldehyde (0.5 mmol), acetone (0.3 mL), in DMSO (2.7 mL) at 20 °C for 6 h.

a. Yield is calculated from HPLC analysis.

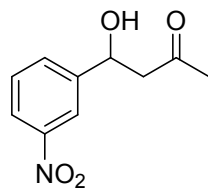
2.4. NMR characterization of reaction products



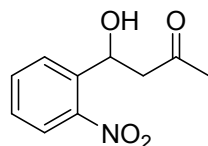
¹H NMR (600 MHz, CDCl₃) δ (ppm): 8.20 (d, 2H), 7.48 (d, 2H), 5.21 (s, 1H), 2.83 (m, 2H), 2.21 (s, 3H).



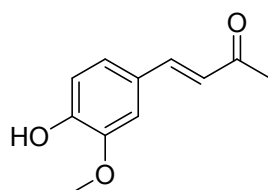
¹H NMR (600 MHz, CDCl₃) δ (ppm): 7.64 (d, 2H), 7.48 (d, 2H), 5.20 (s, 1H), 2.84 (m, 2H), 2.21 (s, 3H).



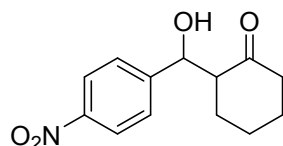
$^1\text{H NMR}$ (600 MHz, CDCl_3) δ (ppm): 8.25 (s, 1H), 8.14 (d, 1H), 7.71 (d, 1H), 7.52 (t, 1H), 5.25 (s, 1H), 2.87 (m, 2H), 2.23 (s, 3H).



$^1\text{H NMR}$ (600 MHz, CDCl_3) δ (ppm): 7.96 (d, 1H), 7.90 (d, 1H), 7.67 (d, 1H), 7.43 (t, 1H), 5.68 (s, 1H), 2.70 (m, 2H), 2.24 (s, 3H).



$^1\text{H NMR}$ (600 MHz, d_6 -DMSO) δ (ppm): 9.83 (s, 1H), 7.44 (d, 1H), 7.06 (m, 2H), 6.93 (d, 1H), 6.57 (d, 1H), 5.87 (s, 1H), 3.94 (s, 3H), 2.37 (s, 3H).



$^1\text{H NMR}$ (600 MHz, CDCl_3) δ (ppm): 8.20 (d, 2H), 7.48 (d, 2H), 5.48 (s, 1H), 2.63 (m, 1H), 2.49 (m, 1H), 2.40 (m, 1H), 2.10-2.12 (m, 2H), 1.68-1.72 (m, 2H), 1.59-1.64 (m, 2H).

2.5 Morphology studies

The morphology of MIP and CMIP was observed by SEM. The MIP (in S.Figs. 6a and b) and CMIP (in S.Figs. 6c and d) have similar morphological structure.

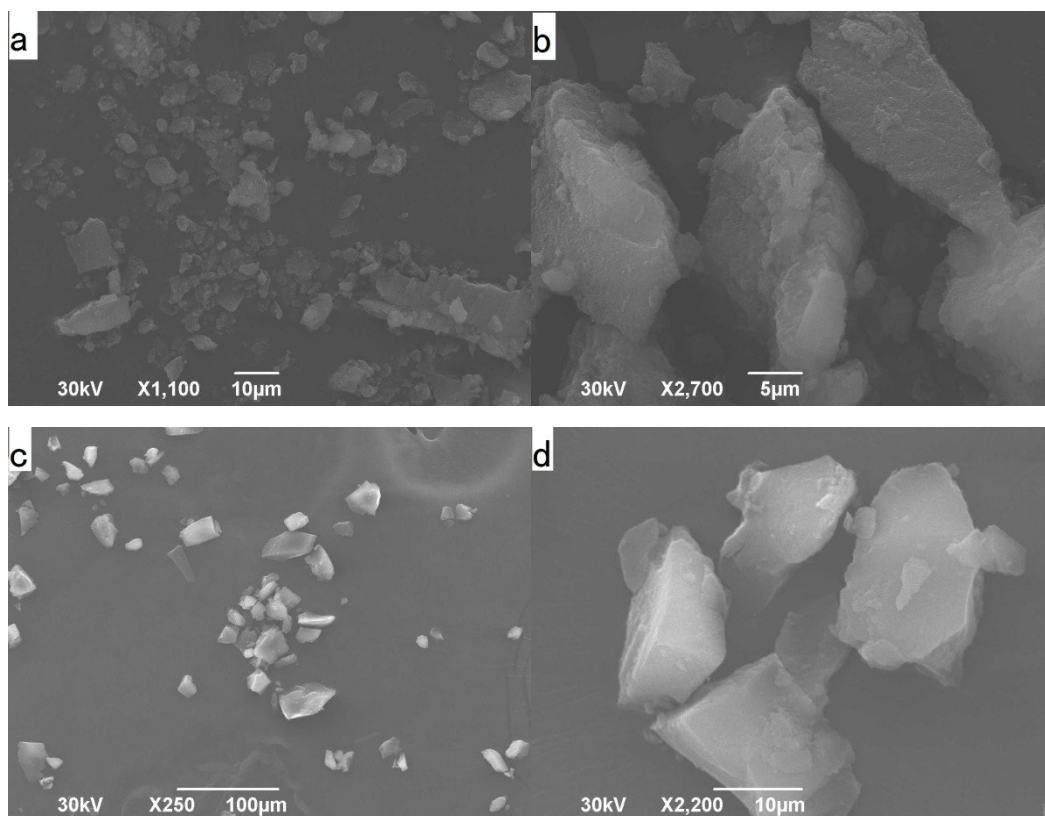


Fig. 6 SEM images of MIP (a, b) and CMIP (c, d).

References

1. C. B. Gong, K. L. Wong and M. H. W. Lam. Photoresponsive Molecularly Imprinted Hydrogels for the Photoregulated Release and Uptake of Pharmaceuticals in the Aqueous Media. *Chem. Mater.*, 2008, 20, 1353-1358.