Tetrahedron 66 (2010) 9888–9893

Contents lists available at ScienceDirect

Tetrahedron

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

Green synthesis of natural benzaldehyde from cinnamon oil catalyzed by hydroxypropyl-β-cyclodextrin

Hongyan Chen [a,b], Hongbing Ji [a,*], Xiantai Zhou [a], Lefu Wang [c]

[a] School of Chemistry and Chemical Engineering, Sun Yat-sen University, Guangzhou 510275, China
[b] Department of Chemical Engineering, Huizhou University, Huizhou 516007, China
[c] School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 12 June 2010
Received in revised form 10 October 2010
Accepted 22 October 2010
Available online 28 October 2010

Keywords:
2-Hydroxypropyl-β-cyclodextrin
Cinnamaldehyde
Natural benzaldehyde
Inclusion complex

ABSTRACT

The efficient synthesis of natural benzaldehyde from natural cinnamon oil catalyzed by 2-hydroxypropyl-β-cyclodextrin (2-HPβ-CD) in water under rather mild conditions has been developed. Various analysis methods, e.g., DSC, UV–vis, ^{1}H NMR, ROESY, and fluorescence measurements had been utilized to demonstrate formation of the 1:1 (molar ratio) complexes between 2-HPβ-CD and cinnamaldehyde. The inclusion equilibrium constant K_a was 928 M^{-1} at 298 K. The inclusion complex activated the substrate and promoted the reaction selectivity. The yield for benzaldehyde could reach 70% under the optimized conditions (323 K, 5 h, 2% NaOH (w/v), cinnamaldehyde: 2-HPβ-CD=1:1 (molar ratio)). Further investigation on kinetics and solubilization revealed that the binding ability between 2-HPβ-CD and cinnamaldehyde is primarily responsible for the catalytic effects.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Natural benzaldehyde, the second largest perfume in the world, has captivated many researchers' interest both in organic synthesis and industry, as benzaldehyde plays important roles in food, beverages, cosmetics, and pharmaceutical industries etc.[1,2] Moreover, compared to chemically synthetic benzaldehyde, natural benzaldehyde is more popular and represents a strong market advantage.[3] Generally natural benzaldehyde is from alkaline hydrolysis of *Laetrile* catalyzed by enzyme, however, the process need thoroughly dispose of the toxic hydrocyanic acid, which results in high cost for production.

In recent years, natural benzaldehyde can also be produced from natural cinnamon oil through various clean processes. Yi and her group reported ozonization of natural cinnamon oils,[4] the reaction conditions were rather harsh (273 K, anhydrous conditions) and the yield of benzaldehyde was 62%. Gao and Lv used near-critical water (553 K, 15 MPa) as solvent for the conversion of cinnamaldehyde, and the yield of benzaldehyde was 57%.[5] As manufacturing method, alkaline hydrolysis of cinnamaldehyde or natural cinnamon oil is desirable,[6–10] but the reaction requires high temperature (373 –393 K), toxic phase transfer or surfactants catalysts, and the yield of benzaldehyde was about 50%. Therefore, those methods did not give a high yield for benzaldehyde. Besides, the severe reaction conditions or strong oxidant would unavoidably decrease the natural essence of benzaldehyde. It is significant to develop a new and clean process under mild reaction conditions with high selectivity for natural benzaldehyde and the natural essence of benzaldehyde is well preserved.

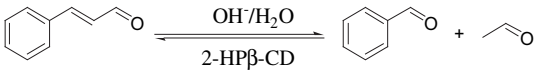
Supramolecular reactivity has attracted much attention over the past decade.[11–13] As one of the important and nontoxic supramolecular hosts, cyclodextrin (CD) has been widely introduced into various aqueous-phase organic reactions including oxidation, reduction, ring opening and hydrolysis etc.[14–20] It is able to catalyze chemical reactions because of its particular inclusion and kinetic properties. Specifically speaking the CDs can selectively form host–guest inclusion complex with guest molecule, which has appropriate size and polarity in aqueous solution under mild conditions, for they own a hollow truncated cylinder-shaped structure with one hydrophobic internal cavity and two hydrophilic external faces.[21,22]

In this paper, a practical challenge is to explore a water-soluble and robust catalyst, that is, able to increase reaction selectivity for the hydrolysis of cinnamaldehyde to benzaldehyde under mild reaction conditions efficiently. For this purpose, 2-hydroxypropyl-β-CD (2-HPβ-CD) was used to catalyze the hydrolysis of cinnamaldehyde (Scheme 1). HPβ-CD is a highly water-soluble derivative of natural β-CD, and is usually produced via a condensation reaction between β-CD and propylene oxide in alkaline solution, which can extend the physicochemical and inclusion properties and

* Corresponding author. Tel.: +86 20 84113658; fax: +86 20 84113654; e-mail address: jihb@mail.sysu.edu.cn (H. Ji).

0040-4020/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2010.10.063

catalytic activities of natural β-CD. 2-HPβ-CD means hydroxypropyl substitution only is at the O2 positions. It has been applied more frequently than CD in food and pharmaceutical industry because of its relatively more flexible cavity sizes, greater water solubility and lower toxicity than the natural β-CD.[23,24]



Scheme 1. Alkaline hydrolysis of cinnamaldehyde to benzaldehyde promoted by 2-HPβ-CD.

