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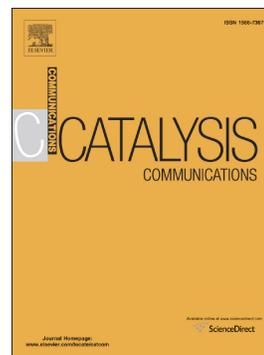
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A Novel Approach to Vapor-phase Synthesis of 2- and 4-methylquinoline from Lactic Acid and Aniline

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ABSTRACT

A novel and green route for vapor-phase synthesis of 2- and 4-methylquinoline was provided in this work, in which lactic acid as one of the reactants was for the first time employed. Various influencing factors, including types of catalysts, reaction temperature and stability of catalyst were investigated systematically. The results showed that a 67.6% total yield of quinolines was obtained over the HBeta catalyst. The characterization by using BET, NH_3-TPD and pyridine-IR techniques revealed that strong Brønsted acid sites are favorable for generation of 2- and 4-methylquinoline whereas Lewis acid sites could increase the proportion of 4-methylquinoline in target products. Besides, a feasible reaction pathway to synthesize 2- and 4-methylquinoline was proposed on the basis of the reaction products.

Keywords: vapor-phase, lactic acid, 2- and 4-methylquinoline, HBeta zeolite

1. Introduction

Quinolines and related compounds constitute an important category of heterocyclic compounds. Among them, 2- and 4-methylquinoline are widely used in medical, agriculture and industries.[1-5] For instance, 4-methylquinoline is one of the most importance intermediates of photosensitive material used for colour cinefilm as sensitizer. In the early years, the traditional liquid-phase synthesis routes,[6-10] including Skraup, Doebner-Miller and Friedlander synthesis, were widely employed to synthesize quinolines. However, they suffer from many disadvantages, *e.g*., expensive, toxic feed and hard recycling of catalysts. There is no doubt that the development of a gas-phase synthesis is of great interest, as it has numerous advantages, including continuous production, simplified product recovery, catalyst regenerability and absence of acid waste stream, relative to the liquid-phase method. [11-13]

In the vapor-phase route, many good approaches have been applied for the synthesis of methylquinolines. For instance, one synthesis from quinoline and methanol (molar ratio of quinoline/methanol was 1:3) to 2-methylquinoline was performed. However, these reagents are either expensive or toxicity.[14] Besides, acetaldehyde was employed to synthesize 2- and 4-methylquiniline with aniline over HBeta zeolite catalyst.[13] Unfortunately, acetaldehyde is toxic and derived from oil resources. Moreover, acetaldehyde is prone to polymerization due to its

strong activity, which results in the serious deactivation of catalyst. Therefore, it is highly desired to exploit a green, sustainable, and low-cost route for the synthesis of 2- and 4-methylquinoline. Lactic acid, as an important product of industrial importance, can currently large-scaled manufacture *via* fermentation approach.[15-18] Moreover, it is cheap, environment-friendly and renewable materials.[19-21] Thus, efficient utilization of abundant lactic acid is highly desired.

In this paper, we reported the vapor-phase synthesis of 2- and 4-methylquinoline, for the first time, utilizing lactic acid as one of the reactants. Zeolite-based catalysts were employed in this reaction because zeolites possess large surface area, high hydrothermal stability as well as flexible adjustable acidity. Many factors like catalysts and reaction temperature are investigated in detail. BET, NH_3-TPD and pyridine-IR techniques are used to reveal the relationship between the structure of catalysts and catalytic performance.

2. Experimental

2.1. Catalysts Preparation.

The Beta, ZSM-5, Y and USY zeolites were supplied by Nankai University Catalyst Factory. The modified-HBeta catalysts were prepared by wet impregnation method. The typical procedures were as follows: the 5.0 g Beta powder was added into a 0.1 M ferric nitrate aqueous solution, according to a calculated liquid / solid ratio, and then stirred vigorously at

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room temperature for 24 h. After that, the mixture was dried at 120 °C for 12 h and calcined at 550 °C for 4 h. The thus-obtained catalyst was denoted as Fe/Beta. The similar procedure was also carried out for the preparations of other metal-loaded Beta zeolite catalysts, which were denoted as metal/Beta, where M = Fe, Co, Mn, Cr, Ni. In the above prepared catalysts, the contents of metal component were all 5 wt%.

