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Cooperation of Brønsted and Lewis acid sites
☆ Excellent activity   ☆ Low active energy (33.6 kJ/mol)
☆ Low toxicity    ☆ Easy separation    ☆ Recyclable

\[
\begin{align*}
\text{SO}_3^{2-} & \quad 1/2\text{Zn}^{2+} \\
\text{N} & \quad \text{SO}_3^{2-} \\
\text{OH} & \quad \text{Methanol} \\
\rightarrow & \quad \text{Yield ca. 95%}
\end{align*}
\]
Syntheses of novel halogen-free Brønsted-Lewis acidic ionic liquid catalysts and their applications for synthesis of methyl caprylate

Xiao-Xiang Han,*a Huan Du,a Chin-Te Hung,b Li-Li Liu,b Pei-Hao Wu,b Da-Hai Ren,c Shing-Jong Huangd and Shang-Bin Liu*

A series of benign halogen-free ionic liquid (IL) catalysts were synthesized by combining the Brønsted acidic ionic liquid [HSO₃-pmim]HSO₄ with ZnO in different composition ratios. The IL catalysts, which possess both Brønsted and Lewis acidity, were employed as acidic catalysts for esterification of n-caprylic acid to methyl caprylate. The [HSO₃-pmim]((½Zn²⁺)SO₄)²⁻, prepared by cooperating equimolar amount of Brønsted and Lewis acid sites, was found to exhibit an optimal catalytic performance and excellent durability. This is attributed to a synergy of Brønsted and Lewis acidity manifested by the catalyst. The response surface methodology (RSM) based on the Box-Behnken design (BBD) was utilized to explore the effects of different experimental variables (viz. catalyst amount, methanol to caprylic acid molar ratio, temperature, and reaction time) on esterification reaction. Analysis of variance (ANOVA) was also employed to study interactions between variables and their effects on the catalytic process. Accordingly, the deduced optimal reaction conditions led to a high methyl caprylate yield of 95.4%, in good agreement with experimental results and that predicted by the BBD model. Moreover, a kinetic study performed under optimal reaction conditions revealed an apparent reaction order of 1.70 and active energy of 33.66 kJ/mol.

Introduction

Esterification of alcohols and carboxylic acids are fundamental and important reactions in organic synthesis. The corresponding products, carboxylic esters, have been extensively applied in areas such as cosmetics, plastics, food, medicine and intermediates. Conventionally, syntheses of carboxylic esters mostly invoke homogeneous catalysts, such as sulfuric, p-toluene sulfonic, and phosphoric acids. However, problems caused by these catalysts are not in conformity with the requirements of sustainable development, e.g., equipment corrosion, environmental pollution, undesirable side reactions, plague catalyst recovery and reuse. To avoid these drawbacks, heterogeneous catalysts such as solid super acids, heteropolyacids, zeolites, resins and enzymes have been employed for esterification. Unfortunately, limited applications were found for these solid catalysts due to the disadvantages such as low activity, easy deactivation, formidable separation and recovery and so on. Hence, it is essential to develop environmental benign catalysts to replace the aforementioned catalysts.

Ionic liquids (ILs), which have been considered as new eco-friendly catalysts, have received considerable attention in various chemical syntheses owing to their unique characteristics such as low melting point, high thermal stability, negligible volatility, easy solubility, adjustable properties, recyclability, and reusability. Acidic ILs may be classified into Brønsted 18-28 and Lewis types 29,30 in accordance with their acidic groups. While various Brønsted-Lewis acidic ILs (B-L AILs) have been extensively developed and applied, 11,12 the most common types, which invoke incorporation of metal halides, are moisture-sensitive and hence are inapplicable for aqueous systems. To overcome this problem, efforts have been made in preparing halogen-free B-L AILs using copper oxide as the source of Lewis acidity. 31 Herein, we report a series of novel halogen-free B-L AIL catalysts synthesized by combining Brønsted acidic IL [HSO₃-pmim]HSO₄ with varied amount of ZnO as precursor for Lewis acidity. The acid catalysts so fabricated were characterized by a variety of different analytical and spectroscopic techniques, such as thermogravimetric analysis (TGA), Fourier transform infrared (FT-IR), and ¹H and ¹³C nuclear magnetic resonance (NMR) spectroscopy. Moreover, the acidic properties of these B-L AILs were investigated by solid-state ¹³P magic-angle spinning (MAS) NMR of adsorbed trimethylphosphine oxide (TMPO) as the probe molecule. 34-36 The catalytic activities of these B-L AILs during esterification of caprylic acid with methanol were investigated and relevant reaction conditions invoked during the synthesis of methyl caprylate were optimized using the response

