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2-Hydroxypropyl-β-cyclodextrin Polymer as a Mimetic Enzyme for Mediated Synthesis of Benzaldehyde in Water

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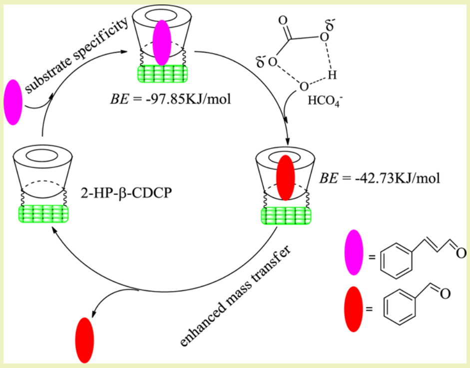
ABSTRACT: 2-Hydroxypropyl-β-cyclodextrin was immobilized onto cellulose with epichlorohydrin as a cross-linker. The obtained polymer, as biomimetic catalyst, was used to mediate synthesis of benzaldehyde in aqueous solution. The functionalized mimetic enzyme played a crucial role on catalytic oxidation of cinnamaldehyde with remarkable substrate conversion and product selectivity. Synergistic effect based on weak interactions between the polymer and the substrate results in significant promotion of the catalytic performance. The catalyst could be recycled without apparent loss of the original activity.



KEYWORDS: *Mimetic enzyme, Synergistic effect, Benzaldehyde, 2-Hydroxypropyl-β-cyclodextrin polymer, Substrate specificity*

INTRODUCTION

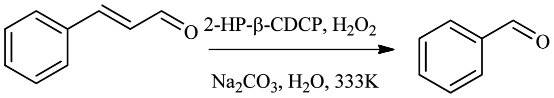
The use of enzymes as biocatalysts in organic media has attracted much interest in recent years. Compared to the noncatalytically chemical reactions, enzymes are able to catalyze chemical reactions with tremendously high catalytic efficiency and selectivity.[1−4] However, most enzymes suffer from some intrinsic drawbacks, in particular their insufficient stability in organic media and limited substrate scope. In order to simulate the catalytic functions of enzymes, some macrocycclic compounds including cyclodextrins, cyclophanes, cavitands, calixarenes, and other synthetic macrocycles have been studied extensively as biomimetic catalysts[5−7] and several reviews of this subject have been reported.[1,8,9]

Cyclodextrins (abbreviated as CDs) are cyclic oligosaccharides composed of six, seven, or eight glucopiranose units linked by glycosidic bonds (named α, β, and γ-CD, respectively). The most important characteristics of cyclodextrins can form inclusion complexes with different guest molecules by non-covalent bonding in aqueous solution or in the solid state, which are extremely similar to the exact molecular recognition of an enzyme to a substrate. They can selectively catalyze chemical reactions by the weak interactions as seen in enzymes.[3,10−12] These features of CDs attracted the researchers to investigate reactions under biomimetic conditions. The astounding catalytic efficiency and substrate specificity have been observed by mimetic enzymes for specific reactions and substrates.[11,13−15]

Benzaldehyde is the second largest perfume in the world and is widely used in dyestuffs, perfumery, and pharmaceutical industries. With more care about food quality, the demand for natural benzaldehyde is increasing quickly.[16] Because of its limited supply and high price, obtaining natural benzaldehyde from natural cinnamon oil, which contains more than 80% of cinnamaldehyde may be used as an alternative route.[17] We have recently reported β-cyclodextrin (abbreviated as β-CD) or 2-hydroxypropyl-β-cyclodextrin (abbreviated as 2-HP-β-CD) as catalyst to attain the alkaline hydrolysis of cinnamaldehyde under mild conditions.[18,19] In spite of the preliminary success, much more investigations are still required to improve the substrate selectivity. According to the previous report,[20] selecting the support microenvironment is crucial, since it brings some weak interactions between the catalyst, support, and the reagents, which might alter reaction rate and selectivity.

In the present study, we report a cellulose cross-linked 2-hydroxypropyl-β-cyclodextrin by epichlorohydrin (abbreviated as 2-HP-β-CDCP), which could efficiently catalyze the oxidation of cinnamaldehyde. Synergistic effect based on the weak interaction between the polymer and the substrate was observed to play a crucial role on the conversion (Scheme 1). Various physico-chemical techniques were used to characterize the structure of the polymer. In additional, a rational mechanism of the oxidation was proposed based on the XPS, experimental, and computational results. The construction of

Scheme 1. Oxidation of Cinnamaldehyde to Benzaldehyde Catalyzed by 2-HP-β-CDCP



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mimetic enzyme via weak interaction might provide a new trial in organic reactions to develop highly efficient catalyst.

EXPERIMENTAL AND COMPUTATIONAL SECTION

Material. Microcrystalline cellulose with average diameter of 90 μm was bought from Aladdin Chemistry Co. Ltd., China. 2-HP-β-CD (average substitution degrees DS = 3.9) was purchased from Wuhan Yuancheng Technology Development Co. Ltd., China. Cinnamaldehyde (>99%) was obtained from Sinopharm Chemical Reagent Co., China. All other reagents and solvents are of analytical grade and used without further purification unless indicated.

Synthesis of 2-HP-β-CDCP. 2-HP-β-CDCP was synthesized by reacting 2-HP-β-CD with cellulose cross-linked by epichlorohydrin in sodium hydroxide solution according to a procedure reported earlier with some modification.[21] A 2 g portion of cellulose was dispersed in 30 mL deionized water containing 7.5 g of NaOH. Then, 7 mL of epichlorohydrin was added dropwise to the mixture. The mixture was further agitated at 40 °C for 4 h. Subsequently, the product was filtered and was rinsed with acetone and water to remove epichlorohydrin thoroughly, then centrifuged and rinsed with water to remove NaOH and any water-soluble impurities until the pH of supernatant approached neutral. The solid was dried under vacuum at 40 °C for 12 h. The celluloses modified by epichlorohydrin (abbreviated as CE) was obtained.

