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Asymmetric Organocatalytic Diels–Alder Reactions on Solid Support

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**Abstract:** Asymmetric organocatalysis on solid support combines the environmental advantages of metal-free catalysts and the ease of operation of solid-supported reagents. Enantioselective organocatalytic Diels–Alder reactions have been demonstrated by two different solid-supported chiral organocatalysts. The catalysts are easy to recover and can be reused. The reactivity of the catalyst can be tuned by changing the solid support.

**Keywords:** asymmetric catalysis; cycloaddition; organocatalysis; solid-phase catalysis

Organocatalytic methods hold considerable promise among novel catalytic asymmetric processes owing to their potential advantages over metal-catalyzed processes: 1) no expensive metals are required to start with, 2) there is no risk of metal leakage into the environment (or the product) and 3) the active catalysts are often easier to study and modify. In addition, effective organocatalysts are very often easily accessible, simple, stable molecules (amino acids, sugar derivatives, peptides or peptidomimetics). Unlike typical metal-catalyzed asymmetric processes, organocatalytic reactions can often be performed in wet solvents and in an aerobic atmosphere. The first examples of asymmetric organocatalysis date back to the proline-catalyzed Hajos–Parrish reaction\[^{[2, b]}\] from the 1970’s and the cinchona-derived organocatalysts\[^{[2, c]}\] from the 1980’s. In recent years, proline catalysis has expanded rapidly to cover asymmetric aldol,\[^{[3, a]}\] Mannich,\[^{[3, b]}\] Michael,\[^{[3, c]}\] Diels–Alder\[^{[3, d]}\] and \(\alpha\)-amination\[^{[3, e]}\] reactions. MacMillan and coworkers,\[^{[3, f]}\] in turn, have demonstrated the utility of chiral imidazolidinones in asymmetric catalytic reactions, such as the Diels–Alder reaction\[^{[3, a, b]}\] 1,3-dipolar cycloaddition,\[^{[4, a]}\] Friedel–Crafts alkylation,\[^{[4, b]}\] and indole alkylation.\[^{[4, c]}\] We envisaged that the advantages of organocatalysis would be best exploited by immobilizing the catalysts on a solid support. In this paper, we present the synthesis of two easily recyclable immobilized organocatalysts and show that they are highly effective in catalytic asymmetric Diels–Alder reactions, affording cycloadducts in up to 99% ee.\[^{[5, a]}\]

We began with the synthesis of the polymer-supported catalyst 5 (Scheme 1). JandaJel\[^{[TM]}\]-NH\(_2\) (1)\[^{[7]}\] was chosen as the solid support due to its compatibility with a wide variety of solvents. Commercially available N-Fmoc-protected (S)-phenylalanine 2 was used for the amide 3 formation.\[^{[6]}\] The formed N-Fmoc-amide 3 was deprotected with 20 wt % piperidine in DMF.\[^{[8]}\] The final catalyst 5 was prepared from the resin bound \(\alpha\)-amino amide 4 by cyclization with 50% acetone in DMF. The product resin 5 was analyzed by Kaiser and chloranil tests.\[^{[8]}\]

We then examined the capacity of our polymer-supported chiral amine catalyst 5 to effect enantioselective Diels–Alder cycloadditions between three different dienes \(6 \rightarrow 8\) and three \(\alpha,\beta\)-unsaturated aldehydes \(9 \rightarrow 11\) (Scheme 2). Cyclopentadiene 6 as the diene component was found to give the best yields (60–73%) with the \(\alpha,\beta\)-unsaturated aldehydes \(9 \rightarrow 11\) tested (Table 1, Entries 1, 3, and 5). Excellent levels of enantioselectivity (83–99% ee) were observed in these...