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*a Department of Applied Chemistry, Zhejiang Gongshang University, Hangzhou, 310035, China. Tel.: +86-571-28008975; E-mail: hxx74@126.com
b Institute of Atomic and Molecular Sciences, Academic Sinica, Taipei 10617, Taiwan. Tel.: +886-2-23668230; E-mail: sblue@sinica.edu.tw
c Department of Chemical & Biomolecular Engineering, Clarkson University, Potsdam, New York 13699-5705, USA
d Instrumentation Center, National Taiwan University, Taipei 10617, Taiwan

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surface methodology (RSM). The effects and correlations of different experimental variables such as catalyst amount, methanol to caprylic acid molar ratio, temperature, and reaction time on the esterification reaction were addressed by the Box-Behnken design (BBD) model, followed by a kinetic study performed under these optimized experimental parameters.

**Experimental**

**Catalyst preparation**

The novel B-L AIL catalysts were synthesized by combining sulfonylic acid-functionalized Brønsted acidic ionic liquid [HSO₃⁻][HSO₄], [HSO₃⁻][½Zn²⁺]SO₄, [HSO₃⁻][½Zn²⁺][½H⁺]SO₃-pmim, [HSO₃⁻][½Zn²⁺][½H⁺]SO₄-pmim, [½Zn²⁺]SO₃-pmim, [½Zn²⁺]SO₄-pmim, [½Zn²⁺]SO₃, and [½Zn²⁺]SO₄, denoted as ILa, ILb, ILC, ILd, and ILC, respectively, as specified in Table 1.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>L/B (%)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILa</td>
<td>0.4</td>
<td>92.0</td>
</tr>
<tr>
<td>ILb</td>
<td>1.3</td>
<td>93.0</td>
</tr>
<tr>
<td>ILC</td>
<td>2.2</td>
<td>94.8</td>
</tr>
<tr>
<td>ILd</td>
<td>3.1</td>
<td>86.7</td>
</tr>
<tr>
<td>ILE</td>
<td>4.0</td>
<td>22.1</td>
</tr>
</tbody>
</table>

The reaction conditions: catalyst amount = 6 wt%, methanol/caprylic acid molar ratio = 5.0, reaction time = 3.0 h, and temperature = 363 K.

**Conversion = (1 - a1/2a2) x 100%**

**Esterification reaction**

n-Caprylic acid (0.1 mol), a desirable amount of methanol, and a known amount of the AIL catalyst were placed into a three-necked flask equipped with a mechanical stirrer, reflux condenser, and a drop funnel containing microporous 3A molecular sieves to absorb water produced from esterification. The esterification of n-caprylic acid with methanol was first carried out at different temperatures for a desired period of time, then, the reaction mixture was cooled to RT. Typically, owing to the self-separation characteristics of the reaction system, the reaction mixture tends to spontaneously separate into two layers. The upper layer was extracted by distillation to obtain the methyl caprylate product, and the lower layer consisting of AIL catalyst was reused after further treatment.

**Design of experiments and response surface methodology**

Response surface methodology (RSM) was employed to obtain optimal experimental conditions for esterification of caprylic acid with methanol. A Box-Behnken design (BBD) was applied to study the effects of three process variables, namely amount of catalyst (x₁), methanol to caprylic acid molar ratio (x₂), and reaction time (x₃), as specified in Table 2. A total of 17 experimental sets, which included 12 factorial points and 5 centring points, were adopted. The three experimental variables were designed at three levels coded with a plus signs (+1; high value), zero (0; central value), or a minus signs (-1; low value).

The coded values of these factors were obtained by the equation:

\[ x_i = \frac{x_i - X_0}{A X_0} \]  

where \( x_i \), \( X_0 \), and \( A X_0 \) (i = 1–3) represents the coded, real, and central value of the independent variable, respectively, and \( A X_0 \) = (variable at high level - variable at low level)/2, which denotes the step change value.

