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Photoactive bimetallic framework for direct aminoformylation of nitroarenes

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A bimetallic catalyst, AgPd@g-C₃N₄, synthesized by reducing silver and palladium salts over the graphitic carbon nitride (g-C₃N₄), performs concerted reductive formylation of aromatic nitro compounds under photo-chemical conditions using formic acid which serves the dual role as hydrogen source and formylating agent.

Introduction:

The synthesis of amines and their conversion to N-formyl derivatives is an important reaction in organic synthesis due to its extensive application in natural product synthesis and drug discovery. Conventionally, amino-formyl derivatives have been synthesized from nitro compounds in two separate steps involving nitro reduction followed by N-formylation. Most of the earlier developed processes in the reduction of nitro group use stoichiometric amount of reagents. The heightened awareness surrounding climate change and the growing importance of pollution prevention have resulted in the dramatic shift to use catalytic reagents instead. In general, the catalytic variant developed for the reduction of nitro group often requires high hydrogen pressure and elevated temperature; safety being a worrisome concern for high pressure hydrogenation on industrial scale. Alternative protocols have been advanced by employing in-situ generated hydrogen along with a precious metal catalyst. Most of these procedures require vigorous stirring in aqueous media under a carbon monoxide atmosphere; a hazardous and toxic contaminant. Formic acid, available from biomass resources, has been introduced as a safer alternative for the transfer hydrogenation of nitro compounds to generate aryl amines. The formylation of amine has to be carried out subsequently in a separate step. Rutile-supported gold catalyst has achieved such direct conversion of nitro compounds to N-formylamines.

However, this reaction is temperature dependent. At elevated temperatures, it leads to the formation of N, N-demethylation whereas slight variation towards lower side (~ 60 °C) doesn’t allow the formylation of reduced products. In addition, it requires an inert atmosphere along with the use of organic solvents. Magnetically retrievable palladium catalyst has also been used for the conversion of nitro-arenes to the corresponding N-formyl derivatives; complexity of the catalyst preparation and its higher loading are the main limitations of this method. Iron metal in combination with corresponding carboxylic acid has been introduced but the lower product yields and heating over extended period of time renders this an unproductive and tedious method. This prompted us to develop a simple and sustainable catalyst which can accomplish this transformation in aqueous media under ambient conditions. In continuation of our ongoing efforts to develop sustainable methods that aim for reduction in chemical waste generation, we have designed a bimetallic AgPd@g-C₃N₄ photoactive heterogeneous catalyst system for the direct transformation of aromatic nitro compounds to N-formylamines.

Synthesis and characterization

Figure 1 Structure of AgPd@g-C₃N₄
Graphitic carbon nitride (g-C\textsubscript{3}N\textsubscript{4}) was synthesized by heating urea in a furnace at 500 °C and the ensuing pale yellow solid was dispersed in water by sonicating over a period of 15 mins\textsuperscript{12}. The silver and palladium salts (AgNO\textsubscript{3} and Pd(NO\textsubscript{3})\textsubscript{2}) were sequentially added and the reaction mixture was stirred for 12 hours. The reaction temperature was raised to 50 °C and the silver and palladium salts were reduced to Ag(0) and Pd(0) nanoparticles using excess of sodium borohydride (NaBH\textsubscript{4}). The reaction temperature was cooled to ambient temperature, centrifuged and the solid was washed with methanol and vacuum dried at 50 °C. The AgPd@g-C\textsubscript{3}N\textsubscript{4} catalyst (Figure 1) was isolated as a fine solid powder.

The catalyst was characterized using transmission electron microscopy, scanning electron microscope, X-ray photoelectron spectroscopy, X-ray diffraction and Inductive coupled plasma atomic emission spectroscopy (ICP-AES). TEM spectra of the catalyst endorse the formation of single phase silver and palladium nanoparticles with spherical morphology (Figure 2). The SEM image of AgPd@g-C\textsubscript{3}N\textsubscript{4} and its EDX confirm the immobilization of silver (Ag) and palladium (Pd) nanoparticles over the surface of g-C\textsubscript{3}N\textsubscript{4} (Figure 3). The concentration of Ag (4.67%) and Pd (4.55%) were found using ICP-AES analysis. The XPS (Figure 4) analysis of AgPd@g-C\textsubscript{3}N\textsubscript{4} corroborated the formation of palladium and silver nanoparticles on the surface of graphitic carbon nitride (Figure 3) which was further supported by XRD (Figure 5).

**Result and discussion**

The most important step in the development of the active catalyst was the design and synthesis of catalytic system for the direct conversion of nitro compounds to N-formylamine derivatives, preferably using visible light to derive this reaction. In view of the known prowess of graphitic carbon nitride (g-C\textsubscript{3}N\textsubscript{4}) as a photo active support,\textsuperscript{13} we pursued this approach using formic acid as the source as well as a formylating agent in presence of bimetallic catalyst.