In contrast to transition-metal catalysts and organocatalysts, supramolecular catalysts employ non-covalent intermolecular interactions between host and guest molecule. The inclusion behavior of 2-HPβ-CD with cinnamaldehyde was investigated by Differential Scanning Calorimetry (DSC), UV–vis, ^{1}H NMR, Rotating-frame Overhauser Effect Spectroscopy (ROESY), and Fluorescence measurement. These characteristic methods served as an aid for better understanding of how weak interactions affect reactivity. In order to get further insight into the catalytic effects of 2-HPβ-CD for the alkaline hydrolysis, the solubilization of the CDs for cinnamaldehyde solubility in water was investigated and the reaction activation energy was calculated using the initial concentrations method. It has been found that the reactivity is driven by the binding ability between the host and the guest for the supramolecular catalytic system. The reported hydrolysis process in the present paper used green catalyst (2-HPβ-CD) and green solvent (water) to realize the clean synthesis of natural benzaldehyde.

2. Results and discussion

2.1. Characterization of inclusion complex

2.1.1. DSC results. DSC reveals some evidence about complex formation between cinnamaldehyde and cyclodextrins. The DSC curves of pure components, physical mixture, and the inclusion complex of cinnamaldehyde/2-HPβ-CD were presented in Fig. 1. A typical thermal curve for pure cinnamaldehyde (curve b) was a broad endothermic peak at 409 K corresponding to its boiling point. For the physical mixture of cinnamaldehyde/2-HPβ-CD, the characteristic thermal profile of cinnamaldehyde (curve c) was distinguishable and shifted to lower temperature of 395 K. The formation of the inclusion complex can be strongly evidenced by the disappearance of the cinnamaldehyde endothermic peak (curve d).

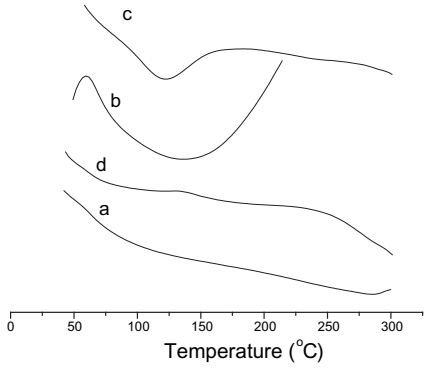


Fig. 1. DSC thermograms of 2-HPβ-CD (a), cinnamaldehyde (b), the physical mixture of 2-HPβ-CD and cinnamaldehyde (c), and the inclusion complex (d).

2.1.2. UV–vis results. The UV absorption spectra of the aqueous solution of the inclusion complex with different concentration of 2-HPβ-CD were shown in Fig. 2. It can be seen clearly from Fig. 2 that the dual absorption peaks of cinnamaldehyde appear at 220 and 290 nm, the former is attributed to aldehyde group and the other one is from its aromatic ring; besides, the absorption maximum gradually increased at 220 nm and decreased at 290 nm along with increasing concentration of 2-HPβ-CD. These behaviors may be considered as the proof of cinnamaldehyde incorporating into the HPβ-CD cavity, that is, both phenyl ring and aldehyde group of cinnamaldehyde were entrapped into the 2-HPβ-CD cavity, because the non-polar cavity of HPβ-CD provided a smaller polar microenvironment, which enhanced dissolution of guest molecule, increased $n\rightarrow\pi^*$ electron transition of aldehyde group and reduced $\pi\rightarrow\pi^*$ electron transition of phenyl ring.[25–28]

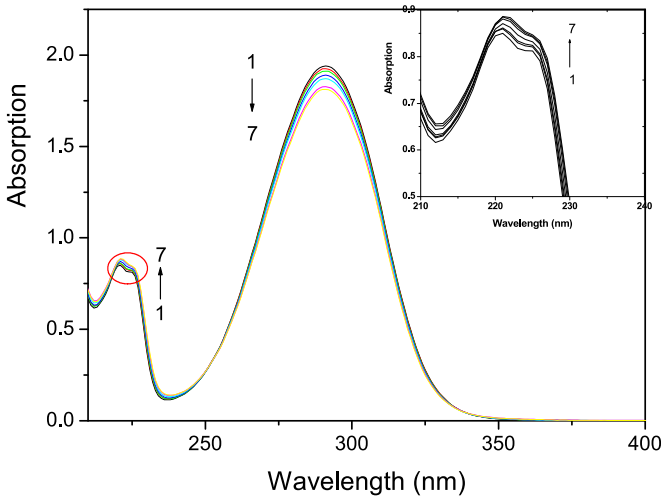


Fig. 2. The absorption spectra of cinnamaldehyde (7.5×10^{-5} mol/L) in the presence of 2-HPβ-CD with different concentrations ($\times10^{-3}$ mol/L) at 298 K: (1) 0, (2)0.5, (3) 1.0, (4) 2.0, (5) 3.0, (6) 4.0, and (7) 5.0.