**Scheme 1.** Preparation of the JandaJel\[^{[TM]}\]-supported organocatalyst 5. Reagents and conditions: a) HOBt, CH\(_2\)Cl\(_2\), DIC, 2.5 h, r.t.; b) 20% piperidine/DMF, 50 min, r.t.; c) 50% acetone/DMF, 20 h, 80 °C. (HOBt = 1-hydroxybenzotriazole hydrate, DIC = diisopropylcarbodiimide).
reactions, equaling or even surpassing those obtained with the corresponding solution phase catalysts.\cite{4a}

As anticipated, catalyst 5 turned out to be easily recoverable. The recycled catalyst could readily be reused: after filtration of the reaction mixture to recover the catalyst, the catalyst was simply treated with a mixture of /C97, /C98-unsaturated aldehyde, diene and the solvent/water mixture to set up another reaction. Addition of acid was not necessary when the recycled catalyst was used. The endo:exo selectivities, enantioselectivities, yields and reaction rates generally remained at similar levels (entries 2, 4, 6 in Table 1 represent experiments with the recovered catalyst). We also found that 5 – 10 mol % of the catalyst 5 was enough to mediate the cycloaddition (entries 2 – 5, 6 and 8).

Probing the scope of the reaction components revealed that with cyclohexa-1,3-diene 7 and isoprene 8, only acrolein 9 was found to afford isolable yields of the cycloaddition products (entries 7 and 8). No reaction was observed with crotonaldehyde 10 and cinnamaldehyde 11 when combined with cyclohexa-1,3-diene 7 and isoprene 8 in the presence of the catalyst 5. We reasoned that the highly polar transition state of the reaction and the iminium ion intermediates\cite{4a} would be better stabilized by a more polar solid support environment, such as silica gel.

Accordingly, as our second catalyst, we prepared the silica-supported\cite{11} chiral imidazolidinone catalyst 21.

Table 1. Enantioselective Diels–Alder cycloadditions catalyzed by JandaJel\textsuperscript{TM}-bound amine catalyst 5.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Diene</th>
<th>Aldehyde</th>
<th>Catalyst [mol %]\textsuperscript{[a]}</th>
<th>t [h]</th>
<th>endo\textsuperscript{[b]} [% ee]</th>
<th>exo\textsuperscript{[b]} [% ee]</th>
<th>Yield [%]\textsuperscript{[c]}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>9</td>
<td>20</td>
<td>24</td>
<td>5.1 (89)</td>
<td>1 (83)</td>
<td>73</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>9</td>
<td>10\textsuperscript{[d]}</td>
<td>24</td>
<td>4.9 (75)</td>
<td>1 (75)</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>24</td>
<td>1.2 (91)</td>
<td>1 (89)</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>10</td>
<td>10\textsuperscript{[d]}</td>
<td>24</td>
<td>1.2 (88)</td>
<td>1 (87)</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>11</td>
<td>20</td>
<td>24</td>
<td>1 (99)</td>
<td>1.2 (99)</td>
<td>70</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>11</td>
<td>10\textsuperscript{[d]}</td>
<td>24</td>
<td>1 (97)</td>
<td>1.2 (95)</td>
<td>65</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>9</td>
<td>20</td>
<td>25</td>
<td>13 (98)</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>9</td>
<td>5</td>
<td>32</td>
<td>(70)</td>
<td>–</td>
<td>24</td>
</tr>
</tbody>
</table>

\textsuperscript{[a]} Calculated based on the amine loading (mmol/g) of the supported catalyst. The loading is based on the original nitrogen loading of the support but a correction has been made for the mass gain of the catalyst during its preparation.

\textsuperscript{[b]} endo:exo ratios were determined by \textsuperscript{1}H NMR from the aldehyde product mixture. For determination of the ee values, the aldehyde products were first reduced to alcohols with excess NaBH\textsubscript{4} in EtOH, and the resulting alcohols were analyzed by GLC using Supelco \textsuperscript{γ}-DEX\textsuperscript{TM} 120 column. Absolute and relative configurations were assigned by chemical correlation to compounds obtained by known solution phase methods\cite{4a,10} or by analogy.