2.2. Catalysts Characterization

N$_2$-physisorption was conducted on a Quantachrome Autosorb-1 instrument at liquid-N$_2$ temperature. Before measurement, the specimen was in situ outgassed in the instrument at 300 °C for 12 h under a vacuum of 10^{-8} Torr. The specific surface area was calculated by multipoint BET equation, and the total pore volume was calculated at relative pressure of P/P_0=0.99.

Temperature programmed desorption of NH$_3$ (NH$_3$-TPD) was determined on a Micromeritics Autochem II 2920 instrument equipped with a thermal conductivity detector (TCD). The catalyst was first pretreated at 400 °C for 30 min in a flow of helium (99.99%) with a flow rate of 60ml/min, followed by cooling to 100 °C. Then, ammonia was repeatedly pulse-injected in a stream of 10 % NH$_3$/He with a flow rate of 50 ml/min until its saturation adsorption over the catalyst had been achieved. After purging with helium at 100 °C for 1.0 h, ammonia was desorbed by heated the catalyst from 100 °C to 800 °C at a rate of

10 °C/min.

Fourier transform infrared (FT-IR) spectroscopy of pyridine absorption was recorded on a Varian 3100 spectrometer equipped with a liquid nitrogen cooled MCT detector and a Cel beamsplitter. The catalyst was first mixed with KBr powders by thoroughly grounding, and then, the mixture was pressed into a disc and pre-heated at 300 °C for 4 h under N_2 atmosphere. After that, the catalyst was cooled to room temperature and exposed to pyridine vapor for 90 min. Finally, the catalyst was heated at 250 °C for 90 min in N_2 atmosphere, followed by exposing to a 10^{-5} Torr vacuum at room temperature for 3 h, removing the gaseous and physisorbed pyridine molecules. The thus-treated catalyst was subjected to the FT-IR determination.

2.3. Catalytic Performance Evaluation

Catalytic performance test was carried out in a fixed-bed stainless steel reactor. Aniline and lactic acid aqueous solution (concentration of Lactic acid = 40 wt%, LHSV of lactic acid=0.5 h^{-1}, molar ratio of aniline/lactic acid =1:1) were initially vapored, respectively, and then fed into the reactor in the presence of N_2 (20 mL/min). The products mixture was analyzed by a Varian Saturn 2200/ CP-3800 gas chromatography-mass spectrometry equipped with two CP8944 capillary columns (VF-5, 30 m × 0.25 mm × 0.25 µm). The yield of products was

calculated as follow based on the converted lactic acid, where the product refers to quinoline, 2- and 4-methylquinoline.

$$\text{Conversion (mol\%)} = \frac{\text{moles of lactic acid converted}}{\text{moles of lactic acid input}} \times \%$$

$$\text{Selectivity (mol\%)} = \frac{2 \times \text{moles of product}}{\text{moles of lactic acid converted}} \times \%$$

$$\text{Yield (mol\%)} = \text{Conversion} \times \text{Selectivity} \times \%$$

3. Result and discussion

3.1. Catalysts Characterization

The detailed textural properties of the pure and modified HBeta zeolite catalysts are listed in Table 1. One can see than the surface area (S_{BET}, S_{ext}, S_{mic}), pore volume (V_{total}, V_{mic}) and micropore size (D_{mic}) over the NaBeta catalyst change little, relative to the pure HBeta one, indicating that weak influence on textural properties of Beta zeolite during Na-ion exchange process. However, the Fe/Beta catalyst has the smaller surface area (S_{BET}, S_{ext}, S_{mic}), pore volume (V_{total}, V_{mic}) as well as micropore size (D_{mic}) than the pure HBeta one. The decrease in the microporosity of the Fe/Beta catalyst may be due to the fact that its micropores are occupied by active components (Fe) during the preparation of catalysts.

