ESTERIFICATION OF SALICYLIC ACID USING Ce⁺⁴ MODIFIED CATION-EXCHANGE RESIN AS CATALYST

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ABSTRACT

The esterification of salicylic acid with methanol was carried out over a series of Ce⁺⁴ modified cation-exchange resins. The effect of different reaction conditions was studied on the conversion of salicylic acid, and the optimal reaction parameters were obtained. The experimental results indicated that Ce(SO₄)₂·001·7 was an effective catalyst for the synthesis of methyl salicylate. The conversion of salicylic acid could reach 93.3% while its selectivity was more than 99.0%. SEM-EDS and TG-DSC analysis were employed to characterize the structure and property of the catalyst. Besides, the catalytic performance of Ce(SO₄)₂·001·7 in the esterification of salicylic acid with different alcohols was compared. The reusability of Ce(SO₄)₂·001·7 was also studied by using salicylic acid and methanol as model substrates. The mechanism was proposed for the esterification of salicylic acid with methanol over Ce⁺⁴ modified cation-exchange resins.

Keywords: Salicylic acid, Esterification, Metal modified, Cation-exchange resin

INTRODUCTION

Organic esters which represent particularly medicinal and chemical characteristics have been extensively used in the synthesis of drugs, plasticizers, food preservatives, pharmaceuticals, solvents, perfumes, cosmetics, and chiral auxiliaries. Conventional mineral catalysts for esterification reactions, such as silica, aluminium oxide, and hydrotalcite, have been studied. However, these catalysts often suffered from inherent problems of corrosiveness, environmental hazards, difficulty in catalyst recovery and reuse, susceptibility to water, and so on. Conventional water-insoluble heterogeneous catalysts such as clays, zeolites, mesoporous materials, sulfated metal oxides and heteropolyacids were developed as solid acid catalysts for esterification reactions. In esterification reactions, the main advantages of solid acid catalysts are non-corrosive and easy to be separated from the reaction mixture for reuse. However, these catalysts had their own shortcomings such as the hybrid acid sites and deconcentrated acidity, leading to low selectivity toward target product. To solve these problems, ionic liquids (ILs) have been explored as a new green reaction media owing to their negligible volatility, excellent thermal stability, and the variety of structures available. However, studies about ILs in esterification were hot compared to conventional mineral catalysts. Therefore, studies about ILs in esterification are needed.

Ion-exchange resins, which have a bead structure, the advantages of solid acid catalysts, and the ability to ion-exchange or chelate metal ions, have been widely applied in many fields, such as purification of water and wastewater, separation of heavy metal ions, esterification and etherification reactions. Besides, Yonenomo and Li have reported on the biodiesel production using anion-exchange and catalysis-exchange resins as heterogeneous catalysts respectively. Furthermore, several references in the form of research articles were available on the application of ILs in esterification industry. However, the high cost restricted the application of ILs in esterification industry.

In the present work, the esterification reaction was carried out over a series of Ce⁺⁴ modified cation-exchange resins. The catalytic performance of Ce(SO₄)₂·001·7 in the esterification of salicylic acid with different alcohols was compared. The reusability of Ce(SO₄)₂·001·7 was also examined using salicylic acid and methanol as model substrates. An attempt was also made to study the mechanism of the esterification reaction.

EXPERIMENTAL

1. Materials

Cation-exchange resins (D001-cc, 001·7, D61, D72, NKC-9) were purchased from the Chemical Plant of Nankai University, China. These resins were pretreated using methods in the previous literature. All reagents (A.R.) were purchased from China National Pharmaceutical Group Corporation (Shanghai) and treated according to standard methods.

Conversion of salicylic acid (SA)(%) = 100 - [salicylic acid] × 100 [methyl salicylate] + [phenol] (1)

Selectivity of methyl salicylate (MS)(%) = [methyl salicylate] × 100 [methyl salicylate] + [phenol] (2)
RESULTS AND DISCUSSION

1. TG-DSC analysis

As is described in Fig. 1, TG-DSC analysis was carried out to investigate the thermal stability of Ce(SO₄)₂/001×7.

![TG and DSC curves of Ce(SO₄)₂/001×7.](image)

In the range of 30-100°C, the weight loss may be caused by the physically absorbed water in the catalyst. From 100 to 310°C, the weight loss may be due to the partial carbonization of the resin. By further heating (from 310 up to 510°C), a two-step endothermic process happened. The weight loss between 310 and 420°C may be attributed to the loss of the sulfonic groups and short alkyl groups in resin. The weight from 420 to 510°C was lost in the transformation of Ce(SO₄)₂ into Ce₂O₃(SO₄)₂ and SO₃. From 510-700°C, the decomposition of styrene-divinylbenzene copolymer took place, and finally Ce₂O₃(SO₄)₂ turned into CeO₂ and SO₃.

2. SEM-EDS analysis

SEM photomicrographs of 001×7 and Ce(SO₄)₂/001×7 are presented in Fig. 2 and Fig. 3. EDS analysis is carried out on fresh Ce(SO₄)₂/001×7 in the SEM equipped with EDS (Fig. 3d).