\textsuperscript{[c]} Yields of isolated, purified aldehydes.

\textsuperscript{[d]} Reaction was performed with catalyst recovered from previous run.
(Scheme 3). Starting from N-Fmoc-protected (5)-phenylalanine 2, coupling with \( n \)-propylamine-functionalized silica gel 18\(^{[12]} \) was achieved via the acid chloride 17\(^{[13]} \). The resulting amide 19\(^{[8]} \) was deprotected (20\% piperidine/DMF) and the final catalyst 21 was prepared from the silica bound \( \alpha \)-amino amide 20 by cyclization with 50\% acetone in DMF. The product 21 was analyzed by Kaiser and chloranil tests.\(^{[8]} \)

The silica gel-supported chiral amine 21 turned out to be a highly active catalyst for enantioselective Diels–Alder cycloadditions. For comparison with the polymer-bound catalyst 5, the same set of reactions between dienes 6 – 8 and \( \alpha,\beta \)-unsaturated aldehydes 9 – 11 (Scheme 2) was employed. The catalyst was effective in amounts as low as 3.3 mol\% (entries 1 – 3, Table 2). Significantly, the enantioselectivities remained generally on a high level (90 – 91\% ee, entries 1, 3 – 5) with catalyst 21. However, reaction of cyclopentadiene with crotonaldehyde 10 gave only moderate ee (52\% ee, endo:exo isomer) (entry 2). The endo:exo selectivities with 21 were slightly higher than those obtained with catalyst 5. Catalyst 21 could also be readily recovered by filtration (see the Experimental Section).

The reactivity of the silica-bound catalyst 21, however, differed considerably from the polymer-bound catalyst 5. Most significantly, 21 was highly effective in the cycloaddition between cyclohexa-1,3-diene 7 or isoprene 8 and acrolein 9 (79 – 83\% yield; Table 2, entries 4 and 5), contrasting favorably with catalyst 5. With cyclopentadiene as the diene component, acrolein 9 (entry 1) afforded a better yield (73\%) of the cycloadduct than did crotonaldehyde 10 or cinnamaldehyde 11 (33 – 41\% yield, entries 2 and 3).

The ease with which these solid-supported organocatalytic Diels–Alder reactions can be performed, and the fact that the reactivity of these organocatalysts appears to be quite sensitive to the nature of the solid support, makes these types of catalysts highly amenable to both high-throughput screening and large-scale process development. It should also be noted that all Diels–Alder cycloadditions performed in this study were conducted at room temperature with wet solvents.

In conclusion, we have synthesized polymer- and silica-supported chiral imidazolidinone catalysts 5 and 21, and demonstrated their effectiveness in catalytic enantioselective Diels–Alder reactions. Furthermore, the reactivity of the catalysts can readily be tailored by changing the support medium. The solid-supported organocatalysts are easily recovered by filtration and the catalyst can be directly reused. Further studies to define and expand the scope of support-tailored organocatalysts are in progress, and a full account of this study is forthcoming.

### Experimental Section

#### Preparation of Catalyst 5

Fmoc-Phe-OH 2 (400 mg, 1.03 mmol, 500 mol\% ) and 1-hydroxybenzotriazole hydrate (141 mg, 1.03 mmol, 500 mol\% ) were dissolved in \( \text{CH}_2\text{Cl}_2 \) (4 mL) and DMF (1 mL). Diisopropylcarbodiimide (131 mg, 1.03 mmol, 500 mol\% ) was dissolved in DMF (1 mL) and added into the reaction mixture. The resulting mixture was stirred for 10 minutes, and then transferred to a flask containing JandaJel\(^{[4]}\)-NH\(_2\) 1 (1 mmol N/g; 206 mg, 0.21 mmol, 100 mol\% ) and \( \text{CH}_2\text{Cl}_2 \) (4 mL). The stirring was continued for 2.5 hours at room temperature and the product resin 3 was filtered, washed with \( \text{CH}_2\text{Cl}_2 \) (4 × 5 mL), DMF (4 × 4 mL), MeOH (2 × 4 mL) and THF (3 × 2 mL). The whitish product resin 3 was subjected to the Kaiser test\(^{[b]} \) and the result was negative (yellowish beads).