The acidity property of the pure and modified HBeta zeolite catalysts by NH$_3$-TPD (left) and FT-IR spectra of pyridine adsorption (right) are shown in Figure 1. For the NH$_3$-TPD characterization, the T_1

peak is present for all catalysts, which is attributed to the weak acid sites relating to the terminal acid silanol groups.[22, 23] The T_2 peak is identified evidently over the HBeta catalyst but virtually absent over the other catalysts, which can be ascribed to strong Brønsted acid sites relating to the bridging Si-(OH)-Al groups. The T_3 peak appears distinctly over the Fe/Beta catalyst, which is attributed to strong Lewis acid sites deriving from Fe attached to Beta zeolite with certain interactions. In the FT-IR spectra of pyridine-absorption, two bands at ca. 1540 and 1450 cm^{-1} are assigned to the Brønsted and Lewis acid sites, respectively. Compared to the NaBeta catalyst, the intensity of peak at 1540 cm^{-1} is larger over the HBeta one but the intensity of peak at 1450 cm^{-1} is larger over the Fe/Beta one. Combining the NH_3-TPD result, it is well concluded that the HBeta catalyst possesses a larger concentration of strong Brønsted acid sites while the Fe/Beta catalyst presents a larger concentration of strong Lewis acid sites. On the contrary, the NaBeta catalyst exhibits a less concentration of both strong Brønsted and Lewis acid sites.

3.2. Catalysts Performances

The catalytic activities of catalysts are presented in Table 1. In this reaction, lactic acid is fully converted at high reaction temperature, and 2-/4-methylquinoline and quinoline are successfully generated. Besides, other products, such as, ethylquinoline, 3-methylindol, 1,2-dimethylindol,

acetaldehyde, acrylic acid, crotonaldehyde, N-ethylaniline, are also identified in the product mixtures *via* Varian GC-MS analysis. One can see that the total yield over different type of zeolite catalysts shows an order HBeta > HZSM-5 > HUSY > HY. This is most probably due to the fact that the USY and Y zeolites exist supercages in which the deep polymerization of intermediates and/or products could be accelerated while the HZSM-5 zeolite exhibits small intersected pore channel (pore sizes: 0.53 nm × 0.56 nm and 0.51 nm × 0.55 nm) which could imposes diffusion limitation of bulky products;[24, 25] on the contrary, the Beta zeolite possesses large pore channel (pore size: 0.66 nm × 0.67 nm and 0.56 nm × 0.56 nm) and its pore size matches well with quinolines molecule size.[26] Thus, this unique property for Beta is favor to conduct the shape selectivity in this reaction and therefore HBeta zeolite catalyst exhibits the best catalytic activity among various zeolites in this work. When metal-modified Beta zeolites are tested, respectively, the total yield decreases in different degrees and the ratio of 4MeQ/2MeQ increases distinctly. It indicates that the addition of metal on Beta zeolite affects the total yield and products distribution, to some extent. Combining the acidity property of catalysts as shown in Figure 1, it shows that HBeta with the larger concentration of strong Brønsted acid sites is favorable for synthesizing 2- and 4-methylquinoline; and the Fe/Beta catalyst with the larger concentration of strong Lewis acid sites could increase the

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proportion of 4-methylquinoline in the target products. As shown in Scheme 1, strong Brønsted acid sites promote the decarbonylation of lactic acid to acetaldehyde and subsequent condensation of acetaldehyde to crotonaldehyde, whereas strong Lewis acid sites could favor the former process but restrain the latter one.

Table 2 shows the effect of reaction temperature for vapor-phase synthesis of quinolines. One can see that with the increase of reaction temperature, the conversion of lactic acid increases and reaches 100% at 440 °C. Total yield increases with the elevation of temperature, achieving 67.6% as its maximums at 440 °C, and then decrease. Besides, the yield of quinoline (Q) exhibits an increasing trend with the increase of temperature, possibly due to dealkylation of alkylquinolines at high temperature. Accordingly, the optimal reaction temperature is 440 °C.