2.1.3. NMR results. In order to provide a definitive proof of the formation of the inclusion complex, ^{1}H NMR spectroscopy was carried out using D_2O as solvent, since the chemical and electronic environments of protons changed during the inclusion complexation process, which is reflected by changes of chemical shifts ($\Delta\delta=\delta_{inclusion}-\delta_{free}$).[29] The comparison of the spectra for the individual components and the cinnamaldehyde/2-HPβ-CD inclusion complex was shown in Fig. 3. The ^{1}H chemical shift values for free cinnamaldehyde and the complex were reported in Table 1. The spectrum of the complex is significantly different from cinnamaldehyde and 2-HPβ-CD. Cinnamaldehyde has six types of protons: aldehyde hydrogen (1-H), olefinic hydrogens (2-H and 3-H), and aromatic protons (4-H, 4′-H, 5-H, 5′-H, and 6-H). From Fig. 3, all protons of cinnamaldehyde had clear chemical shifts. Remarkable shift was observed for 1-H, 3-H, 4-H, and 4′-H protons in Table 1. It demonstrates that inclusion complex was formed, and the highly hydrophobic phenyl ring and unsaturated double bond entered into the cavity of 2-HPβ-CD.

2D NMR studies revealed some useful information on the nature of the inter- and intra-actions between guest and cyclodextrin in the inclusion complexes.[30] The contour map expansion for the inclusion complex with 1:1 cinnamaldehyde/2-HPβ-CD (molar ratio) was presented in Fig. 4. The 2D ROESY spectra show correlations between the protons of 2-H (olefinic hydrogen) and 1-H (aldehyde hydrogen) in cinnamaldehyde and the protons of the internal hydrogen (H-3) and methyl hydrogen (CH_3) in 2-HPβ-CD, respectively, which suggest the benzene ring and –C=C– were included into the 2-HPβ-CD cavity, moreover the aldehyde group of cinnamaldehyde was near the secondary face of 2-HPβ-CD, and might form hydrogen bond with the hydroxypropyl group of 2-HPβ-CD. The results were consistent with those obtained by ^{1}H NMR and UV–vis experiments.

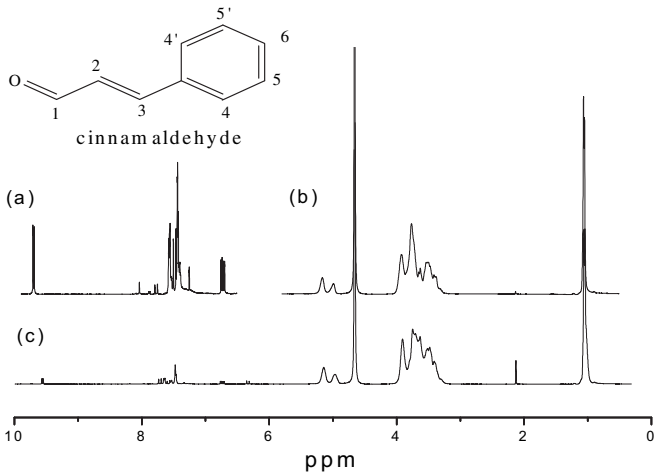


Fig. 3. ^{1}H NMR spectra of (a) cinnamaldehyde, (b) 2-HP-β-CD and (c) cinnamaldehyde complexed with 2-HPβ-CD.

Table 1
^{1}H NMR chemical shift of cinnamaldehyde, and the inclusion complex of 2-HPβ-CD with cinnamaldehyde

	1H	2H	3H	4H and 4′H	5H and 5′H	6H
Cinnamaldehyde	9.702	6.731	7.568	7.486	7.440	7.428
Inclusion	9.556	6.737	7.715	7.586	7.475	7.460
$\Delta\delta$ (ppm)	−0.146	−0.006	0.147	0.100	0.035	0.032

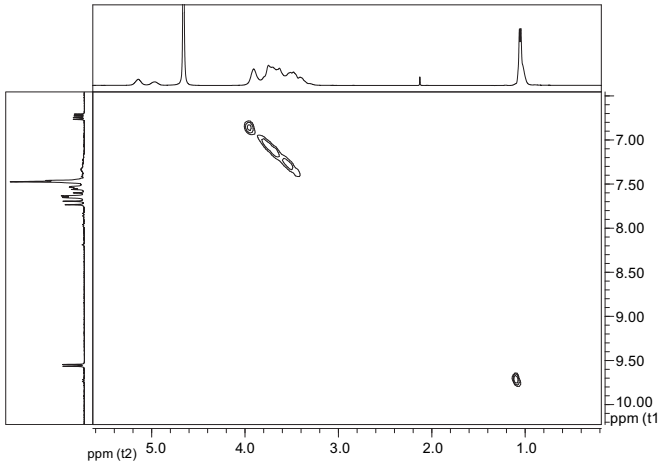


Fig. 4. The 2D ROESY spectrum of the inclusion complex.

2.1.4. Fluorescence results. Fig. 5(a) shows the changes of fluorescence intensity of cinnamaldehyde with various CDs concentration at room temperature. The maximum excitation and emission wavelengths were 248 and 322 nm, respectively. It is clear that the fluorescence intensity of cinnamaldehyde was enhanced with increasing CDs concentration, which is attributed to CD hydrophobic cavity providing an apolar environment for cinnamaldehyde molecule and thus increasing the quantum yield for the fluorescence of cinnamaldehyde. It is notable that considerable enhancement was observed for the 2-HPβ-CD system. Moreover the emission wavelengths had a small red shift from 322 nm to 329 nm with increasing concentration of 2-HPβ-CD. A reasonable explanation is that the substitution group of hydroxypropyl in 2-HPβ-CD provided a large and deep cavity as well as strong hydrogen bond between the host and the guest,[31] thus included the guest much tightly.