The process for the preparation of 2-HP-β-CDCP was the following: 2 g of CE powder was dispersed in 30 mL 25 wt % sodium hydroxide by sonication. And then, 1 g of 2-HP-β-CD was added. The reaction mixture was stirred at 40 °C for 6 h. The solid product was separated by centrifugation and washed to neutral with distilled water. Finally, the prepared 2-HP-β-CDCP was dried under vacuum at 60 °C for 24 h. The amount of 2-HP-β-CD immobilized on cellulose was determined as 0.180 mmol/g with the reported method.[22]

Characterizations of 2-HP-β-CDCP and Its Inclusion Complex. Fourier transform infrared (FTIR) spectra were measured by KBr pellets. All the infrared spectra were recorded on a Bruker TENSOR 37 FTIR spectrometer with the wavenumber ranging from 4000 to 400 cm^{-1} and resolution of 4 cm^{-1}.

The X-ray powder diffraction (XRD) patterns were measured on a Rigaku Denki MAX III diffractometer with Na-filtered Cu−Kα radiation. Step-scans were recorded for all samples in the θ range of 5−80°. The XRD peaks were analyzed using the Rigaku program "JADE-5".

Thermogravimetric analysis (TGA) was performed on a Netzsch STA-449C thermal analysis system. The flow rate of nitrogen was about 40 mL/min, and a heating rate of 10 °C/min was employed.

The X-ray photoelectron spectroscopy (XPS) analysis was performed on a Vacuum Generator ESCALAB 250 spectrometer using an Al Kα monochromatic X-ray source and a hemispherical analyzer. Fixed analyzer transmission (FAT) mode with a pass energy of 150 eV was used for survey scans, and high-resolution scans of core-level regions were recorded using a 20 eV pass energy. All core-level spectra were referenced to the C1s neutral carbon peak at 284.5 eV and obtained at a takeoff 90° to the sample surface.

Evaluation of Catalytic Performance. A 1 mmol portion of trans-cinnamaldehyde (0.1322 g) was dissolved in 25 mL deionized water at 60 °C in a 100 mL three-necked flask equipped with a reflux condenser and electromagnetic stirrer. A 0.072 mmol portion of 2-HP-β-CDCP (0.4000 g) was then added with stirring for 30 min. A 1.5 mmol portion of sodium carbonate (0.1590 g) dissolved in 2 mL hydrogen peroxide (30%, w/w) was added dropwise into the mixture. After stirring for 1 h at 60 °C, the reaction mixture was extracted by with 50 mL ethyl acetate and centrifuged twice. The organic phase was analyzed by GC-MS with naphthalene as an internal standard. The reproducibility of data was within 5%.

Kinetic Experiments. Cinnamaldehyde solutions (0.0025, 0.005, 0.010, and 0.015 mol/L) were added into a 100 mL three-necked flask equipped with a reflux condenser and electromagnetic stirrer, respectively. These solutions were heated to reaction temperature (303, 313, 323, or 343 K). Then, 2 mL hydrogen peroxide (30%, w/w), 1.5 mmol sodium carbonate, or/and 0.102 g 2-HP-β-CDCP was added rapidly into the solutions, respectively. In the absence of 2-HP-β-CDCP, reaction mixture (0.5 mL) was sampled at intervals of 30, 20, 15, and 10 min, respectively. In the presence of 2-HP-β-CDCP, reaction mixture (0.5 mL) was sampled at intervals of 3, 2, 1.5, and 1 min, respectively. Each sample was diluted to 100 mL with deionized water and its absorbance at 290 nm was determined for the quantitation of cinnamaldehyde. The reproducibility of data was within 5%.

DFT Calculation. The formation of complex was examined at molecular level using quantum-chemical calculations, which can provide information of binding energy and structure of the inclusion complexes. In order to explain the host−guest interaction mechanism, a basic assumption was proposed that the binding sites in the polymer are glucopyranoside unit of 2-HP-β-CD in the isolated 2-HP-β-CDCP, and that the global properties of these sites are not significantly different from the properties of 2-HP-β-CDCP molecule. On the basis of theoretical analysis, hydrophobic interactions are postulated to be the main driving forces in the inclusion complexation of cinnamaldehyde or benzaldehyde with the isolated 2-HP-β-CD in 2-HP-β-CDCP.

The computations were carried out using the program package DMol3 method[23] in Materials Studio (version 4.0) of Accelrys Inc. All calculations were performed with using the local density approximation (LDA) in the Perden−Wang (PWC) form at the DND basis set level.

The binding energy (BE) could be expressed as

$$BE = E_{complex} - E_{guest} - E_{host} \tag{1}$$

$E_{complex}$ was the total energy of the inclusion complex, E_{guest} was the sum of total energy of guests, and E_{host} was the total energy of host. The isolated 2-HP-β-CDCP was used as host, and cinnamaldehyde or benzaldehyde was selected as model guests. The more negative the binding energy is, the more thermodynamically favorable is the inclusion complex.