The JandaJel bound amide 3 was treated with 20\% piperidine in DMF (4 mL) and the stirring was continued at r.t. for 50 min. The resulting resin 4 was washed with DMF (4 × 4 mL), MeOH (2 × 4 mL) and THF (3 × 2 mL) and dried in vacuum to give 365 mg of yellowish resin. The product resin 4 was subjected to the Kaiser test\(^{[b]} \) and the result was positive (blue beads).

The JandaJel bound \( \alpha \)-amino amide 4 (365 mg) was treated with DMF (2.5 mL) and acetone (2.5 mL). The mixture was stirred under argon atmosphere at 85 – 90 °C (bath temperature) for 15.5 h. After this time, more acetone (1 mL) and DMF (1 mL) were added. The stirring was continued at 85 – 90 °C for 4.5 h. The reaction mixture was allowed to cool to r.t. and the resulting resin 5 was washed with DMF (4 × 4 mL), MeOH (2 × 4 mL) and THF (3 × 2 mL). The product resin 5 was dried in vacuum to give 273 mg of yellowish resin. Catalyst 5 was subjected to the Kaiser test\(^{[b]} \) and the result was negative.

**Table 2.** Enantioselective Diels–Alder cycloadditions catalyzed by silica-supported amine catalyst 21.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Diene</th>
<th>Aldehyde</th>
<th>Catalyst [mol %](^{[a]} )</th>
<th>t [h]</th>
<th>endo(^{[b]} ) [% ee]</th>
<th>exo(^{[b]} ) [% ee]</th>
<th>Yield [%](^{[c]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>9</td>
<td>3.3</td>
<td>24</td>
<td>6.6 (91)</td>
<td>1 (-)</td>
<td>73</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>10</td>
<td>3.3</td>
<td>25</td>
<td>2.5 (52)</td>
<td>1 (6)</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>11</td>
<td>3.3</td>
<td>64</td>
<td>1.1 (90)</td>
<td>1 (90)</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>9</td>
<td>20</td>
<td>24</td>
<td>14 (90)</td>
<td>1</td>
<td>83</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>9</td>
<td>20</td>
<td>24</td>
<td>(90)</td>
<td>–</td>
<td>79</td>
</tr>
</tbody>
</table>

\(^{[a]} \) Calculated as described in Table 1.

\(^{[b]} \) The endo:exo selectivities and the ee values were determined as described in Table 1.

\(^{[c]} \) Yields of isolated, purified aldehydes.
subjected to the Kaiser test[8a] and the result was negative in a vacuum to give 397 mg of yellowish resin. Catalyst resulting resin was subjected to the chloranil test [8b] and the result was positive (blue beads).

Preparation of Catalyst 21

A mixture of n-propylamino-functionalized silica gel 18 (0.53 mmol N/g; 400 mg, 0.21 mmol, 100 mol%) and Fmoc-Phe-CI 17 [8c] (260 mg, 0.64 mmol, 305 mol %) was treated with CH2Cl2 (5 mL). The resulting mixture was stirred for 2 minutes and cyclohexa-1,3-diene (5 mL) was added. The reaction mixture was stirred 24 hours at room temperature in a sealed vial. The silica-supported catalyst was filtered off and the filtrate was washed with CH2Cl2 (3 mL). The resulting mixture was stirred for 2 minutes and cyclohexa-1,3-diene (5 mL) and MeOH (3 x 3 mL) and THF (3 x 3 mL). The product resin 21 was dried in vacuum to give 468 mg of white resin. The resulting amide 19 was subjected to the chloranil test [8b] and the result was positive (blue beads).