The association constant (K_a) and the stoichiometry of the cinnamaldehyde/2-HPβ-CD complex can be calculated based on the Benesi–Hildebrand plots[32] from the fluorescence data.

$$\frac{1}{F-F_o}=\frac{1}{\alpha K_a[G]_o[CD]_o}+\frac{1}{\alpha[G]_o}$$

Here F and F_o represent the fluorescence intensity of cinnamaldehyde in the presence and absence of CD, respectively; K_a is the association constant; $[G]_o$ is the concentration of guest; $[CD]_o$ is the concentration of CD; α is the fluorescence measurement coefficient, which is a constant. The double reciprocal plots of $1/(F-F_o)$ versus $1/[CD]_o$ was shown in Fig. 5(b). The Benesi–Hildebrand plot exhibits good linearity, which suggests the stoichiometry of the inclusion complex is 1:1. The association constant K_a for the complexes was 928 M^{-1}, and the corresponding standard free energy change $\Delta_\gamma G_m^\ominus$ (298 K) was −16.93 kJ mol^{-1}. The negative values of ΔG indicated the formation of host–guest inclusion complexes in aqueous solution at 298 K was spontaneous.

2.2. Reaction studies

The reaction in the presence of 2-HPβ-CD was carried out under the condition (the concentration of NaOH was 2% (w/v), cinnamaldehyde: CD (molar ratio)=1:1), and the results were illustrated in Table 2.

Benzaldehyde (70%) was obtained at 323 K, the optimum reaction temperature. Comparing with other reports of producing benzaldehyde from cinnamaldehyde,[4–10] this method provided the highest yield for benzaldehyde under much milder conditions, which is very important to preserve natural essence of benzaldehyde.

In order to further verify the efficiency of the present catalytic system, a large-scale experiment was carried out as shown in

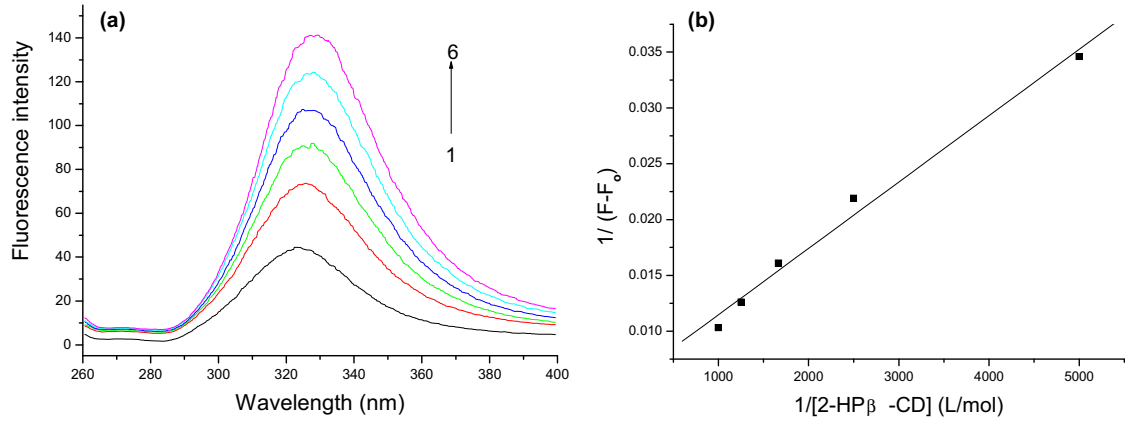


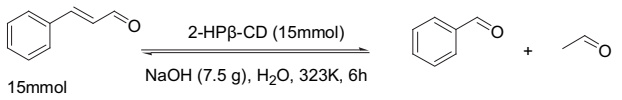
Fig. 5. (a) Fluorescence spectra of 1×10^{-4} mol/L cinnamaldehyde in the presence of CD with different concentrations ($\times10^{-4}$ mol/L) at 298 K: (1) 0, (2) 2, (3) 4, (4) 6, (5) 8 and (6)10; (b) the corresponding Benesi–Hildebrand plot of $1/(F-F_0)$ versus 1/[CD] for the cinnamaldehyde complexed with 2-HPβ-CD.

Table 2
Influence of 2-HPβ-CD on the hydrolysis of cinnamaldehyde under different reaction temperature

Temperature (K)	Reaction time (h)	Conversation of cinnamaldehyde (%)	Yield of benzaldehyde (%)
313	6	86	52
323	5	95	70
333	4	90	68

Reaction condition: 2-HPβ-CD/cinnamaldehyde (mol/mol) =1:1, cinnamaldehyde (1 mmol), NaOH (0.5 g), H_2O (25 mL).

Scheme 2. The isolated yield of benzaldehyde was 61% based on the natural cinnamon oil used. This is because of the effective activation of cinnamaldehyde via complexation with 2-HPβ-CD.



Scheme 2. Large-scale alkaline hydrolysis of natural cinnamal oil to benzaldehyde catalyzed by 2-HPβ-CD.