![SEM photomicrographs of the surface of the catalysts: (a) resin 001×7, (b) fresh Ce(SO₄)₂/001×7, and (c) Ce(SO₄)₂/001×7 after the first recycling reaction. Magnification: 150.](image)
As is shown in Fig. 2 and Fig. 3, SEM photographs are under the magnification of 150 and 5000, respectively. In Fig. 2a, the surface of resin 001×7 was smooth like most of gel resins. After the introduction of Ce(SO₄)₂, the surface of Ce(SO₄)₂/001×7 (Fig. 2b) changed obviously in comparison to 001×7. At high magnifications, the surface of Ce(SO₄)₂/001×7 (Fig. 3b) was rough, whereas the surface of 001×7 (Fig. 3a) was relatively plain. Compared with Fig. 2b and Fig. 3b, Fig. 2c and Fig. 3c showed that there were no obvious changes on the surface of Ce(SO₄)₂/001×7 after esterification reaction. EDS analysis also indicated Ce(SO₄)₂ existed on the surface of the resin. The Na signal in the EDS was from the rudimental sodium ion in the resin after pretreatment, and the Au was sprayed when preparing the sample (Fig. 3d).

3. Effect of different reaction systems

As could be indicated in Table 1, cerium sulfate was effective for the esterification of salicylic acid. It was clear that catalytic performance of the resin was obviously improved after modified with Ce(SO₄)₂ and Ce(SO₄)₂/001×7 was relatively active. With the incorporation of Ce(SO₄)₂, the total acid sites of the catalysts greatly increased and the catalytic activity could be effectively enhanced. Besides, the selectivity for methyl salicylate was more than 99.0%, which was closely related to the strong acid strength and the distribution of the catalyst. Ce(SO₄)₂/001×7 was used as a typical catalyst to obtain the optimal reaction parameters for the synthesis of methyl salicylate.

Table 1: Effect of different esterification systems

<table>
<thead>
<tr>
<th>Entry</th>
<th>Type of resin</th>
<th>SA conversion of different esterification systems (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modified with Ce(SO₄)₂</td>
<td>Without Ce(SO₄)₂</td>
</tr>
<tr>
<td>1</td>
<td>001×7</td>
<td>93.3</td>
</tr>
<tr>
<td>2</td>
<td>D061</td>
<td>90.6</td>
</tr>
<tr>
<td>3</td>
<td>D001-cc</td>
<td>88.2</td>
</tr>
<tr>
<td>4</td>
<td>D72</td>
<td>81.4</td>
</tr>
<tr>
<td>5</td>
<td>NKC-9</td>
<td>83.5</td>
</tr>
</tbody>
</table>

* Reaction conditions: molar ratio of SA to methanol, 1:3; temperature, 368 K; time, 12 h; catalyst weight, 0.4 g.

4. Optimization of reaction conditions

The esterification reaction was carried out using different molar ratios of salicylic acid (SA) to methanol varied from 1:2 to 1:6 under the same reaction condition (Fig. 4). When the molar ratio reached a critical value (1:3), the conversion of SA for the catalyst Ce(SO₄)₂/001×7 was at the top level 93.3%. In the case of Ce(SO₄)₂/D061 and Ce(SO₄)₂/D001-cc, for the same molar ratio from 1:2 to 1:6, the conversion levels were lower than that of Ce(SO₄)₂/001×7. The selectivity for methyl salicylate in all cases remained above 99.0%.

Figure 3 SEM photomicrographs of the surface of the catalysts: (a) resin 001×7, (b) fresh Ce(SO₄)₂/001×7, (c) Ce(SO₄)₂/001×7 after the first recycling reaction, and (d) EDS of fresh Ce(SO₄)₂/001×7. Magnification: 5000.

Figure 4 Esterification of salicylic acid with methanol, effect of molar ratio of salicylic acid to methanol. Reaction conditions: catalyst weight, 0.4 g; time, 12 h; temperature, 368 K.

In Fig. 5, the esterification reaction was executed with different amounts of Ce(SO₄)₂/001×7 under the same reaction condition. As the amount of the catalyst increased from 0.1 g to 0.5 g, the conversion of SA was improved from 46.7% to 94.1%. This could be attributed to the number of Lewis acid sites increasing as the catalyst amount increased. When the catalyst concentration exceeded 0.4 g, the increase of SA conversion was not obvious. In all cases, the selectivity for methyl salicylate was more than 99.0%.

Figure 5 Esterification of salicylic acid with methanol, effect of catalyst weight. Reaction conditions: molar ratio of SA to methanol, 1:3; reaction time, 12 h; reaction temperature, 368 K.