Figure 2 shows the stability of the HBeta catalyst. The yield of 2-methylquinoline decreases with nearly constant rate, whereas that of 4-methylquinoline decreases slightly before 10 h and distinctly after 10 h. The ratio of 4MeQ/2MeQ increases obviously, arriving ca. 1 as its maximum at reaction time of 9 h, and then decreases distinctly. The results indicate that 2-methylquinoline is more favorable to generate on active sites, while its pathway is restrained more easily because of catalyst deactivation. The total yield decreases at almost nearly speed and still ca. 39% total yield can be obtained at 9 h, indicating that still more

than 50% residual catalytic activity on catalyst can be remained after 9 h. Anyway, a good stability of catalyst can be obtained in this reaction.

3.3. Reaction pathways

When the reaction employing single lactic acid without aniline as reactant is carried out over HBeta catalyst under the same reaction condition, the major proportion of acetaldehyde and crotonaldehyde are detected in the products based on GC-MS. Meanwhile, Brosius et al. [13] reported that acetaldehyde could react with aniline to form 2- and 4-methylquinoline readily over Beta zeolite via different reaction pathway. Thus, the generation of methylquinoline from lactic acid and aniline undergoes two steps, namely, involving decarbonylation of lactic acid to acetaldehyde and subsequent condensation of acetaldehyde and aniline over acid sites (Eq. (1),).

$$2CH_3CH(OH)COOH \xrightarrow[\text{acid sites}]{} 2CH_3CHO \xrightarrow[\text{acid sites}]{PhNH_2} \text{Methylquinoline} \quad \text{Eq. (1)}$$

The specific reaction pathways are shown in Scheme 1. Lactic acid firstly converts to acetaldehyde via decarbonylation over acid sites. Subsequently, crotonaldehyde (generated from the condensation of acetaldehyde) reacts with aniline via Michael addition and subsequent ring-closing electrophilic aromatic substitution to produce 2-methylquinoline (2MeQ). By contrast, acetaldehyde reacts directly with aniline to form enamine, and then the enamine further reacts with another

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acetaldehyde and generates 4-methylquinoline (4MeQ) *via* intramolecular electrophilic aromatic substitution.

4. Conclusion

A new efficient and convenient route was provided for vapor-phase synthesis of 2- and 4-mthylquinoline from readily available starting materials of lactic acid and aniline in this work. The reaction process consists of decarbonylation of lactic acid to acetaldehyde and subsequent condensation of acetaldehyde and aniline to 2- and 4-methylquinoline. The HBeta catalyst exhibits the best catalytic activity and good catalytic life. The strength and type of acid sites on catalyst significantly affects the total yield and products distribution. Strong Brønsted acid sites are favorable for synthesis of 2- and 4-methylquinoline; and the Lewis acid sites increase the proportion of 4-methylquinoline in target products. A plausible reaction pathway for the vapor-phase synthesis of 2- and 4-methylquinoline from lactic acid and aniline was proposed.

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Table 1. The detailed textural properties of the pure and modified HBeta zeolite catalysts

Catalysts	$S_{BET}(m^2/g)$	$S_{ext}(m^2/g)$	$S_{mic}(m^2/g)$	$V_{total}(cm^3/g)$	$V_{mic}(cm^3/g)$	$D_{mic}(nm)$
HBeta	543.2	122.4	420.8	0.35	0.17	0.61
NaBeta	531.3	140.4	390.9	0.34	0.17	0.61
Fe/Beta	403.6	76.47	327.1	0.24	0.14	0.58

Note: S_{BET}, S_{ext} and S_{mic} refers to specific surface area, external surface area and micropore surface area, respectively, and $S_{BET} = S_{ext} + S_{mic}$; V_{total} and V_{mic} refers to total pore volume and micropore volume, respectively. D_{mic} refers to micropore pore size calculated by SF method.