2.3. Kinetic studies

In order to investigate the catalytic nature of the present system, the reaction kinetics in the presence or absence of 2-HPβ-CD were studied using the initial concentration method. The obtained rate orders and rate constants were listed in Table 3.

Table 3
The rate orders (n) and rate constants (k) of the alkaline hydrolysis of cinnamaldehyde at different reaction temperatures

T (K)	n^a	n^b	k^a (min^{-1})	k^b (min^{-1})
313	0.87	1.01	0.0178	0.0532
323	1.06	1.11	0.0428	0.0888
333	0.97	1.08	0.0722	0.1410
343	1.02	1.16	0.1260	0.2170

[a] In the absence of 2-HPβ-CD.
[b] In the presence of 2-HPβ-CD.

From Table 3, it was concluded that the rate orders were nearly equal to 1 for all cases, which indicated that the hydrolysis of cinnamaldehyde or its inclusion complex with 2-HPβ-CD was first-order reaction. The rate constants apparently increased with raising reaction temperature. Furthermore, the rate constants for the 2-HPβ-CD system were higher than that without 2-HPβ-CD, which suggested the hydrolysis rate for the 2-HPβ-CD system was much higher than that without 2-HPβ-CD. Fig. 6 shows an Arrhenius analysis for Table 3. The plots were linear and the calculated activation energy E_a from the slopes was 41.72 kJ/mol for the 2-HPβ-CD system and 57.11 kJ/mol for the blank experiment, respectively. Obviously, 2-HPβ-CD decreased the activation energy of the hydrolysis reaction, and it enhanced the selectivity for benzaldehyde. As a result, 2-HPβ-CD was an efficient catalyst for the hydrolysis of cinnamaldehyde to natural benzaldehyde.

The catalytic proficiency ($(k_{cat}/K_M)/k_{uncat}$) provides a measure for the catalytic effect of the supramolecular catalysts, that is, a measure of how affinity affects the reaction compared with the uncatalyzed reaction under similar conditions.[33,34] For 2-HPβ-CD, the catalytic proficiencies was $3.48\times10^3\ M^{-1}$ at 298 K. The data suggested that the catalytic hydrolysis effects primarily depended on the K_M values for the CDs, in other words, CDs can activate cinnamaldehyde by forming host–guest include complex and promote the hydrolysis reaction.

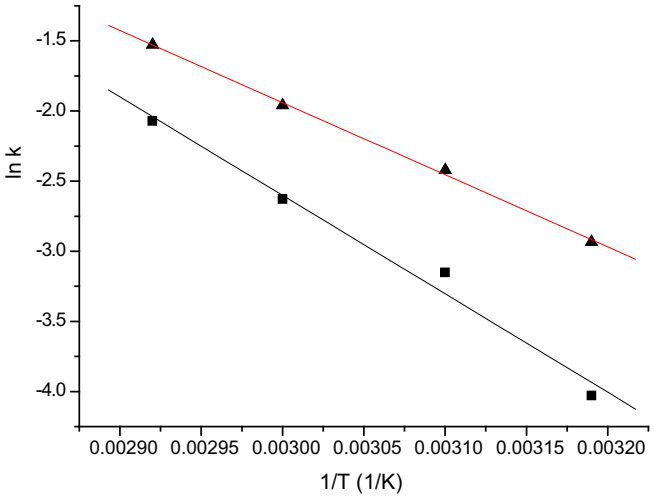


Fig. 6. Arrhenius plots of the rate constants for the alkaline hydrolysis.

2.4. Solubilization studies

In order to further characterize how the weak interactions between host and guest affected reactivity, the influence of 2-HPβ-CD on the apparent solubility of cinnamaldehyde in water had been investigated, as listed in Table 4. Not surprisingly, the hydrophilic CD derivate was much effective for increasing the apparent solubility (increased 18.8-folds at 40% w/w). The phase diagram (Fig. 7) showed a linear increase of guest solubility as a function of 2-HPβ-CD concentration though a slightly negative deviation at higher concentrations and was classified as A_L type, indicating formation of a 1:1 stoichiometry complex. Great increase of cinnamaldehyde solubility in water enlarges the contact area of the two phases, resulting in acceleration of reaction and increase the yield for the target production.

Table 4
Apparent solubility of cinnamaldehyde in cyclodextrin solutions with different concentration at 298 K

CD	CD concentration (w/w) %	Cinnamaldehyde solubility (mg/mL)	Solubility enhancement factor
None	0.0	4.33	1.00
2-HPβ-CD (DS=3.9)	1.5	5.85	1.35
	10.0	25.40	5.87
	20.0	49.95	11.54
	40.0	81.43	18.81

These results suggested that the intensity and the pattern of molecular interactions between guest and the CDs had a direct consequence on their solubilization efficiency. The intramolecular hydrogen bonding formed between the hydroxyl groups at the C3 of the glucose units and the hydroxyl alcohol enhances the 2-hydroxypropyl groups at the O2 positions to adopt a more spread-out configuration, that is, the O2 hydroxypropyl substitution increases the size of cavity for the natural β-CD (diameters of the natural β-CD cavity: 6.0–6.5 Å).[31] This feature was manifested as the remarkable enhancement of binding and solubility of the cinnamaldehyde/2-HPβ-CD inclusion complex.

