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Energy-Efficient Green Catalysis: Supported Gold Nanoparticle-Catalyzed Aminolysis of Esters with Inert Tertiary Amines by C–O and C–N Bond Activations

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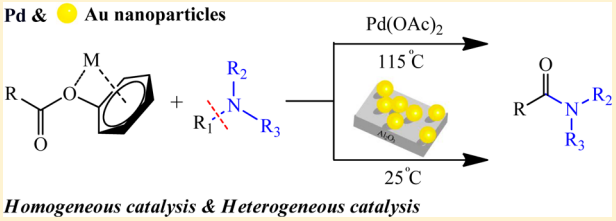
Supporting Information

ABSTRACT: Catalyzed by supported gold nanoparticles, an aminolysis reaction between various aryl esters and inert tertiary amines by C–O and C–N bond activations has been developed for the selective synthesis of tertiary amides. Comparison studies indicated that the gold nanoparticles could perform energy-efficient green catalysis at room temperature, whereas $Pd(OAc)_2$ could not.

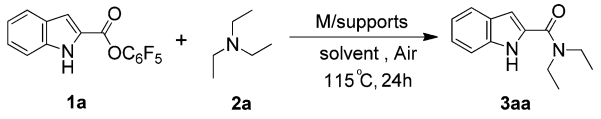


The synthesis of amides under smooth, atom-economical conditions starting from carboxylic acids or esters was recognized as one of the pending challenges for the synthetic chemical and pharmaceutical industries by the American Chemical Society Green Chemistry Institute in 2007. The conventional aminolysis of esters is performed mainly by the reaction between esters and amines under the catalysis of acids or bases. In recent years, main efforts have been devoted to the development of Lewis bases,[1] imidazolylidene carbenes,[2] and anionic nucleophiles[3] as efficient catalysts to improve the aminolysis of esters with primary or secondary amines. However, to the best of our knowledge, there has been no report on the selective aminolysis of esters with inert tertiary amines to form tertiary amides via C–N bond activation, although many C–N bond activation reactions of tertiary amines have been reported.[4]

We recently developed the $Pd(OAc)_2$-catalyzed aminolysis reaction of aryl esters using inert tertiary amines as amino donors via C–O and C–N bond activations.[5] In that study we found that when $PdCl_2$ was used as the catalyst, a palladium mirror appeared on the tube wall at the end of the reaction, which indicated that this reaction may be performed via a Pd^0/Pd^{II} catalytic cycle. Therefore, we postulated that $Pd(OAc)_2$ could be replaced by heterogeneous catalysis with metallic palladium or other metals. In recent years, metal nanoparticles (NPs), especially PdNPs and AuNPs, have been proven to be efficient and selective heterogeneous catalysts for many reactions, such as oxidation of alcohols and aldehydes, epoxidation of propylene, hydrochlorination of ethyne, and carbon–carbon coupling.[6,7]

Therefore, to test the possibility of heterogeneous catalytic aminolysis of tertiary amines with esters, PdNPs and AuNPs supported on three various oxide powders, including Al_2O_3, ZrO_2, and CeO_2, were prepared by the impregnation–reduction method[7d] (see the Experimental Section) and applied to the reaction of perfluorophenyl indole-2-carboxylate (**1a**) with triethylamine (TEA, **2a**). After 24 h of refluxing in PhCl in the presence of 3% Pd/Al_2O_3, 3% Pd/ZrO_2, and 3% Pd/CeO_2, the desired product, *N*,*N*-diethylindole-2-carboxamide (**3aa**) was isolated in yields of 71%, 72%, and 68%, respectively (Table 1, entries 1–3). These results further confirmed the hypothesis that the $Pd(OAc)_2$-catalyzed aminolysis reaction was performed via a Pd^0/Pd^{II} catalytic cycle that began with Pd^0. However, comparison of the yields of **3aa** showed that the catalytic activity of PdNPs was apparently lower than that of $Pd(OAc)_2$ (entry 4). Alternatively, a series of supported AuNPs

Table 1. Screening of Heterogeneous Catalysts for the Aminolysis Reaction[a]



1a **2a** **3aa**

entry	catalyst	solvent	yield (%)[b]
1	3% Pd/Al_2O_3	PhCl	71
2	3% Pd/ZrO_2	PhCl	72
3	3% Pd/CeO_2	PhCl	68
4	3% $Pd(OAc)_2$	PhCl	87
5	3% Au/CeO_2	PhCl	86
6	3% Au/ZrO_2	PhCl	83
7	3% Au/Al_2O_3	PhCl	91
8	2% Au/Al_2O_3	PhCl	83
9	1% Au/Al_2O_3	PhCl	77
10	γ-Al_2O_3	PhCl	0

[a]Reaction conditions: **1a** (0.2 mmol), **2a** (2 equiv), and catalyst (10 mol %) in solvent (1.5 mL) for 24 h at 115 °C. [b]Isolated yields.