First, Pd (10 mol %) was immobilized on g-C\textsubscript{3}N\textsubscript{4} and tested for the aqueous reductive formylation of the nitro group using formic acid as an hydrogent source; the formation of 47% of desired product after 12 hours of exposure to visible light (Table, entry 1) was encouraging. Increasing palladium load (Table 1, entry 2) did not improve catalytic activity whereas low-loading decreased the yield to 30% (Table 1, entry 3). These results suggested that the Pd@g-C\textsubscript{3}N\textsubscript{4} was not sufficiently active to accomplish this transformation. We sought to enhance its activity by adding a catalytic promoter, preferably an abundant material such as copper. Consequently, copper-palladium CuPd@g-C\textsubscript{3}N\textsubscript{4} catalysts were synthesized and used which afforded higher yields (65%) of the desired product (Table 1, entry 4). Various amounts of copper and palladium loadings were next examined (Table 1, entries 5-6). The CuPd@g-C\textsubscript{3}N\textsubscript{4} catalyst with 10% Cu and 5% Pd (Table 1, entry 5) gave the desired product in 55% yield, whereas CuPd@g-C\textsubscript{3}N\textsubscript{4} catalyst with 5% Cu and 10% Pd gave 69% of
product. A recent report on the use of Ag-Pd system on an ultrathin support,\textsuperscript{14} encouraged us to explore the use of silver as co-catalyst partner, and therefore we synthesized AgPd@g-C\textsubscript{3}N\textsubscript{4} framework. The reaction of nitrobenzene with formic acid in the presence of bimetallic AgPd@g-C\textsubscript{3}N\textsubscript{4} gave a quantitative yield of N-formyl aniline (Table 1, entry 7, 2 h). The variation in Ag and Pd concentration in the catalyst played a crucial role in the reductive formylation of the nitro group. The catalyst with 10% Ag and 5% Pd loading required 5 h for the completion of reaction (Table 1, entry 8). On the other hand, the catalyst system comprising 5% Ag and 10% Pd gave a quantitative yield of the desired product within 2 h (Table 1, entry 9). Further reduction in silver concentration led to an increase in reaction time and decrease in the product yield (Table 1, entry 10). The reaction with silver alone, Ag@g-C\textsubscript{3}N\textsubscript{4}, did not show any evidence of reductive formylation product even after 24 hours (Table 1, entry 11).

After establishing the ideal reaction conditions for the catalyst, it was imperative to evaluate the performance of AgPd@g-C\textsubscript{3}N\textsubscript{4} with a wide variety of substrates. Accordingly, an array of nitro derivatives were subjected to reductive formylation reaction (Table 2, entries 1-9); all the substrates bearing electron donating (Table 2, entries 2-3) and electron withdrawing substituents (Table 2, entries 4-9) were converted to the corresponding amino formyl derivatives. It was difficult to corroborate the reactivity pattern in line with the nature of the substituents and electronic behavior as most of the reactions were completed within 2 hours.

Table 1 Screening of catalysts for N-formylation

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Time</th>
<th>Yield\textsuperscript{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pd@g-C\textsubscript{3}N\textsubscript{4} (10% Pd)</td>
<td>12 h</td>
<td>48%</td>
</tr>
<tr>
<td>2</td>
<td>Pd@g-C\textsubscript{3}N\textsubscript{4} (20% Pd)</td>
<td>12 h</td>
<td>49%</td>
</tr>
<tr>
<td>3</td>
<td>Pd@g-C\textsubscript{3}N\textsubscript{4} (5% Pd)</td>
<td>12 h</td>
<td>31%</td>
</tr>
<tr>
<td>4</td>
<td>CuPd@g-C\textsubscript{3}N\textsubscript{4} (10% Cu : 10% Pd)</td>
<td>12 h</td>
<td>65%</td>
</tr>
<tr>
<td>5</td>
<td>CuPd@g-C\textsubscript{3}N\textsubscript{4} (10% Cu : 5% Pd)</td>
<td>12 h</td>
<td>55%</td>
</tr>
<tr>
<td>6</td>
<td>CuPd@g-C\textsubscript{3}N\textsubscript{4} (5% Cu : 10% Pd)</td>
<td>12 h</td>
<td>69%</td>
</tr>
<tr>
<td>7</td>
<td>AgPd@g-C\textsubscript{3}N\textsubscript{4} (10% Ag : 10% Pd)</td>
<td>2 h</td>
<td>99%</td>
</tr>
<tr>
<td>8</td>
<td>AgPd@g-C\textsubscript{3}N\textsubscript{4} (10% Ag : 5% Pd)</td>
<td>5 h</td>
<td>88%</td>
</tr>
<tr>
<td>9</td>
<td>AgPd@g-C\textsubscript{3}N\textsubscript{4} (5% Ag : 10% Pd)</td>
<td>2 h</td>
<td>99%</td>
</tr>
<tr>
<td>10</td>
<td>AgPd@g-C\textsubscript{3}N\textsubscript{4} (2% Ag : 10% Pd)</td>
<td>5 h</td>
<td>85%</td>
</tr>
<tr>
<td>11</td>
<td>Ag@g-C\textsubscript{3}N\textsubscript{4} (10% Ag)</td>
<td>24 h</td>
<td>-</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Reaction conditions: 1 mmol of nitrobenzene; Formic acid (2 mmol); Water (1.0 mL); Catalyst (25 mg); 40 watt domestic bulb; \textsuperscript{b} Isolated yield