2.5. Proposed reaction mechanism

In fact, the mechanism of alkaline hydrolysis of cinnamaldehyde to benzaldehyde was considered as retro-Aldol condensation and base acted as nucleophile. It was well known that the mechanism of

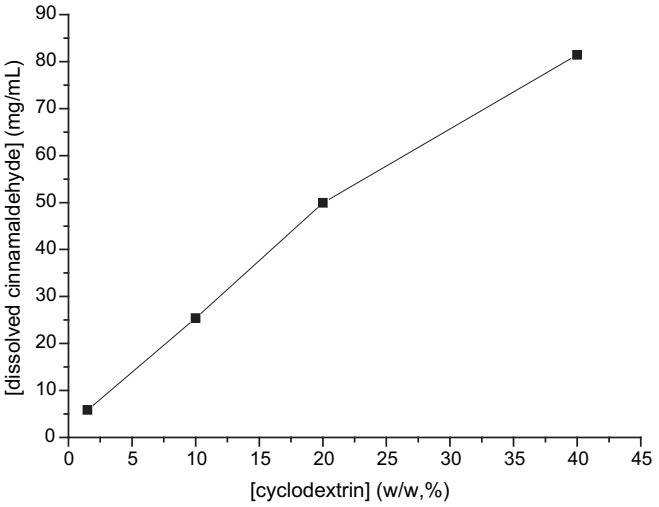


Fig. 7. Experimental phase solubility diagrams of cinnamaldehyde for 2-HPβ-CD at 298 K.

CD-mediated hydrolysis was related with the formation of CD/guest inclusion complex. As a result, owing to intermolecular interactions among the inclusion complex of cinnamaldehyde with 2-HPβ-CD, the hydrolysis mechanism in the present paper was different from that without 2-HPβ-CD. Based on the above experimental results, a possible reaction mechanism has been proposed for the alkaline hydrolysis of cinnamaldehyde in the presence of 2-HPβ-CD (Fig. 8).

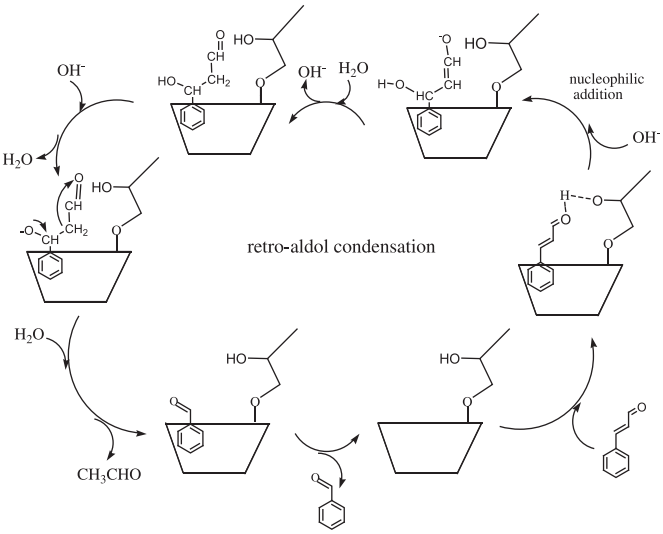


Fig. 8. The possible mechanism of the alkaline hydrolysis of cinnamaldehyde catalyzed by 2-HPβ-CD.

As shown in Fig. 8, first of all, 2-HPβ-CD and cinnamaldehyde can form the inclusion complex with the intermolecular hydrogen bond O–H···O at the secondary rim. It is the hydrogen bond between aldehyde group in cinnamaldehyde and hydroxypropyl groups in 2-HPβ-CD, that is, able to facilitate formation of the oxygen anion (O^-) and the nucleophilic addition of external hydroxide ion (OH^-) to cinnamaldehyde, which results in the acceleration of 2-HPβ-CD over alkaline hydrolysis of cinnamaldehyde. Through the retro-Aldol condensation of cinnamaldehyde in the 2-HPβ-CD-mediated alkaline solution, the target product, benzaldehyde was produced.

3. Conclusion

The combination of DSC, UV–vis, ^{1}H NMR, ROESY, and fluorescence measurements was used to investigate interactions between cinnamaldehyde and 2-HPβ-CD. Because of its expanding entrance size, 2-HPβ-CD was suitable for including cinnamaldehyde. Its association constant was 928 M^{-1} at 298 K. Moreover, the aldehyde group of cinnamaldehyde formed strong hydrogen bond with the hydroxypropyl group of 2-HPβ-CD, which promoted the conversion of cinnamaldehyde to benzaldehyde. As expected, it was demonstrated 2-HPβ-CD conferred high activity and selectivity for the alkaline hydrolysis of cinnamaldehyde. Further investigation on kinetics and solubilization indicated that weak molecular interactions between guest and CDs had a direct relevance on their solubilization efficiency, and the binding abilities among CDs and substrate mainly affected the hydrolysis reactivity. The benign, mild and straightforward methodology for the conversion of cinnamaldehyde to benzaldehyde may find its application in industry and provide a general method for production of other similar aldehyde or ketone fragrant compounds.

4. Experimental

4.1. General

GC–MS analysis was performed on a Shimadzu GC-MS-QP2010 plus with capillary column (Shimadzu Rtx-5MS, 30 m, 250 μm, 0.25 μm).