RESULTS AND DISCUSSION

FTIR Characterization. The FTIR spectra of 2-HP-β-CD, cellulose, and 2-HP-β-CDCP were shown in Figure 1. The FTIR spectrum of 2-HP-β-CDCP is similar to that of 2-HP-β-CD, indicating that the frame of 2-HP-β-CD is not changed. The peaks of 2-HP-β-CDCP at 3400 and 2870 cm^{-1} are stronger than those of 2-HP-β-CD, and the increased intensity may be attributed to the presence of more hydroxyl and methylene groups in the 2-HP-β-CDCP. It is clearly observed

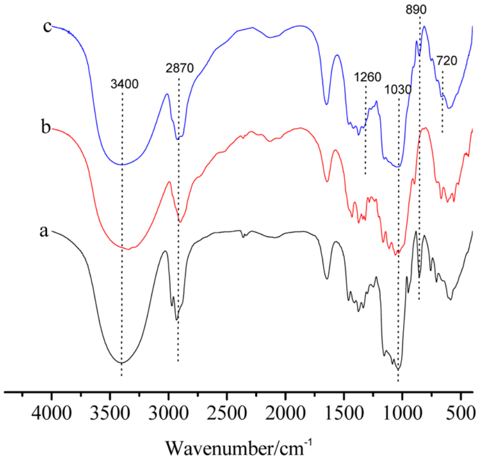


Figure 1. FTIR spectra of 2-HP-β-CD (a), cellulose (b), and 2-HP-β-CDCP (c).

that the band at 1030 cm^{-1} due to the C−O−C group is observed in 2-HP-β-CDCP, whereas no band assigned to the epoxy ring is observed at 1260 cm^{-1}. This result strongly suggests that the epoxy ring of epichlorohydrin molecule is opened by the hydrolysis reaction to form the polymer network.[24] In addition, the peak at 890 cm^{-1} is the characteristic band of α-(1,4) glucopyranose in 2-HP-β-CD,[25] which appears in 2-HP-β-CDCP. It could be concluded that 2-HP-β-CD had been immobilized successfully onto cellulose.

XRD Characterization. The XRD patterns of cellulose (a) and 2-HP-β-CDCP (b) were shown in Figure 2. Cellulose has shown characteristic intense peaks at 2θ = 16° and 23° due to its crystalline nature.[26] The peaks at 2θ = 16° disappeared, and the peak at 2θ = 23° decreased greatly in 2-HP-β-CDCP. The results demonstrated that chemical modification of cellulose followed by grafting with 2-HP-β-CD using epichlorohydrin as a cross-linker destroyed its original crystallinity to some extent.

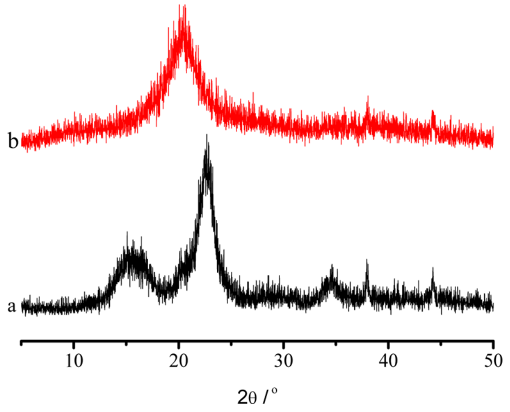


Figure 2. XRD of cellulose (a) and 2-HP-β-CDCP (b).

TG Characterization. TG curves of cellulose (a), 2-HP-β-CD (b), and 2-HP-β-CDCP (c) were shown in Figure 3. It could be seen that 2-HP-β-CDCP exhibits three weight loss steps. Weight loss of 7.9% was observed in the temperature range from 30 to 110 °C, and this phenomenon was caused by dehydration. The second stage starts at about 230 °C with weight loss of 44.3% due to heat decomposition of 2-HP-β-CDCP. The third stage was the carbonization process above 460 °C with weight loss of 13.8%. Cellulose and 2-HP-β-CD showed two degradation stages. The first mass loss step, from about 50−120 °C, is concerned mainly the loss of water. The second degradation stage of cellulose exhibited a higher temperature (337 °C) than that of 2-HP-β-CDCP (230 °C) and 2-HP-β-CD (308 °C). The result indicated that the modified cellulose is less stable than cellulose due to the weak cross-linkage.

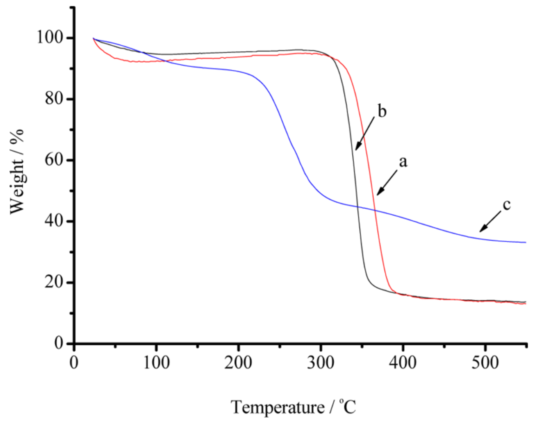


Figure 3. TGA curves of cellulose (a), 2-HP-β-CD (b), and 2-HP-β-CDCP (c).

Catalytic Activity Investigation. As shown in Scheme 1, oxidation of cinnamaldehyde was carried out at 60 °C under 1 atm. From Figure 4, 2-HP-β-CDCP showed significantly higher activity (TOF of 135 h^{-1}) than that of 2-HP-β-CD (TOF of 0.32 h^{-1}) for the oxidation of cinnamaldehyde. Only 5% cinnamaldehyde was converted into benzaldehyde in the absence of catalyst, and the yield of benzaldehyde was up to 20% by the addition of hydrogen peroxide and sodium carbonate. 81% yield of benzaldehyde was obtained in the presence of hydrogen peroxide, sodium carbonate, and 2-HP-β-CDCP, which is significantly higher than that of the previous report (70%).[19] The catalytic performance was greatly influenced by the deficiency of the above components. However, the addition of cellulose could not significantly improve catalytic activity. These studies suggest that the weak interactions between 2-HP-β-CD and substrate might be vital for the oxidation of cinnamaldehyde. However, the support associated with 2-HP-β-CD has a significant positive influence for the reaction system, which is attributed to the synergistic effects via the various intermolecular weak interactions between 2-HP-β-CD and the functional group of cellulose.