Silica bound amide 19 (448 mg) was treated with 20% piperidine in DMF (4 mL) and the stirring was continued at room temperature for 60 minutes. The resulting resin 20 was washed with DMF (3 x 4 mL), MeOH (3 x 4 mL) and THF (3 x 3 mL), affording a mass balance of 636 mg of whitish resin. The product resin 20 was subjected to the Kaiser test [8b] and the result was positive (blue beads).

The silica bound α-amino amide 20 (605 mg) was treated with DMF (2 mL) and acetone (2 mL). The mixture was stirred under argon atmosphere at 80–85 °C for 18 hours. After this, a second portion of acetone (1 mL) and DMF (1 mL) was added. The stirring was continued at 80–85 °C for 2 h. The reaction mixture was allowed to cool to room temperature and the resulting resin 21 was washed with DMF (3 x 3 mL), MeOH (3 x 3 mL) and THF (3 x 3 mL). The product resin 21 was dried in a vacuum to give 397 mg of yellowish resin. Catalyst 21 was subjected to the Kaiser test[8b] and the result was negative (brownish beads). Catalyst 21 was also subjected to the chloranil test[8b] and the result was positive (blue beads).

Typical Procedure for the Diels–Alder Cycloaddition (Table 2, entry 5)

The silica-supported catalyst 21 (53 mg, 0.1 mmol, 20 mol %) was treated with CH2CN (2 mL) and 0.4 M aqueous solution of HCl (0.25 mL). The mixture was stirred for 2 minutes and acrolein 9 (100 µL, 1.5 mmol, 300 mol %) was added. The resulting mixture was stirred for 2 minutes and cyclohexa-1,3-diene 7 (50 µL, 0.5 mmol, 100 mol %) was added. The resulting mixture was stirred 24 hours at room temperature in a sealed vial. The catalyst 21 was filtered off and the filtrate was concentrated to a volume of 0.5 mL. The crude product was purified by flash chromatography (silica gel, 5% ether/pentane) to give the product as colorless oil; yield: 56 mg (83%); 90% ee. Analytical data of the product matched those reported in the literature.[10] The enantiomeric excess was determined as follows: A small portion of the aldehyde product mixture was diluted with EtOH (1 mL) and excess NaBH4 was added. The resulting mixture was stirred for 1 h and 5 wt % aqueous citric acid (1 mL) was added to quench the reaction. The reaction mixture was extracted with Et2O (3 x 3 mL) and the organics were washed with brine (3 mL). The combined organics were dried (MgSO4), filtered through a 2 cm pad of silica and concentrated to give the pure alcohols. The ee was determined by GLC (Supelco γ-DEX™ 120 column (30 m x 0.25 mm, 0.25 µm film), He carrier gas, velocity 28 cm/sec, FID detection (300 °C)); for the (R)-endo-cycloadduct t, 10.3 min and for the (S)-endo-cycloadduct t, 10.7 min.

Acknowledgements

Financial support has been provided by the Neste Foundation and the National Technology Agency (TEKES). We also thank Prof. Kyösti Kontturi (HUT) for GC time.

References and Notes


[8] We used the Kaiser\textsuperscript{[8a]} and chloranil\textsuperscript{[8b]} tests to detect the presence of primary and secondary free amines, respectively, for the purposes of monitoring the reactions on solid support. See: a) E. Kaiser, R. L. Colescott, C. D. Bossinger, P. I. Cook, \textit{Anal. Biochem.} 1970, 34, 595 (Kaiser test); b) T. Vojkovsky, \textit{Pept. Res.} 1995, 8, 236 (chloranil test).


[12] The $n$-propylamine loading was 0.53 mmol/g in the silica gel used.


[14] MeOH was also used successfully as the solvent with the catalyst 5. In this case, however, the product aldehydes were converted into their corresponding dimethyl acetics.