2-HPβ-CD (average substitution degrees DS=3.9) was purchased from Wuhan Yuancheng Technology Development Co. Ltd. Cinnamaldehyde was obtained from Sinopharm Chemical Reagent. Natural cinnamal oil containing of 93% cinnamaldehyde, was bought from Fulong Spice Co. Sodium hydroxide, petroleum ether and ethyl acetate were obtained from Guangzhou Chemical Reagent Factory, China. All chemicals were of analytical grade and were used without further purification. Deionized water was applied for all the experiments.

4.2. Preparation of the inclusion complex of cinnamaldehyde with 2-HPβ-CD

2-HPβ-CD (1 mmol) and 1 mmol cinnamaldehyde were mixed in 25 mL deionized water. After stirred at 323 K for 2 h the mixture was utterly clear. It was frozen for 24 h in refrigerator and then lyophilized by freeze dryer (ALPHA 1-2LD, Christ, Germany). The white amorphous powder, which is the inclusion complex of cinnamaldehyde with 2-HPβ-CD was obtained.

4.3. Characterization of the inclusion complex

Differential Scanning Calorimetry (DSC) data were obtained on an STA 409 PC/PG (NETZSCH Gerätebau GmbH). Each sample (2–6 mg) was exactly weighed in an aluminum crucible and was heated from 313 to 673 K at the rate of 20 °C/min in nitrogen gas.

UV–vis spectra were measured on a UV-2450 UV–vis spectrophotometer (Shimadzu, Japan). The absorption spectra of cinnamaldehyde (7.5×10^{-5} mol/L) were measured with different concentrations of 2-HPβ-CD (0.0, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0×10^{-3} mol/L).

^{1}H NMR and 2D ROESY spectra were carried out at room temperature in D_2O on a Bruker Advance DRX-400 spectrometer (Bruker BioSpin, Rheinstetten, Germany) equipped with a 5 mm inverse probe with *z*-gradient coil. ^{1}H NMR experiment was achieved with a spectral width 8012 Hz, acquisition time 2.04 s and a relaxation delay 2 s with 32 scans. ROESY was conducted by using the roesyetgp pulse sequence in the phase sensitive mode with

a spin-lock mixing time of 200 ms and other parameters equal to those of ^{1}H NMR spectra.

Fluorescence measurements were performed on F-4500 Fluorescence spectrophotometer (Hitachi, Japan) to calculate the inclusion equilibrium constant and thermodynamic parameters. Quartz cell (1 cm) was used. The excitation wavelength was set at 248 nm and the emission at 322 nm with both the slits at 10 nm.

4.4. General procedure for the alkaline hydrolysis of cinnamaldehyde to benzaldehyde

All reactions were performed in a 100 mL glass reaction flask equipped with a condenser. In a typical experiment, cinnamaldehyde (1 mmol) was mixed with deionized water (25 mL), NaOH (0.5 g), and 2-HPβ-CD (1 mmol) at 323 K while stirring. The reaction mixture was extracted by ethyl acetate and subsequently analyzed by GC–MS with naphthalene as an internal standard. The reproducibility for all the data was within 5%.

Large-scale alkaline hydrolysis of natural cinnamal oil catalyzed by 2-HPβ-CD was carried out as follows: the mixture of NaOH (7.5 g), 2-HPβ-CD (20.4 g) and 375 mL deionized water was stirred at 323 K. After the mixture was clear, natural cinnamal oil (2.132 g) was added. The process was monitored by GC–MS with naphthalene as the internal standard. Finally, the mixture was extracted by ethyl acetate and separated by column chromatography on silica gel (200–300 mesh) using the mixture of ethyl acetate and petroleum ether (1:30, volume ratio) as eluent.

4.5. Kinetic experiments

The initial concentration method was taken without considering the reverse and side reactions. Owing to $[H_2O]>>$[cinnamaldehyde], kinetic experiments were carried out under pseudo-first-order conditions for the alkaline hydrolysis of cinnamaldehyde catalyzed by 2-HPβ-CD. In a 100 mL 3-necked round bottom flask equipped with magnetic stirrer, 1 mmol (or 0.25 mmol, 0.50 mmol, and 0.75 mmol) cinnamaldehyde was added into the mixture of 0.5 g NaOH and 1 mmol 2-HPβ-CD dissolved in 25 mL of deionized water at 323 K (or at 313, 333, and 343 K) while stirring. Initial rates were measured for the first 10 min of reaction time and determined by the consumption of cinnamaldehyde and formation of products analyzed by GC–MS with naphthalene as the internal standard. The reproducibility for the rate constants measured was all within 5%.

Kinetic experiments without 2-HPβ-CD were carried out in the same way.

4.6. Solubilization

In order to investigate the effect of 2-HPβ-CD on the solubility of cinnamaldehyde in water, excessive amount of cinnamaldehyde was added to 10 mL aqueous 2-HPβ-CD solution with different concentration (from 0 to 40% w/w). The resulting suspensions were stirred for 72 h at 298 K. After reaching complexation equilibrium, the samples were filtered through a 0.45 μm membrane filter, diluted with deionized water, and the cinnamaldehyde concentration was analyzed by UV-2450 UV–vis spectrophotometry at 290 nm.