Effect of Reaction Conditions. The mass transfer of the components between two phases and the catalyst is also an important factor affecting the catalytic performance in the development of heterogeneous reaction. In this work, the solution was agitated to enhance the mass transfer of components between two phases. Effect of stirring speed on the conversion of cinnamaldehyde to benzaldehyde using 2-HP-β-CDCP as a stable biomimetic catalyst was investigated in the range of 0−600 rpm (Figure 5).

As shown in Figure 5, below 500 rpm, the reaction was mass-transfer-controlled. In fact, the organic phase was not fully dispersed within the aqueous phase at low agitation speeds, and increasing the agitation speed mainly resulted in the organic phase being more fully dispersed within the aqueous phase. However, a further increase in the agitation showed no significant change in cinnamaldehyde conversion, indicating the mass transfer is no longer a key step.

The insights into the crucial factors that determined the high yield for the oxidation of cinnamaldehyde were summarized in Table 1. The reaction with the bicarbonate-activated hydrogen peroxide as oxidant in the presence of 2-HP-β-CDCP in aqueous solution gave 81% benzaldehyde yield, significantly higher than that of the previously reported data,[19] indicating 2-HP-β-CDCP can significantly improve the yield of benzaldehyde than that of 2-HP-β-CD. On the other hand, a significant decrease in yield was observed in the absence of sodium carbonate. The result suggests that sodium carbonate plays a vital role in activating oxidation and is in good agreement with the previously reported results.[27,28] The insoluble precipitation (2-HP-β-CDCP) could be easily recycled by centrifugation after the reaction. The obtained precipitation was washed with ethanol and deionized water, respectively. After drying, the catalyst was reused for the next run under the same conditions. The results indicated the catalytic activity was not affected (Figure 6). Similar conversion and selectivity was obtained when the recovered 2-HP-β-CDCP was reused four times.

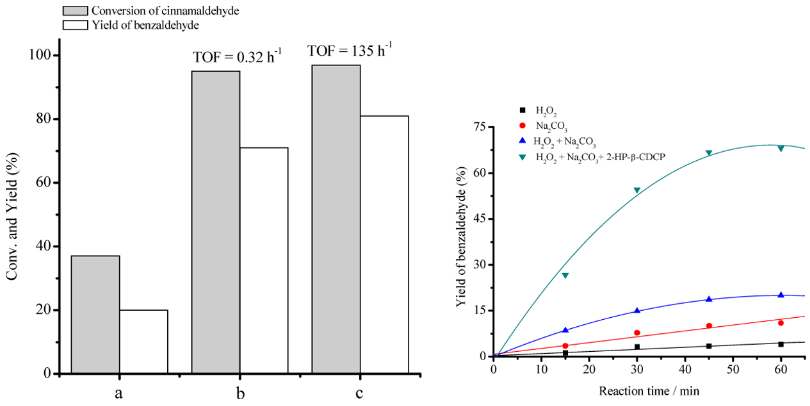


Figure 4. Catalytic activity of various catalysts: (a) cinnamaldehyde (1 mmol), cellulose (1.541g), Na_2CO_3 (1.5 mmol), H_2O_2 (2 mL, 30%, w/w), 60 °C, 500 rpm, reaction time 180 min; (b) cinnamaldehyde (1 mmol), 2-HP-*β*-CD (1.541 g), Na_2CO_3 (1.5 mmol), H_2O_2 (2 mL, 30%, w/w), H_2O (25 mL), 60 °C, 500 rpm, reaction time 180 min; (c) cinnamaldehyde (1 mmol), 2-HP-*β*-CDCP (0.4g), Na_2CO_3 (1.5 mmol), H_2O_2 (2 mL, 30%, w/w), 60 °C, 500 rpm, reaction time 60 min. TOF: mmol oxidized cinnamaldehyde/(mmol *β*-CD in the catalyst × time). Selectivity: mmol produced benzaldehyde/mmol oxidized cinnamaldehyde.

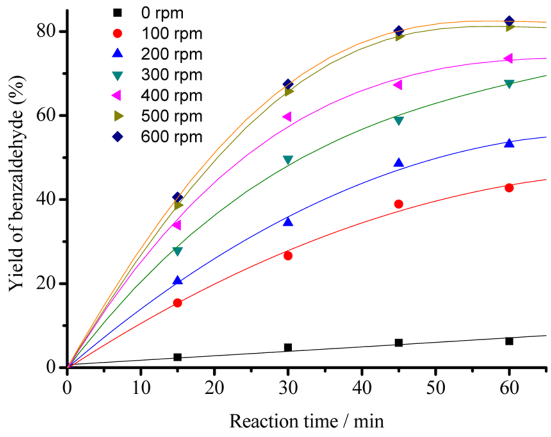


Figure 5. Effect of agitation speed on the yield of benzaldehyde. Reaction condition: cinnamaldehyde (1 mmol), 2-HP-*β*-CDCP (0.4 g), Na_2CO_3 (1.5 mmol), H_2O_2 (2 mL, 30%, w/w), 60 °C, reaction time 60 min.

Effect of Cavity Size of Cyclodextrins. After the success of cinnamaldehyde oxidation catalyzed by 2-HP-*β*-CDCP in water, different cellulose-supported cyclodextrin catalysts were used to assess their effectiveness under the optimized reaction condition. The results were shown in Table 2.

Our experimental results indicate that the oxidation of cinnamaldehyde was significantly affected by the cavity size of cyclodextrins. The activities of the different catalysts are in the order 2-HP-*β*-CD > *β*-CD > *α*-CD, which showed cavity diameter with a bigger size provides higher activity. It is probably attributed to the fact that cyclodextrin with a bigger size has higher enzyme−substrate binding affinities via the weak molecular forces such as van der Waals forces, *π*−*π* stacks, and hydrogen bonds, etc. to improve the reaction selectivity.