Table 2. Catalytic activity of various catalysts

Catalyst	Conversion (%)	Selectivity (%)				total yield [e]	4MeQ/2MeQ
		Q [a]	2MeQ [b]	4MeQ [c]	Other [d]		
HY	100.0	1.1	2.1	11.2	85.6	14.4	5.33
HUSY	100.0	0.7	4.7	11.2	83.4	16.6	2.38
HZSM-5	100.0	10.4	22.4	11.5	55.7	44.3	0.51
HBeta	100.0	5.1	40.7	21.8	32.4	67.6	0.54
Fe/Beta	100.0	5.4	26.3	25	43.3	56.7	0.95
NaBeta	99.3	5.2	30.3	14.3	50.2	49.5	0.47
Co/Beta	99.0	3.7	22.8	17.1	56.4	43.2	0.75
Mn/Beta	99.5	4.7	19.6	19.5	56.2	43.6	0.99
Cr/Beta	99.8	3.4	18.2	14.2	64.1	35.8	0.78
Ni/Beta	100.0	4.8	15.7	14.1	65.4	34.6	0.90
F/Beta	98.8	4.9	35.0	18.1	42.0	57.3	0.52
P/Beta	99.4	6.7	21.0	11.4	60.9	38.9	0.54

Reaction temperature: 440 °C.

[a~c] corresponds respectively to quinoline, 2- and 4-methylquinoline.

[d] other quinoline base products (1,2,3,4-tetrahymethyldroquinoline, ethylquinoline, butylquinoline), indol base products (indol, 3-methylindol, 1,2-dimethylindol, N-methy-2,3-dimethylindol), acetaldehyde, acrylic acid, crotonaldehyde, N-ethylaniline, coking substances and etc.

[e] total yield of Q, 2MeQ and 4MeQ.

Table 3. Effect of reaction temperature over HBeta catalyst.

Temperature (^{o}C)	Conversion (%)	Selectivity (%)				total yield (%) [e]
		Q [a]	2MeQ [b]	4MeQ [c]	Other [d]	
380	88.1	0.9	8.6	15.8	74.7	22.3
410	94.2	1.7	36.0	25.3	37.0	59.4
440	100.0	5.1	40.7	21.8	32.4	67.6
470	100.0	5.7	34.0	22.9	37.4	62.6

[a~e] see the table 1.
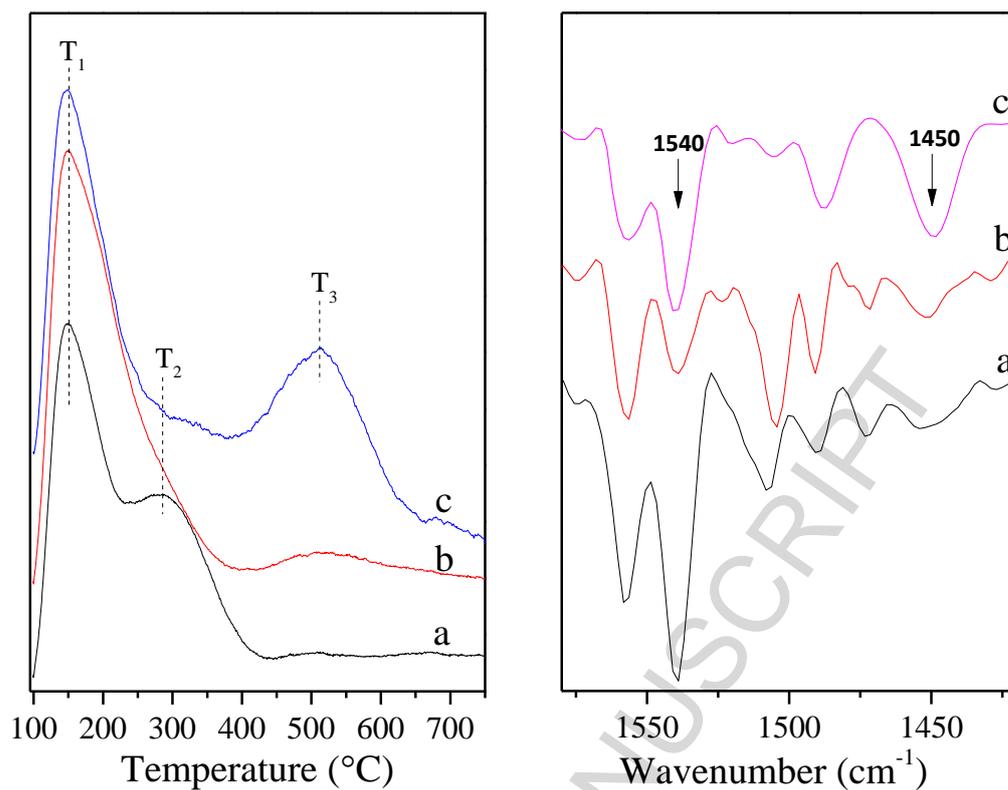
Figure 1. The acidity property of the pure and modified HBeta zeolite catalysts by NH$_3$-TPD (left) and FT-IR spectra of pyridine adsorption (right). (a) HBeta; (b) NaBeta; (c) Fe/Beta.