**Table 1** Characteristics of various acidic IL catalyst and their catalytic performances during esterification of caprylic acid with methanol

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>L/B (%)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILa</td>
<td>[HSO₃⁻][HSO₄]</td>
<td>0.4</td>
<td>92.0</td>
</tr>
<tr>
<td>ILb</td>
<td>[HSO₃⁻][½Zn²⁺]SO₄</td>
<td>1.3</td>
<td>93.0</td>
</tr>
<tr>
<td>ILC</td>
<td>[½Zn²⁺][½H⁺]SO₄-pmim</td>
<td>2.2</td>
<td>94.8</td>
</tr>
<tr>
<td>ILd</td>
<td>[½Zn²⁺][½H⁺]SO₃-pmim</td>
<td>3.1</td>
<td>86.7</td>
</tr>
<tr>
<td>ILE</td>
<td>[½Zn²⁺]SO₃-pmim</td>
<td>4.0</td>
<td>22.1</td>
</tr>
</tbody>
</table>

**Table 2** List of symbols and coded levels for corresponding experimental variables and ranges adopted for the esterification process

<table>
<thead>
<tr>
<th>Variable (unit)</th>
<th>Symbol</th>
<th>Range and level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst amount (wt%)</td>
<td>x₁</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>Methanol/caprylic acid ratio (mol/mol)</td>
<td>x₂</td>
<td>2.5 5.0 7.5</td>
</tr>
<tr>
<td>Reaction time (h)</td>
<td>x₃</td>
<td>1.5 2.0 2.5</td>
</tr>
</tbody>
</table>

*Over the [HSO₃⁻][½Zn²⁺]SO₄ catalyst at 363 K.*
A model equation based on quadratic polynomial given by RSM was used to reveal interactive effects between experimental variables, to optimize the reaction process, and to predict the yield of the product (i.e., methyl caprylate). The model equation may be expressed as:

\[ Y = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ij} x_i x_j + \sum_{i=1}^{3} \beta_{ijk} x_i x_j x_k \]  

(3)

where \( Y \) is the predicted response (i.e., product yield), \( x_i \) and \( x_j \) are the coded levels of the independent variables, \( \beta_0, \beta_i, \beta_{ij}, \) and \( \beta_{ijk} \) denote the regression coefficient representing the offset, linear, quadratic, and interaction term, respectively. A Design-Expert 6.0.5 software (Stat-Ease, USA) was used to analyze the experimental data, to perform analysis of variance (ANOVA), and to evaluate the regression equation. Accordingly, the fitted polynomial equation may further be expressed in terms of response surface and contour plots to facilitate visualization of the correlations between the response and experimental variables at various coded levels, and to infer optimized process conditions. The coefficient of determination (R2) may be used to evaluate the accuracy and applicability of the second order multiple regression model. The significance of its regression coefficient was checked with the F-test value.

Kinetic study

The reaction rate (\( r \)) for esterification of \( n \)-caprylic acid to methyl caprylate may be expressed as:

\[ r = -\frac{dC_A}{dt} = k_A C_A^{\alpha} C_B^{\beta} - k_{-} C_C^{\gamma} C_D^{\eta} \]  

(4)

where \( C_A, C_B, C_C, \) and \( C_D \) represent the instant concentration of \( n \)-caprylic acid, methanol, methyl caprylate, and water, respectively, while \( \alpha, \beta, \gamma, \) and \( \eta \) denote their corresponding reaction order. Whereas \( k_A \) and \( k_{-} \) account for the rate constants associated with the forward and inverse reaction, respectively.

Given that water had been effectively removed by microporous 3A zeolite adsorbent during esterification reaction, the reaction could be considered as an irreversible process. In this context, the second term associated with inverse process in Eq. (4) may be ignored. Moreover, since the concentration of methanol is always much higher than that of \( n \)-caprylic acid, \( k_A C_B^{\beta} \) in Eq. (4) could be deemed as constant, leading to a simplified rate equation:

\[ r = -\frac{dC_A}{dt} = k A C_A^{\alpha} \]  

(5)

where \( k = k_A C_B^{\beta} \) refers to the modified rate constant. By taking the natural logarithm, Eq. (5) may further be expressed as:

\[ \ln r = \ln k + \alpha \ln C_A \]  

(6)

The values of \( k \) and \( \alpha \) at different temperatures may therefore be obtained easily by linear fitting of the ln \( r \) vs ln \( C_A \) curve using the Origin 8.5 software.

It is well-known that the variation of reaction rate with temperature may be expressed by the Arrhenius equation as:

\[ \ln k = \ln k_0 - \frac{E_A}{RT} \]  

(7)

Thus, the activation energy (\( E_A \)) and pre-exponential factor (\( k_0 \)) may be derived from the slope and intercept of the Arrhenius (\( k \) vs 1/T) plot.