As is shown from Fig. 6, the esterification system composed of salicylic acid (SA), methanol and the catalyst Ce(SO₄)₂/001×7 was used to research the influence of various reaction time and temperatures. The conversion of SA increased at different temperatures with the increase of time. For instance, the conversion of SA at 368 K increased from 75.1% to 93.8% when reaction time reached 14 h. Besides, the results displayed that the reaction activity was the best at 368 K for 12 h, and the conversion of SA could reach 93.3%. However, at 373 K and 363 K, it only got to 91.5% and 87.7%, respectively.
From the above study, the suitable condition for the reaction could be found as follows: molar ratio of SA to methanol, 1:3; temperature, 368 K; time, 12 h; catalyst weight, 0.4 g. The selectivity for methyl salicylate in all cases remained above 99.0%.

5. Esterification of different alcohols catalyzed by Ce(SO$_4$)$_2$/001×7

Data in Table 2 illustrated the catalytic performance of Ce(SO$_4$)$_2$/001×7 in the esterification of salicylic acid with methanol and other kinds of alcohols under the same condition. For methanol, the SA conversion was the highest, 93.3%. Besides, the SA conversions for ethanol, butanol, pentanol, hexanol, and octanol were much lower, which were 71.5%, 70.6%, 46.0%, 61.3%, and 46.0%, respectively. These results showed that the SA conversion of alcohols was related to the length of carbon chain and the dielectric constant$^{31}$. Alcohols with shorter carbon chain gave higher conversion. It was due to the increase of steric hindrance when the carbon chain grew longer. This would hinder the esterification reaction to the direction of ester formation. The dielectric constant indicated how easy a material could be polarized by imposition of an electric field on an insulating material. The dielectric constants of methanol, ethanol, butanol, pentanol, hexanol, and octanol were 33.0, 25.3, 17.8, 13.9, 13.3, and 8.1 at room temperature respectively$^{32}$. Alcohols with higher dielectric constant gave higher SA conversion. Hence, the length of carbon chain and the dielectric constant may have synergistically effect on the esterification of salicylic acid.

### Table 2 Esterification of different alcohols catalyzed by Ce(SO$_4$)$_2$/001×7

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alcohol</th>
<th>Conversion (%)</th>
<th>Selectivity (%)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Methanol</td>
<td>93.3</td>
<td>99.9</td>
</tr>
<tr>
<td>2</td>
<td>Ethanol</td>
<td>71.5</td>
<td>99.9</td>
</tr>
<tr>
<td>3</td>
<td>Butanol</td>
<td>70.6</td>
<td>90.1</td>
</tr>
<tr>
<td>4</td>
<td>Pentanol</td>
<td>46.0</td>
<td>99.9</td>
</tr>
<tr>
<td>5</td>
<td>Hexanol</td>
<td>61.3</td>
<td>99.4</td>
</tr>
<tr>
<td>6</td>
<td>Octanol</td>
<td>46.0</td>
<td>91.8</td>
</tr>
</tbody>
</table>

$^a$ Reaction conditions: molar ratio of SA to alcohol, 1:3; temperature, 368 K; time, 12 h; catalyst weight, 0.4 g.

$^b$ Selectivity for esters (base on salicylic acid).

6. Recycling capability of Ce(SO$_4$)$_2$/001×7

The reusability of Ce(SO$_4$)$_2$/001×7 was examined using salicylic acid and methanol as model substrates. After reaction, Ce(SO$_4$)$_2$/001×7 was readily separated and washed with diethyl ether for three times. After removal of water at 80°C for 6 h, it could be directly used for the next cycle. As is shown in Fig. 7, the conversion of SA decreased from 93.3% to 80.0% after reusing for 5 times. The decrease of the reusability may be attributed to the swelling effect of the resin and the loss of active sites after reaction$^{33}$. Besides, the selectivity for methyl salicylate of all cases was more than 99.0%.

7. Mechanism of the esterification system

The esterification of salicylic acid with methanol is a nucleophilic substitution. This reaction was so slow that it needed to be activated by high temperature or a catalyst to facilitate the overall reaction$^{34, 35}$. A possible mechanism of methyl salicylate formation was illustrated in Scheme 1, which involved the nucleophilic attack by methanol on carboxyl$^{27}$. The observed activity could be explained as follows: On the surface of the resin, SA was absorbed and activated on the acid sites by its carbonyl oxygen, and then the formation of methanol attacking the unstabilizing cationic intermediate took place. After electron transfer reaction happened, the reaction product methyl salicylate could be obtained.
CONCLUSION

From the detailed studies on the esterification of salicylic acid with methanol, the following conclusion could be derived. A series of Ce–modified cation-exchange resins were successfully synthesized and showed high selectivity for methyl salicylate through the esterification of the –COOH group of salicylic acid while the –OH group remaining nearly unreacted. With the incorporation of Ce(SO$_4$)$_2$, the catalytic activity of the cation-exchange resins were greatly improved. Besides, the optimal reaction parameters for the synthesis of methyl salicylate were obtained. A mechanism that involved salicylic acid being activated on acid sites via its carbonyl oxygen and nucleophilic attack by methanol on the carboxyl atom was proposed.

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REFERENCES