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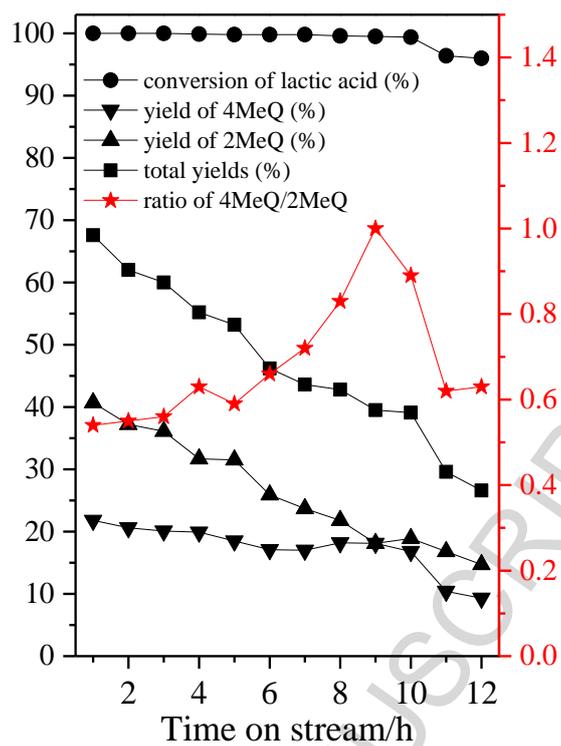
Figure 2. Stability of HBeta catalyst.
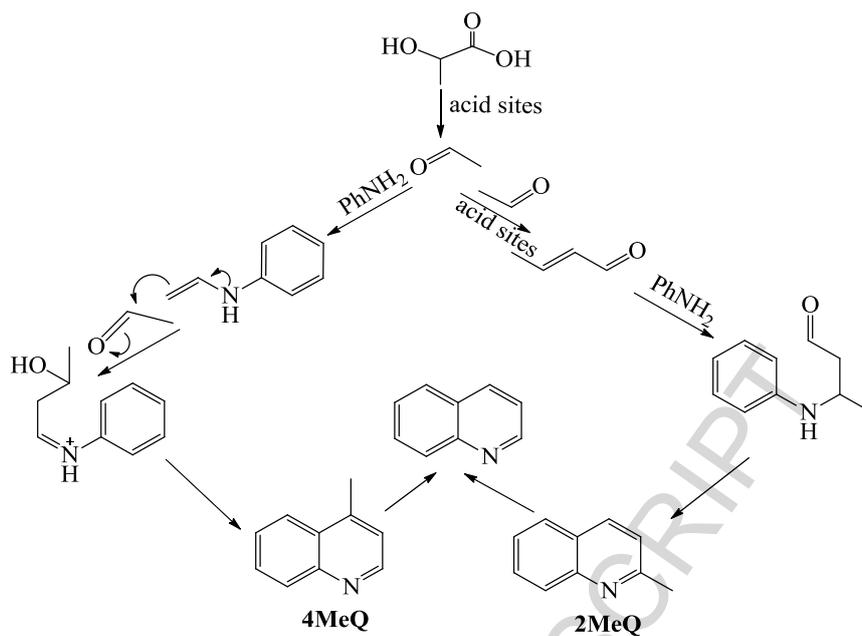
Scheme 1. Proposed reaction pathways for synthesis of 2- and 4-quinoline from lactic acid and aniline

Highlights

- 2- and 4-methylquinoline was synthesized with lactic acid as one of reactants.
- As high as 67.6% total yield of quinolines were achieved over HBeta catalyst.
- The strength and type of acid sites on catalyst affected the total yields.
- The addition of metal on catalyst influenced the products distribution.

Highlights

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