Results and discussion

Catalyst characterization

Similar 1H and 13C NMR spectra were observed for various B-L AIL catalysts. As an example, the NMR data obtained from [HSO3-pmim]+[(½Zn2+)SO4]2- (i.e., ILc) catalyst having equimolar amount of Bronsted and Lewis acid sites are depicted below: 1H NMR (500 MHz, D2O) \( \delta \) 2.31 (m, 2H), 2.91 (t, 2H), 3.89 (s, 3H), 4.36 (t, 2H), 7.44 (s, 1H), 7.51 (s, 1H), 8.74 (s, 1H) ppm; 13C NMR (500 MHz, D2O) \( \delta \) 27.57, 38.20, 49.69, 50.21, 124.68, 126.26, 138.68 ppm.

Fig. 1 displays the FT-IR spectra of various IL catalysts specified in Table 1. In spite of the marginal variations in peak intensities and peak positions, distinct characteristic vibrational bands responsible for Bronsted acidic IL [HSO3-pmim]+[HSO4-] were observed before (ILa) and after substitution of protons (H+) with Zn2+ cations. The absorption peaks at 1638 and 1573 cm\(^{-1}\) may be attributed to the stretching vibrations of C=C and C=N bonds on the imidazole ring, respectively. The peak at 2930 cm\(^{-1}\) should be associated with asymmetric stretching vibration of –CH\(_3\) and the bonds at 1460 and 748 cm\(^{-1}\) may be assigned to bending and rocking vibrations of =CH\(_3\), respectively. Whereas the strong absorption bonds at 1080 and 1045 cm\(^{-1}\) may be attributed to the asymmetric and symmetric stretching vibrations of S=O, respectively. Moreover, a notable decrease in peak intensity of the band responsible for =OH vibration at 3400 cm\(^{-1}\) with increasing substitution of H+ with Zn2+ ions (i.e., increasing L/B ratio in Table 1) was observed, revealing the progressive incorporation of Lewis acidity onto the pristine Bronsted acidic (ILa) catalyst.41,42

TGA-DTG analyses were performed to investigate thermal stability of various AIL catalysts. Since similar TGA-DTG profiles were observed for most B-L AIL catalysts over the temperature range from RT to 873 K, only assorted TGA-DTG results obtained from the zwitterion 1-sulfonicacidpropyl-3-methylimidazolium (MIMPS), Bronsted acidic ILa ([HSO3-...
on ILb and ILc, corresponding to single broad resonance peak was observed for TMPO adsorbed also accompanied by a gradual decrease in become broaden due to consistent increase in viscosity. This is attributed to the presence of Lewis acidity. Thus, we assign and Ile, among them, the peak in the vicinity of 63 ppm may be attributed to desorption of physisorbed water, while the second weight-loss peak was observed at 625 K, corresponding to the decomposition of the organic MIMPS (Fig. 2a). By comparison, the TGA-DTG profile of [HSO3-pmim]+(½Zn2+)SO4 catalyst, an initial weight loss occurred at 356 K (Fig. 2b), which may be attributed to desorption of physisorbed water, while the second weight-loss peak was observed at 625 K, corresponding to the decomposition of the organic MIMPS (Fig. 2a). By comparison, the TGA-DTG profile of [HSO3-pmim]+(½Zn2+)SO4 - (i.e., ILc) shown in Fig. 2c revealed two major weight-loss peaks at 333 and 636 K. Thus, the acidic ILC catalyst appeared to be thermally more stable than ILa after incorporating Lewis acidity. It is noteworthy that these novel B-L AILs (such as [HSO3-pmim]+(½Zn2+)SO4) retain their structural integrity over the range of reaction temperatures (323–363 K) examined.

Solid-state 31P MAS NMR of adsorbed TMPO has been proven to be a feasible and powerful approach for characterization of acid properties of solid acid catalysts. The base TMPO probe molecule tends to interact with the acidic proton to form TMPOH+ complex. It has been demonstrated that a linear correlation between the observed 31P NMR chemical shift (δ31P) and acidic strength of Brønsted acidity may be inferred by means of such 31P-TMPO NMR approach. A higher observed δ31P value of the adsorbed TMPO therefore represents stronger acidic strength of the catalyst, and vice versa. Fig. 3 shows 31P NMR spectra of TMPO adsorbed on various catalysts. The 31P spectrum of ILa exhibited a sharp singlet at 86.2 ppm, indicating the sole presence of Brønsted acidity whose average strength is in the proximity of the threshold for superacidity (86 ppm). It is indicative that the parent [HSO3-pmim]+HSO4 catalyst indeed possesses ultra-strong Brønsted acidity. Upon progressing incorporation of Lewis metallic center (Zn2+), the 31P resonances become broaden due to consistent increase in viscosity. This is also accompanied by a gradual decrease in δ31P. For example, a single broad resonance peak was observed for TMPO adsorbed on ILb and Ile, corresponding to δ31P of 81 and 77 ppm, respectively. Clearly, Brønsted acidity becomes weaker as more H+ are being substituted by the Zn2+ ion, creating Lewis acidity. On the other hand, multiple resonances were observed for ILd and Ile, among them, the peak in the vicinity of 63 ppm may be attributed to the presence of Lewis acidity. Thus, we assign the two peaks observed for ILd at 77 and 66 ppm due to TMPO adsorbed on Brønsted and Lewis acid sites, respectively. In this context, the broad multiple resonance around 63 ppm in ILc indicates that the AIL mainly manifests Lewis acidity. In terms of viscosity of these AILs, ILa, ILb, and ILc were found to exhibit a linear phase with increasing viscosity, but ILd appeared to be a mixture of liquid with solid, whereas ILc was a solid powder. These results are in line with the δ31P and corresponding linewidths of the adsorbed TMPO in various catalyst substrates.