Kinetic Studies. The kinetic experiments were carried out at different temperatures ranging from 313 to 343 K in terms of the initial concentration method. The obtained rate orders *k* (rate constant, min^{-1}), rate orders (*n*), and correlation coefficient (*R*) in the presence or absence of 2-HP-*β*-CDCP were shown in Table 3.

As shown in Table 3, the rate orders were nearly equal to 1 in the absence of 2-HP-*β*-CDCP, indicating the reactions followed pseudo-first-order kinetics for the oxidation for cinnamaldehyde. However, in the presence of 2-HP-*β*-CDCP, the rate orders almost increased by 1.9. Here, the synergistic effect based on the intermolecular weak interactions via 2-HP-*β*-CD and the functional group of cellulose has played a crucial role in the reaction processes. They make cinnamaldehyde penetrate and the produced benzaldehyde escape the hydrophobic cavity more easily due to the difference between the two binding energies of cinnamaldehyde and benzaldehyde with 2-HP-*β*-CDCP. Therefore, 2-HP-*β*-CDCP also can be used to enhance the mass transfer significantly.

Table 1. Effect of the Different Reaction Conditions on the Oxidation of Cinnamaldehyde[a]

entry	2-HP-*β*-CDCP (g)	temp (°C)	H_2O_2 (mL)	Na_2CO_3 (mmol)	conversion (%)	yield (%)[b]
1	0	60	2.0	1.5	38	20
2	0.1	60	2.0	1.5	60	49
3	0.2	60	2.0	1.5	70	60
4	0.3	60	2.0	1.5	81	69
5	0.4	60	2.0	1.5	97	81
6	0.5	60	2.0	1.5	97	78
7	0.4	30	2.0	1.5	80	56
8	0.4	40	2.0	1.5	85	62
9	0.4	50	2.0	1.5	92	75
10	0.4	70	2.0	1.5	93	77
11	0.4	60	0	1.5	20	12
12	0.4	60	0.5	1.5	51	41
13	0.4	60	1.0	1.5	70	58
14	0.4	60	1.5	1.5	84	71
15	0.4	60	2.5	1.5	97	81
16	0.4	60	2.0	0	5	4
17	0.4	60	2.0	0.25	41	30
18	0.4	60	2.0	0.5	85	59
19	0.4	60	2.0	1.0	95	75
20	0.4	60	2.0	2.0	98	79

[a] Reaction conditions were carried out using cinnamaldehyde (1 mmol), H_2O (25 mL), 60 min, and 500 rpm. [b] Isolated yield.

According to the rate constants in Table 2, Arrhenius plots of ln *k* and 1/*T* were drawn in Figure 7. A good linear correlation was found between ln *k* and 1/*T*, and activation energies E_a in the presence and absence of 2-HP-*β*-CDCP were calculated as 34.33 and 46.39 kJ·mol^{-1}, respectively. It is obvious that 2-HP-*β*-CDCP could reduce the energy barrier for the oxidation of

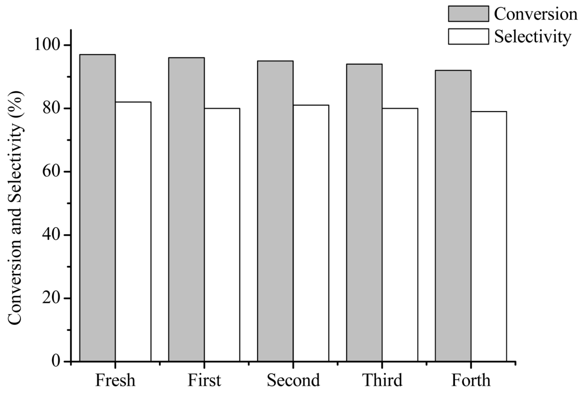


Figure 6. Recyclability data of catalyst for cinnamaldehyde oxidation. Reaction condition: cinnamaldehyde (1 mmol), 2-HP-*β*-CDCP (0.4 g), H_2O (25 mL), H_2O_2 (2 mL, 30%, w/w), Na_2CO_3 (1.5 mmol), 60 °C, 500 rpm, reaction time 60 min.

cinnamaldehyde and enhance the mass transfer significantly, that is why the reaction rates is greatly promoted.

Plausible Mechanism for the Reaction. *FTIR Analysis of the Inclusion Complex.* It has been demonstrated that FTIR is a very useful tool to prove the presence of both guest and host components in the inclusion complexes.[29]

The IR spectra of cinnamaldehyde (a), 2-HP-*β*-CDCP (b), and the inclusion complex (c) were recorded from 400 to 4000 cm^{-1} as shown in Figure 8. The spectra of the inclusion complex (c) are similar to that of 2-HP-*β*-CDCP (b), indicating that the main structure between the inclusion complex and 2-HP-*β*-CDCP is unchanged. However, for the spectrum of the inclusion complex (c), an obvious difference of characteristic absorption peaks for benzene ring of the guest could be found: (1) The $\sigma_{C=C}$ peak (1610 cm^{-1}) vanished. (2) Moreover, the cyclic carbonyl (C=O) stretching band of cinnamaldehyde at 1688 cm^{-1} reduced its intensity and shifted to 1668 cm^{-1} in its inclusion complex suggesting the strong interactions through intermolecular hydrogen bonds between cinnamaldehyde and 2-HP-*β*-CD moiety. (3) σ_{C-H} (3030 cm^{-1}) in the benzene ring and σ_{C-H} at 2820 and 2750 cm^{-1} in the aldehyde group for cinnamaldehyde disappeared in the IR spectrum of the inclusion complex. This is probably attributed to the fact that cinnamaldehyde enters into the cavity of 2-HP-*β*-CDCP as well. (4) σ_{C-O-H} peaks at 1335 and 1250 cm^{-1} in the cinnamaldehyde/2-HP-*β*-CDCP inclusion complexes have much higher intensity compared to that of 2-HP-*β*-CDCP. These are the evidence of formation of hydrogen bonds between the hydroxyl groups of 2-HP-*β*-CDCP and the carbonyl groups of cinnamaldehyde. The electron cloud density of the oxygen atom of carbonyl in cinnamaldehyde might lead to the formation of the hydrogen bond between 2-HP-*β*-CDCP and cinnamaldehyde. Our study showed that synergistic effect based on the weak interactions (e.g., O—H···O and C—H···O etc.) play an important role in the cinnamaldehyde oxidation.[30]