The recyclability of the catalyst in terms of practical and sustainable use were established using recycling experiments for the reductive formylation of nitrobenzene. After the completion of the first reaction, AgPd@g-C\textsubscript{3}N\textsubscript{4} was recovered and reused for the reductive formylation of fresh batch of nitrobenzene. AgPd@g-C\textsubscript{3}N\textsubscript{4} was found to be stable and could be reused several times without losing its activity (ESI, S2); even after 6\textsuperscript{th} cycle, the nitrobenzene was efficiently converted into N-formyl aniline. The reactivity and stability of the catalyst could be attributed to the graphitic carbon nitride (g-C\textsubscript{3}N\textsubscript{4}) which holds Ag and Pd nanoparticles tightly. The metal leaching in the AgPd@g-C\textsubscript{3}N\textsubscript{4} catalyst was studied using ICP-AES analysis of the reaction solvent and the recycled catalyst before and after the reaction. The absence of metals in the mother liquor and the percentage of Ag (4.65%) and Pd (4.54%) in recycled catalyst confirmed that g-C\textsubscript{3}N\textsubscript{4} holds the metals tightly. The trifling metal leaching may be attributed to high porosity and polarity of the g-C\textsubscript{3}N\textsubscript{4} support which holds these metals via non-covalent interactions.

Table 2 N-formylation of nitroarenes catalyzed by AgPd@g-C\textsubscript{3}N\textsubscript{4}\textsuperscript{a}

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reactant</th>
<th>Product</th>
<th>Time</th>
<th>Yield\textsuperscript{b}</th>
</tr>
</thead>
</table>
| 1     | \[
\begin{array}{c}
\text{NO}_2 \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{CH}_2 \\
\text{CHO}
\end{array}
\] | 2 h | 99% |
| 2     | \[
\begin{array}{c}
\text{NO}_2 \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{CH}_2 \\
\text{CHO}
\end{array}
\] | 2 h | 98% |
| 3     | \[
\begin{array}{c}
\text{MeO} \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{MeO} \\
\text{CHO}
\end{array}
\] | 2 h | 96% |
| 4     | \[
\begin{array}{c}
\text{Cl} \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{Cl} \\
\text{CHO}
\end{array}
\] | 2 h | 97% |
| 5     | \[
\begin{array}{c}
\text{Br} \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{Br} \\
\text{CHO}
\end{array}
\] | 2 h | 97% |
| 6     | \[
\begin{array}{c}
\text{COOH} \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{COOH} \\
\text{CHO}
\end{array}
\] | 2 h | 96% |
| 7     | \[
\begin{array}{c}
\text{CH}_2 \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{CH}_2 \\
\text{CHO}
\end{array}
\] | 2 h | 97% |
| 8     | \[
\begin{array}{c}
\text{NO}_2 \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{NO}_2 \\
\text{CHO}
\end{array}
\] | 2 h | 97% |
| 9     | \[
\begin{array}{c}
\text{COOH} \\
\text{CHO}
\end{array}
\] | \[
\begin{array}{c}
\text{COOH} \\
\text{CHO}
\end{array}
\] | 2 h | 96% |

\textsuperscript{a} Reaction conditions: Nitroarenes (1 mmol); Formic acid (2 mmol); Water (1.0 mL); Catalyst (25 mg); 40 watt domestic bulb; \textsuperscript{b} Isolated yield

Conclusions

The silver Pd\textsuperscript{N} and palladium were recovered in 76% yield. The synthesis of AgPd@g-C\textsubscript{3}N\textsubscript{4} catalyst was used for the direct amino formylation of aromatic nitro...
group under photochemical condition using visible light as a source of energy and formic acid as a reducing as well as formylating agent. The bimetallic catalyst is highly effective in decomposing formic acid into hydrogen and using it as a formylating agent in a concerted process.

Acknowledgements
RBNB and SV were supported by the Postgraduate Research Program at the National Risk Management Research Laboratory administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the U.S. Environmental Protection Agency.

Disclaimer
The U.S. Environmental Protection Agency, through its Office of Research and Development, funded and managed the research described herein. It has been subjected to the Agency’s administrative review and has been approved for external publication. Any opinions expressed in this paper are those of the author(s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Notes and references
Photoactive bimetallic framework for direct aminoformylation of nitroarenes

A bimetallic catalyst AgPd@g-C₃N₄ on graphitic carbon nitride enables concerted reductive formylation of aromatic nitro compounds under photo-chemical conditions; formic acid serves the dual role as hydrogen source and formylating agent.