![Figure 2](image-url)  
Fig. 2 TG-DTG curves of (a) MIMPS, (b) [HSO3-pmim]+HSO4, and (c) [HSO3-pmim]+(½Zn2+)SO4.

![Figure 3](image-url)  
Fig. 3 31P NMR spectra of various acidic IL catalysts: ILa = [HSO3-pmim]+HSO4, ILb = [HSO3-pmim]+(½H+·½Zn2+)SO4, Ile = [HSO3-pmim]+(½Zn2+)SO4, Ild = [(½H+·½Zn2+)·SO3-pmim]+(½Zn2+)SO4, ILc = [(½Zn2+)SO3-pmim]+(½Zn2+)SO4. The asterisks in the spectra denote spinning sidebands.

Role of Brønsted and Lewis acidity on catalytic activity

To explore the effects and correlations of Lewis and Brønsted acid sites on catalytic performance during esterification of n-caprylic acid with methanol. Catalytic activities of various AIL catalysts were attained, as summarized in Table 1. Accordingly, it is indicative that Brønsted acid sites played the primary role than Lewis acidity during catalytic esterification reaction. This may be seen by the notable decreases in conversion and product yield with increasing Lewis acidity. Nevertheless, the ILa catalyst, which solely possesses ultra-strong Brønsted acidity, showed inferior catalytic activity compared to ILb and Ile. This reveals that ultra-strong acidity may be unfavorable for esterification reaction, likely due to the occurrence of acid-catalysed reverse reactions. Interestingly, optimal conversion (94.8%) and methyl caprylate yield (94.3%) were obtained when equimolar Lewis and Brønsted acid sites were incorporated in the AIL (i.e., Ile). On the basis of these results, it is indicative that a synergy of Lewis and Brønsted acid sites manifests the catalytic activity during formation of methyl caprylate over these novel AIL catalysts, particularly when an equimolar amount of both types of acidities was implemented. A possible catalytic mechanism is proposed in Scheme 1. In brief, the Lewis center (Zn2+) may incorporate with...
the oxygen atom in the carbonyl groups, which possess strong electronegativity, to induce interactions between the oxygen in the alcohol hydroxyl group and the carbon atom in the carbonyl group. On the other hand, couplings of Brønsted acidic $\text{H}^+$ with the oxygen atom in the carbonyl group tends to lower the negative charge, hence, is favorable for the release of $\text{Zn}^{2+}$.

\begin{equation}
\text{\text{Scheme 1 Possible mechanism invoked during esterification of n-caprylic acid with methanol over the B-L AIL \([\text{HSO}_4^{-}-\text{pmmim}]\{\%\text{Zn}^{2+}\}\text{SO}_4^{2-}\) catalyst.}
\end{equation}