Table 3. Rate Orders and Rate Constants at Different Reaction Temperature in the Presence and Absence of 2-HP-*β*-CDCP

	in the presence of 2-HP-*β*-CDCP			in the absence of 2-HP-*β*-CDCP		
T (K)	*k* (min^{-1})	*n*	*R*	*k* (min^{-1})	*n*	*R*
303	0.0705	1.81	0.9927	0.0294	0.99	0.9983
313	0.115	1.87	0.9975	0.046	1.03	0.9962
323	0.188	1.89	0.9962	0.0921	1.02	0.9961
333	0.234	1.84	0.9937	0.1483	0.97	0.9948

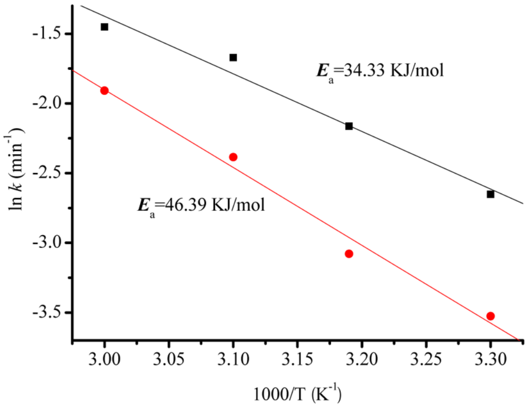


Figure 7. Arrhenius plots of the rates constants for cinnamaldehyde oxidation. (■, in the presence of 2-HP-*β*-CDCP; ●, in the absence of 2-HP-*β*-CDCP).

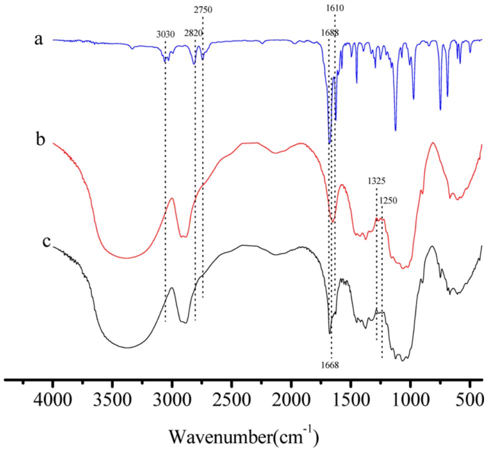


Figure 8. FTIR spectra of cinnamaldehyde (a), 2-HP-*β*-CDCP (b), and inclusion complex between 2-HP-*β*-CDCP and cinnamaldehyde (c).

XPS Analysis of the Inclusion Complex. XPS was carried out to evaluate the surface elements and the ratio of elements, as shown in Figure 9. C and O were found on the surface of the

Table 2. Effect of Catalyst on the Oxidation of Cinnamaldehyde and Yield of Benzaldehyde[a]

entry	catalysts	CDs	modified group	cavity diameter, Å	conversion (%)	yield (%)[b]
1	*α*-CDCP	*α*-CD		~5.2	91	59
2	*β*-CDCP	*β*-CD		~6.6	95	71
3	2-HP-*β*-CDCP	2-HP-*β*-CD	$-CH_2-CH(OH)-CH_3$	~9.6	97	81

[a] Reaction conditions were carried out using cinnamaldehyde (1 mmol), H_2O_2 (2 mL, w/w), Na_2CO_3(1.5 mmol), H_2O (25 mL), 60 min, 60 °C, and 500 rpm. [b] Isolated yield.

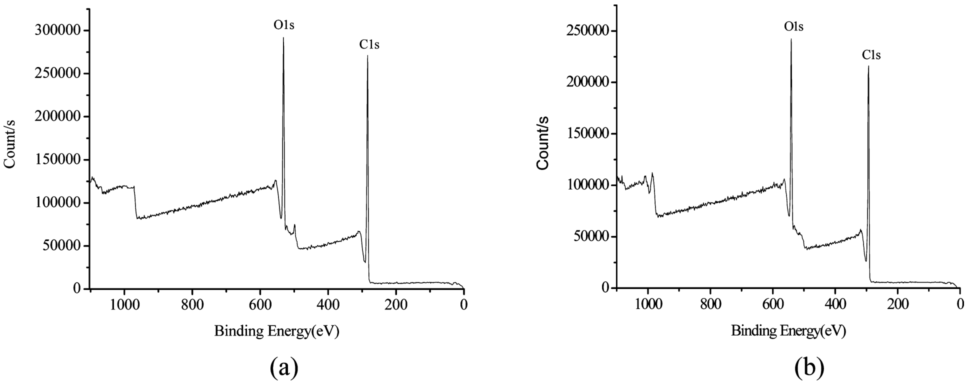


Figure 9. XPS graph of 2-HP-*β*-CDCP (a) and its inclusion complex with cinnamaldehyde (b).