Acknowledgements

The authors thank the National Natural Science Foundation of China (Nos 21036009 and 20776053), higher-level talent project for Guangdong provincial universities, the Fundamental Research Funds for the Central Universities and the Combination of Industry, Schools and Research Institutions Project in Zhongshan City (2009CXY011) for providing financial supports for this project.

Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2010.10.063.

References and notes

1. Wolken, W. A. M.; Tramper, J.; Van Der Werf, M. J. *Flavour Frag. J.* **2004**, *19*, 115–120.
2. Berger, R. G. *Flavours and Fragrances*; Springer: Berlin Heidelberg, 2007.
3. Krings, U.; Berger, R. G. *Appl. Microbiol. Biotechnol.* **1998**, *49*, 1–8.
4. Yi, F. P.; Li, W. G.; Liu, X. M.; Lan, T. C.; Zhou, Y. H. *Fine Chem.* **1996**, *13*, 32–34.
5. Gao, F.; Lv, X. Y. *J. Chem. Ind. Eng. (China)* **2006**, *20*, 544–547.
6. Chen, L.T.; Huang, T.S.; Zhu, J.Q.; Lai, G.Y. Patent CN1634837A, 2004.
7. Cui, J. G.; Wang, C. S.; Liao, X. H. *Chem. World* **2002**, *6*, 315–317.
8. Pittet, A.O.; Muralidhara, R.; Liberman, A.L. U.S. Patent 46,833,42A, 1986.
9. Zhu, F. G.; Zhou, S. H. *Fine Chem.* **2002**, *19*, 678–681.
10. Ye, J.D.; Zhou, W.Y. Patent CN1179934C, 2003.
11. Dalgarno, S. J.; Power, N. P.; Atwood, J. L. *Coord. Chem. Rev.* **2008**, *252*, 825–841.
12. Koblenz, T. S.; Wassenaar, J.; Reek, J. N. H. *Chem. Soc. Rev.* **2008**, *37*, 247–262.
13. Oshovsky, G. V.; Reinhoudt, D. N.; Verboom, W. *Angew. Chem., Int. Ed.* **2007**, *46*, 2366–2393.
14. Ji, H. B.; Huang, L. Q.; Shi, D. P.; Zhou, X. T. *Chin. J. Org. Chem.* **2008**, *28*, 2072–2080.
15. Chan, W. K.; Yu, W. Y.; Che, C. M.; Wong, M. K. *J. Org. Chem.* **2003**, *68*, 6576–6582.
16. Ji, H. B.; Shi, D. P.; Shao, M.; Li, Z.; Wang, L. F. *Tetrahedron Lett.* **2005**, *46*, 2517–2520.
17. Reddy, M. A.; Bhanumathi, N.; Rao, K. R. *Chem. Commun.* **2001**, *19*, 1974–1975.
18. Surendra, K.; Krishnaveni, N. S.; Nageswar, Y. V. D. *J. Org. Chem.* **2003**, *68*, 4994–4995.
19. Fernandez, M. A.; Rossi, R. H. *J. Org. Chem.* **1997**, *62*, 7554–7559.
20. Chen, H. Y.; Ji, H. B. *AIChE J.* **2010**, *56*, 466–476.
21. Schneiderman, E.; Stalcup, A. M. *J. Chromatogr., B* **2000**, *745*, 83–102.
22. Koji, K. *Colloid Polym. Sci.* **2008**, *286*, 79–84.
23. Uzqueda, M.; Martőn, C.; Zomoza, A.; Sánchez, M.; Martőnez-Ohárriz, M. C.; Vélaz, I. *Pharm. Res.* **2006**, *23*, 980–988.
24. Nasongkla, N.; Wiedmann, A. F.; Buening, A.; Beman, M.; Ray, D.; Bornmann, W. G.; Boothman, D.; Gao, J. M. *Pharm. Res.* **2003**, *20*, 1626–1633.
25. Divakar, S.; Maheswaran, M. M. *J. Inclusion Phenom. Mol. Recognit. Chem.* **1997**, *27*, 1113–1126.
26. Ilichev, Y. U.; Kuhnle, W.; Zachariasse, K. A. *J. Phys. Chem. A* **1998**, *102*, 5670–5680.
27. Kim, Y. H.; Cho, D. W.; Yoon, M. *J. Phys. Chem.* **1996**, *100*, 15670–15676.
28. Jiang, Y. B. *J. Photochem. Photobiol., A* **1995**, *88*, 109–116.
29. Ishizu, T.; Tsutsumi, H.; Yamamoto, H.; Harano, K. *Magn. Reson. Chem.* **2009**, *47*, 283–287.
30. Jullian, C.; Orosteguis, T.; Pérez-Cruz, F.; Sánchez, P.; Mendizabal, F.; Olea-Azar, C. *Spectrochim. Acta, Part A* **2008**, *71*, 269–275.
31. Yong, C. W.; Washington, C.; Smith, W. *Pharm. Res.* **2008**, *25*, 1092–1099.
32. Benesi, H. A.; Hildebrand, J. H. *J. Am. Chem. Soc.* **1949**, *71*, 2703–2707.
33. Pluth, M. D.; Bergman, R. G.; Raymond, K. N. *J. Org. Chem.* **2009**, *74*, 58–63.
34. Miller, B. G.; Wolfenden, R. *Annu. Rev. Biochem.* **2002**, *71*, 847–885.