**Effects of experimental variables on esterification**

Since the \([\text{HSO}_4^{-}-\text{pmmim}]\{\%\text{Zn}^{2+}\}\text{SO}_4^{2-}\) AIL catalyst having the Lewis/Brønsted molar ratio of 1:1 exhibited the best catalytic performance, the ILc catalyst was chosen for further process optimization study. Four important experimental variables, namely the catalyst amount, methanol/n-caprylic acid reactant ratio, reaction time, and temperature, were investigated. Among them, the amount of catalyst used plays a key role during esterification due to its high effectiveness to the whole reaction process. Fig. 4a shows the effect of \([\text{HSO}_4^{-}-\text{pmmim}]\{\%\text{Zn}^{2+}\}\text{SO}_4^{2-}\)-loading on catalytic activity during esterification of n-caprylic acid with methanol. It is noteworthy that while performing the experiments with varied catalyst loading, other experimental parameters were kept constants: methanol/caprylic acid ratio = 5.0, reaction time = 3.0 h, and temperature = 363 K. Accordingly, a consistent increase in both conversion and methyl caprylate yield with increasing amount of catalyst dosage was observed, eventually reaching a respective plateau for conversion (94.8%) and product yield (94.3%) at a reaction time of 3 h and a catalyst loading of 6 wt%. This is likely due to the suitable amount of active moieties desirable for the reaction. However, as the catalyst amount exceeded 6 wt%, the conversion of n-caprylic acid and yield of methyl caprylate retained practically unchanged. This may be attributed to dissolution of the AIL catalyst in the presence of methanol, but the catalyst is practically unsoluble in methyl caprylate. As such, at a prolonged reaction time, as the product ester became the primary component of the reaction mixture, leading to the limited solubility of the catalyst. Thus, in view of the observed high yield of methyl caprylate and the relevant cost effectiveness issue of the process, an optimal catalyst amount of ca. 6 wt% may be inferred.

Regarding to the effect of feeds, Fig. 4b displays the variation of methanol to n-caprylic acid molar ratio on esterification activity. It was found that, as the reactant ratio increased, the initial yield of ester also increased significantly and eventually leveled off at 94.3% when the ratio of methanol to caprylic acid reached 5:1. Since esterification is a reversible reaction, an adequate amount of methanol is required to drive the equilibrium towards formation of methyl caprylate. Meanwhile, the AIL catalyst is highly soluble in methanol, thus, resulted in a homogeneous distribution of catalyst in the reaction mixture to provoke efficient esterification reaction. Nonetheless, as the ratio of methanol to caprylic acid exceeded 5:1, the excessive methanol no longer had decisive impact on the conversion rate and product yield due to dilution of the catalyst in the reaction mixture.

Influence of reaction time and temperature on the esterification was also investigated, as shown in Figs. 4c and 4d. It is evident that the methyl caprylate yield reached ca. 88.9% rapidly during the initial stage (1.0 h), then increased gradually till reaching a maximum of 94.4% at 2.0 h. A marginal decrease in product yield beyond reaction time of 2.0 h was observed, mostly likely due to partial hydrolyzation of methyl caprylate. As for the effect of reaction temperature, the yield of methyl caprylate reached a maximum as the temperature reached 363 K at 2.0 h. However, while water removal by methanol evaporation may be more efficient at higher temperatures, no further increase in n-caprylic acid conversion and product yield was observed above 363 K, likely due to inevitable loss of methanol above its boiling point.

**Process and product optimization**

The factorial experimental design was applied to minimize the waste of catalyst and to reduce the number of cumbersome experiments without significant loss of information. The design of experiments, experimental results, and predicted responses for the esterification of n-caprylic acid with methanol over the \([\text{HSO}_4^{-}-\text{pmmim}]\{\%\text{Zn}^{2+}\}\text{SO}_4^{2-}\) catalyst are summarized in Table 3. No significant difference between experimental results and predicted data can be found. The methyl caprylate yield (Y) may be correlated with independent experimental variables by a quadratic model, which can be expressed as:

\begin{equation}
Y = +94.37 + 2.78x_1 + 8.80x_2 + 3.17x_3 - 2.97x_1^2 - 8.23x_2^2 - 1.88x_3^2 - 0.67x_1x_2 - 1.37x_1x_3 - 1.69x_2x_3
\end{equation}

where $x_1$, $x_2$ and $x_3$ are the coded values respectively representing three experimental variables, namely catalyst amount, molar ratio of alcohol to acid, and reaction time (cf. Table 2).
Table 3 List of experimental design and response values during esterification of n-caprylic acid with methanol over the [HSO₃⁻]SO₄²⁻ catalyst

<table>
<thead>
<tr>
<th>Entry</th>
<th>Variable and level</th>
<th>Methyl caprylate yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x₁ x₂ x₃</td>
<td>Experimental</td>
</tr>
<tr>
<td>1</td>
<td>-1 -1 -1</td>
<td>71.01</td>
</tr>
<tr>
<td>2</td>
<td>1 -1 -1</td>
<td>77.18</td>
</tr>
<tr>
<td>3</td>
<td>-1 1 0</td>
<td>90.51</td>
</tr>
<tr>
<td>4</td>
<td>1 1 0</td>
<td>94.00</td>
</tr>
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</tr>
<tr>
<td>6</td>
<td>1 0 -1</td>
<td>90.93</td>
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<td>15</td>
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<tr>
<td>17</td>
<td>0 0 0</td>
<td>94.89</td>
</tr>
</tbody>
</table>

* Variables and levels specified in Table 2.