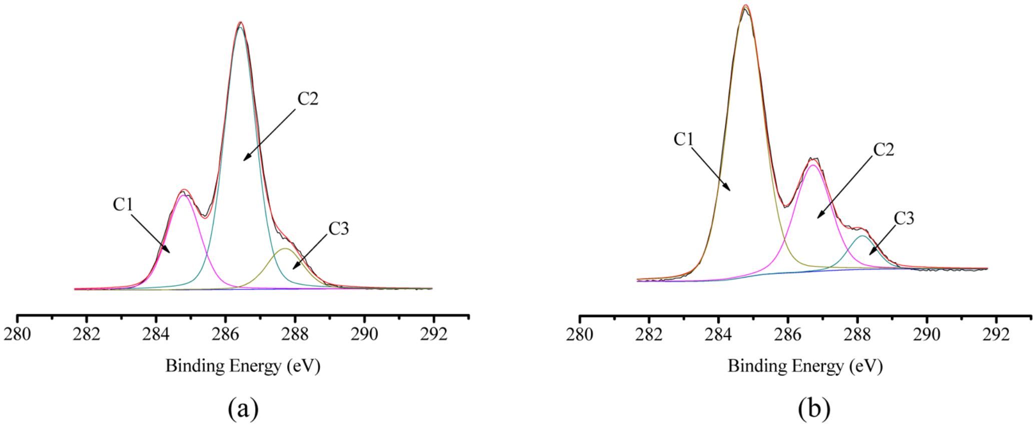
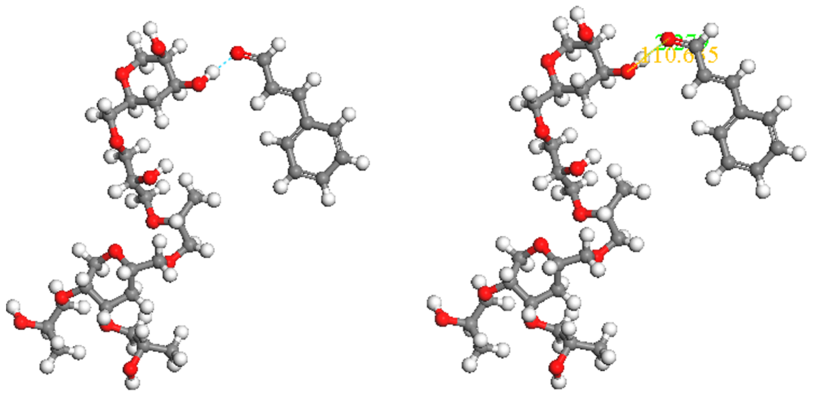


Figure 10. XPS of C1s (a) core level spectra of 2-HP-*β*-CDCP and C1s (b) core level spectra of 2-HP-*β*-CDCP/cinnamaldehyde inclusion complex (c).

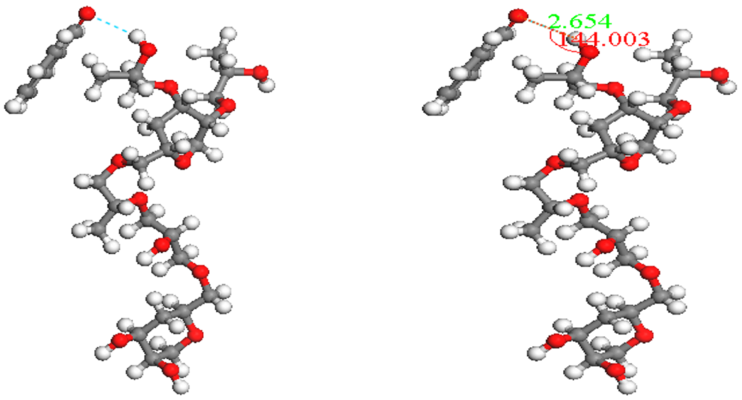
inclusion complexes, and the mole ratio of C/O was 3.4, higher than the ratio of C/O of 2-HP-*β*-CDCP, 3.1, which means that some carbon has been incorporated into the complex.

The C1s spectra of 2-HP-*β*-CDCP before and after inclusion with cinnamaldehyde are shown in Figure 10. The position of these peaks are found at 248.6, 286.6, and 288.4 eV, arising from C1(C—C), C2 (C—O), and C3 (O—C—O and/or C═O), respectively.[31] A relative increase and a significant decrease of the XPS peaks corresponding to the C1 atoms and the C2 atoms were observed in Figure 10. The results indicate that the concentration of C1 atoms and C2 atoms increased from 26.10% to 67.90% and decreased from 63.80% to 25.80%, respectively. From the above discussion, 2-HP-*β*-CDCP has formed host−guest inclusion complexes with cinnamaldehyde by weak intermolecular interaction, which significantly changed the chemical environment of carbon in the inclusion complex.

DFT Calculation. Geometries and energies of the most stable inclusion complexes of glucopyranoside unit in the isolated 2-HP-*β*-CDCP with cinnamaldehyde or benzaldehyde optimized by the program package DMol3 method were displayed in Figure 11. The negative binding energies further demonstrate that glucopyranoside unit in the isolated 2-HP-*β*-CDCP can interact with cinnamaldehyde or benzaldehyde to form highly stable inclusion complexes, respectively. One type of hydrogen bond interaction e.g. O−H···O has been considered. As previously reported,[32] the cutoff criteria of hydrogen bond interactions is the O···O distance from O−H···O hydrogen bond (≤3.2 Å), and the bond angle (≥90°). The bond lengths of hydrogen bonds of O−H···O (a) and (b) are in turn 2.270 and 2.654 Å, and the corresponding bond angles are in turn 110.635° and 144.003°, which indicate that the hydrogen bond between cinnamaldehyde or benzaldehyde and the isolated 2-HP-*β*-CDCP plays a vital role in the reaction processes. They effectively promote substrate specificity as a functionalized mimetic enzyme, significantly improving the selectivity of benzaldehyde. On the other hand, synergistic effects among the various weak interactions between function groups of host and guest can lead to the difference of binding energies of substrates. According to the previous report,[29,32] the difference between the two binding energies of cinnamaldehyde and benzaldehyde is the basis for the selective separation of the different substrates via 2-HP-*β*-CD inclusion in 2-HP-*β*-CDCP. And the more negative the binding energy, the more stable the corresponding 2-HP-*β*-CDCP/guest complex. It should be noted that different binding energies will lead to difference in stability between cinnamaldehyde or benzaldehyde and glucopyranoside unit in the 2-HP-*β*-CDCP. Herein, the binding energy for the glucopyranoside unit/cinnamaldehyde (−97.85 kJ/mol) is negative and much lower than that of the glucopyranoside unit/benzaldehyde (−42.73 kJ/mol) in the isolated 2-HP-*β*-CDCP. It should be noted that the more negative the binding energy is, the more stable the corresponding 2-HP-*β*-CDCP/guest complex. Cinnamaldehyde prefers to penetrate the hydrophobic cavity rather than stay in the bulk of the aqueous phase. The produced benzaldehyde tends to escape the cavities of 2-HP-*β*-CD in 2-HP-*β*-CDCP owing to the much higher binding energy. 2-HP-*β*-CDCP can be used to enhance the mass transfer, that is why the ratio