Table 4 Estimated regression coefficients and corresponding F- and P-values for methyl caprylate yield.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>Degree of Freedom</th>
<th>Mean square</th>
<th>F-value</th>
<th>P-value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>model</td>
<td>1142.19</td>
<td>9</td>
<td>126.91</td>
<td>309.76</td>
<td>&lt; 0.0001</td>
<td>**</td>
</tr>
<tr>
<td>x₁</td>
<td>61.72</td>
<td>1</td>
<td>61.72</td>
<td>150.63</td>
<td>&lt; 0.0001</td>
<td>**</td>
</tr>
<tr>
<td>x₂</td>
<td>619.34</td>
<td>1</td>
<td>619.34</td>
<td>1511.67</td>
<td>&lt; 0.0001</td>
<td>**</td>
</tr>
<tr>
<td>x₃</td>
<td>80.33</td>
<td>1</td>
<td>80.33</td>
<td>196.06</td>
<td>&lt; 0.0001</td>
<td>**</td>
</tr>
<tr>
<td>x₁²</td>
<td>37.08</td>
<td>1</td>
<td>37.08</td>
<td>90.51</td>
<td>&lt; 0.0001</td>
<td>**</td>
</tr>
<tr>
<td>x₂²</td>
<td>284.86</td>
<td>1</td>
<td>284.86</td>
<td>695.28</td>
<td>&lt; 0.0001</td>
<td>**</td>
</tr>
<tr>
<td>x₃²</td>
<td>14.81</td>
<td>1</td>
<td>14.81</td>
<td>36.14</td>
<td>0.0005</td>
<td>**</td>
</tr>
<tr>
<td>x₁ x₂</td>
<td>1.80</td>
<td>1</td>
<td>1.80</td>
<td>4.38</td>
<td>0.0746</td>
<td></td>
</tr>
<tr>
<td>x₁ x₃</td>
<td>7.45</td>
<td>1</td>
<td>7.45</td>
<td>18.19</td>
<td>0.0037</td>
<td>**</td>
</tr>
<tr>
<td>x₂ x₃</td>
<td>11.46</td>
<td>1</td>
<td>11.46</td>
<td>27.97</td>
<td>0.0011</td>
<td>**</td>
</tr>
<tr>
<td>Residual</td>
<td>2.87</td>
<td>7</td>
<td>0.41</td>
<td></td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>Lack of fit</td>
<td>1.72</td>
<td>3</td>
<td>0.57</td>
<td>2.00</td>
<td>0.2559</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>1.15</td>
<td>4</td>
<td>0.29</td>
<td></td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Cor total</td>
<td>1145.06</td>
<td>16</td>
<td>72.31</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Variables and levels specified in Table 2.

** represents highly significant.

The three dimensional (3-D) response surface and contour plots obtained from the predicted model are shown in Fig. 5. The correlations between methanol/n-caprylic acid molar ratio and catalyst amount at a fixed reaction temperature and time are shown in Figs. 5a and 5d. It is clear that the yield of methyl caprylate rapidly increased to the optimal value with increasing methanol/acid molar ratio, however, no much improvement in the response for the latter over 5:1 was observed. Meanwhile, the yield improved gradually as the amount of catalyst increased but 45 yield decreased slightly thereafter. On the other hand, the yield only changed slightly with the catalyst amount. Nonetheless, the contour plot in Fig. 5e revealed that the interaction between catalyst amount and reaction time played an important role in esterification, as also indicated by the results shown in Table 4. Figs. 5c and 5f illustrate the interaction between reaction time and methanol/caprylic acid molar ratio with respect to the product yield. The yield increased significantly before the methanol/acid molar ratio reached 5:1, but remained practically unchanged beyond this ratio. A slight reduction in ester yield was observed at prolonged reaction time (> 2 h). Again, this is attributed to partial hydrolysis of the methyl caprylate product when the reaction time exceeded its maximum value (2 h). Since esterification is a reversible reaction, the hydrolysis rate of ester would increase with reaction time while the yield of methyl caprylate decreased. The effect of interaction of these two variables was also significant, revealing an ellipse mound shape (Fig. 5e), in good agreement with the ANOVA result (Table 4).
Optimized responses and model verification