(a) ***BE*** = -97.85 KJ/mol



(b) ***BE*** = -42.73 KJ/mol

Figure 11. Optimized structure of glucopyranoside unit/cinnamaldehyde (a) and glucopyranoside unit/benzaldehyde (b) in the isolated 2-HP-*β*-CDCP obtained by the DMol3 method.

(cinnamaldehyde:2-HP-*β*-CDCP) is much lower than previously reported data (1:1).[18] Therefore, enhanced substrate specificity and mass transfer by 2-HP-*β*-CDCP significantly improves catalytic activity and selectivity of the reaction.

On the basis of the above experimental data, together with FTIR, XPS, and computational results, a plausible reaction mechanism has been proposed for the oxidation of cinnamaldehyde using 2-HP-*β*-CDCP as a functionalized biomimetic catalyst. First, under mechanical stirring (500 rpm), 2-HP-*β*-CD in the HP-*β*-CDCP and cinnamaldehyde can form the inclusion complex with the intermolecular hydrogen bond O−H···O (Figure 12). ^{1}H NMR and 2D ROESY has proved the host−guest interaction between cinnamaldehyde and parent 2-HP-*β*-CD.[19] Second, due to nucleophilic attack of hydroxide ion via the hydrolysis of sodium carbonate on the substrate, a small amount of benzaldehyde was directly produced via hydrolysis of cinnamaldehyde, and the result was in accordance with that previously reported.[18] On the other hand, hydrogen peroxide and the produced bicarbonate by the hydrolysis of sodium carbonate can combine in an equilibrium process to produce peroxymonocarbonate (HCO_4^-), with structure $HOOCO_2^-$.

$$CO_3^{2-} + H_2O = HCO_3^- + OH^- \tag{2}$$

$$HCO_3^- + H_2O_2 = HCO_4^- + H_2O \tag{3}$$

It is well-known that bicarbonate−H_2O_2 systems can epoxidize alkenes through the nucleophilic attack of

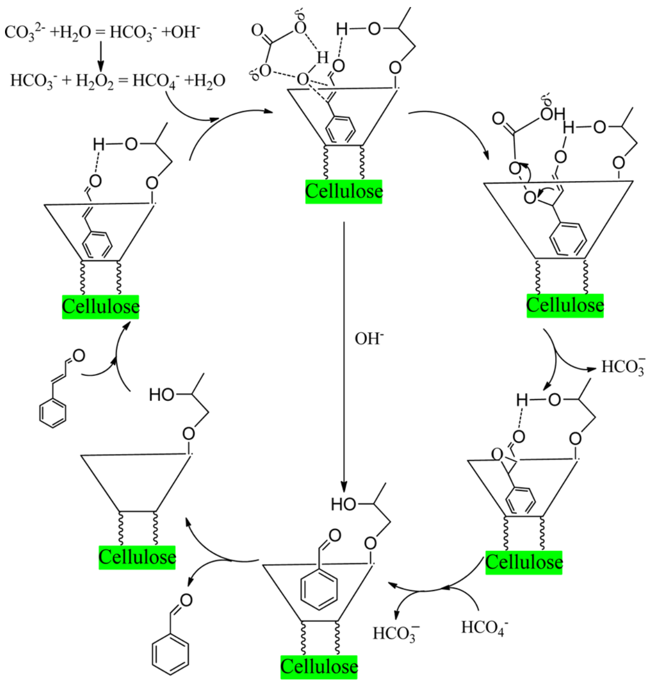


Figure 12. Plausible mechanism of the oxidation of cinnamaldehyde catalyzed by 2-HP-*β*-CDCP in the presence of H_2O_2 and Na_2CO_3 in water.

$HOOCO_2^-$ species to the C═C double bond.[27,28] The noncovalent intermolecular interactions between 2-HP-β-CDCP and cinnamaldehyde also promoted the nucleophilic attack. Then, cinnamaldehyde was converted to its epoxide, and the further nucleophilic attack on the epoxide led to the generation of benzaldehyde. It should be mentioned that alkaline hydrolysis effect is weak in the present catalytic system, and only 12% yield of benzaldehyde is derived from contribution of hydrolysis.

■ CONCLUSIONS

2-Hydroxypropyl-β-cyclodextrin was successfully cross-linked onto cellulose by epichlorohydrin as a cross-linker. The polymer exhibited excellent catalytic performance for the oxidation of cinnamaldehyde with good stability. This method is bestowed with merits like high yield, cost effectiveness, weak alkaline aqueous phase conditions, and environmentally benign nature. It might be a promising method for the fabrication of benzaldehyde.

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Notes

The authors declare no competing financial interest.

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