Based on RSM results, the mathematical model predicted an optimal methyl caprylate yield of 96.16\% for esterification of n-caprylic acid with methanol over the [HSO3-pmim\]+[½Zn2+]SO4\textsuperscript{2−} AIL catalyst under the following process conditions: x1 = 6.59 wt\% (catalyst amount), x2 = 6.17:1 (methanol/n-caprylic acid molar ratio), and x3 = 2.26 h (reaction time) at a reaction temperature of 363 K. To confirm the validity of the model and optimal process conditions, three additional experiments were conducted in parallel at 363 K with x1 = 7 wt\%, x2 = 6.11, x3 = 2.0 h. Accordingly, methyl caprylate yields of 95.1, 95.5, and 95.7\% were obtained, leading to an average experimental yield of 95.4\%, in good agreement with the predicted value. Thus, it is conclusive that the model was reliable and that the regression equation could truly reflect influence of the three variables on the yield of esterification.

Catalyst recycling

To evaluate the reusability of such B-L AIL catalyst, cyclic experiments were conducted under the same optimal operating conditions obtained above over the [HSO3-pmim\]+[½Zn2+]SO4\textsuperscript{2−} B-L AIL catalyst, additional experiments were conducted with x1 = 7 wt\%, x2 = 6.11, x3 = 2.0 h at different temperatures. During the reaction, ca. 1 mL sample was withdrawn from the mixture for analysis at different time intervals. The variations of instantaneous concentration of n-caprylic acid (C\textsubscript{a}) versus reaction time at five different temperatures (323, 333, 343, 353, and 363 K) are shown in Fig. 6. Accordingly, the instant reaction rate (r) may be estimated by performing differentiation of the decay curve using a software package (Origin 8.5) to employ in the subsequent linear curve fitting to obtain values of k and α in Eq. (6).

Table 5 Stability of the [HSO3-pmim\]+[½Zn2+]SO4\textsuperscript{2−} AIL catalyst during esterification of n-caprylic acid with methanol over the [HSO3-pmim\]+[½Zn2+]SO4\textsuperscript{2−} catalyst (Reaction conditions: x1 = 7 wt\%, x2 = 6:1, x3 = 2 h, and T = 363 K)

<table>
<thead>
<tr>
<th>Recycle time</th>
<th>Conversion (%)</th>
<th>Methyl caprylate yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95.9</td>
<td>95.4</td>
</tr>
<tr>
<td>2</td>
<td>95.6</td>
<td>95.1</td>
</tr>
<tr>
<td>3</td>
<td>95.2</td>
<td>94.6</td>
</tr>
<tr>
<td>4</td>
<td>93.8</td>
<td>93.2</td>
</tr>
<tr>
<td>5</td>
<td>93.0</td>
<td>92.6</td>
</tr>
</tbody>
</table>

Kinetic model

To establish the kinetic model for esterification of n-caprylic acid to methyl caprylate over the [HSO3-pmim\]+[½Zn2+]SO4\textsuperscript{2−} B-L AIL catalyst, additional experiments were conducted with x1 = 7 wt\%, x2 = 6.11, x3 = 2.0 h at different temperatures.

Taking the experiment conducted at 323 K as an example, the plot of ln r versus C\textsubscript{a} fitted Eq. (6) well with a correlation coefficient (R) of 0.9841, as shown in Fig. 7a. Likewise, satisfactory fits were achieved for plots obtained at other temperatures. Accordingly, the k and α value so deduced from various temperatures are summarized in Table 6, from which an average reaction order α of 1.70 was derived for the esterification.
Conclusions

A series of new halogen-free Brønsted-Lewis acidic ionic liquids were synthesized and exploited to catalyse esterification of n-caprylic acid with methanol. The [HSO₄·pmmim][½Zn⁷⁺]SO₄²⁻ catalyst, which exhibited the highest catalytic activity, was employed for process optimization to obtain optimal esterification conditions at a reaction temperature of 363 K, catalyst amount of 7 wt%, methanol/n-caprylic acid molar ratio of 6, reaction time of 2.0 h, leading to a maximum methyl caprylate yield of 95.4%. These optimized experimental values were in good agreement with those predicted by response surface methodology based on the Box-Behnken design model. A reaction order of 1.7 and activation energy of 33.66 kJ/mol was deduced from the kinetic model developed. In addition to superior catalytic activity, the Brønsted-Lewis acidic ionic liquid catalysts reported herein are also advantaged by facile recovery and recycle use without significant loss in catalytic activity. Our results indicate that the novel eco-friendly [HSO₄·pmmim][½Zn⁷⁺]SO₄²⁻ catalyst is a promising substitute for conventional catalyst and of great value in chemical industry.

Acknowledgements

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References