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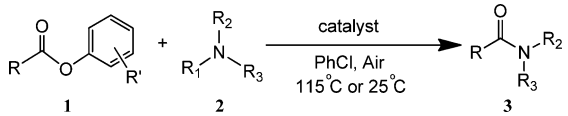
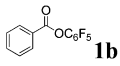
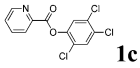
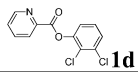
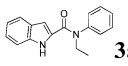
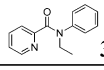
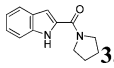
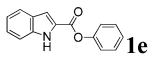
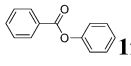
were investigated to study their catalytic performance in the model reaction. We were pleased to find that AuNPs not only smoothly catalyzed the aminolysis reaction but also gave **3aa** in significantly higher yields than the PdNP-catalyzed reaction (entries 5−7). Moreover, the catalytic performance of 3% Au/Al_2O_3 was superior to that of $Pd(OAc)_2$ in the model reaction. Since a gold loading higher than 3 wt % will led to aggregation of the NPs,[7d] we tested lower loadings of gold (2 and 1 wt % Au/Al_2O_3). The results showed that the catalytic efficiency was significantly reduced when the gold loading was decreased (entries 8 and 9). It was noteworthy that no reaction was observed in a blank experiment conducted with γ-Al_2O_3 powder instead of AuNPs under otherwise identical conditions (entry 10).

To compare homogeneous- and heterogeneous-catalyzed systems, a variety of esters and amines were subjected to the conditions from Table 1, entry 7, and representative results are summarized in Table 2. Other esters including perfluorophenyl

Table 2. Comparative Study of the Catalytic Activities of Au/Al_2O_3 and $Pd(OAc)_2$ in Aminolysis Reactions[a]



1 2 3

entry	esters	products	catalysts	T(°C)	yield(%)[b]
1	 **1b**	 **3ba**	Au/Al_2O_3	115	85
			$Pd(OAc)_2$	115	91
2	 **1c**	 **3ca**	Au/Al_2O_3	115	79
			$Pd(OAc)_2$	115	80[5]
3	 **1d**	**3ca**	Au/Al_2O_3	115	78
			$Pd(OAc)_2$	115	79[5]
4	**1a**	 **3ab**	Au/Al_2O_3	115	48
			$Pd(OAc)_2$	115	82[5]
5	**1c**	 **3bb**	Au/Al_2O_3	115	36
			$Pd(OAc)_2$	115	70
6	**1a**	 **3ac**	Au/Al_2O_3	115	93
			$Pd(OAc)_2$	115	92
7	 **1e**	**3ac**	Au/Al_2O_3	25	85
				115	86
			$Pd(OAc)_2$	25	0
				115	83
8	 **1f**	 **3fc**	Au/Al_2O_3	25	51
			$Pd(OAc)_2$	25	0
				115	50

[a]Reaction conditions: **1** (0.2 mmol), **2** (2 equiv), and catalyst (10 mol %) in PhCl (1.5 mL) for 24 h. [b]Isolated yields.

benzoate (**1b**), 2,4,5-trichlorophenyl picolinate (**1c**), and 2,3-dichlorophenyl picolinate (**1d**) were used instead of **1a** to react with TEA (**2a**) (entries 1−3). Under the catalysis of AuNPs or $Pd(OAc)_2$, all three esters underwent this aminolysis reaction to give the corresponding tertiary amides in similar yields. However, when *N*,*N*-diethylaniline (**2b**), which contains a $C(sp^2)$−N bond, was chosen as the amine source, the yields with the AuNP-catalyzed reaction system were much less than with $Pd(OAc)_2$ (entries 4 and 5). As in the homogeneous catalytic reaction, when the AuNP catalyst was used, 1-methylpyrrolidine (**2c**) reacted with **1a** exclusively at the exocyclic C−N bond to give (indol-2-yl)(pyrrolidin-1-yl)-methanone (**3ac**) in 93% yield; the $Pd(OAc)_2$-catalyzed reaction afforded **3ac** in 92% yield (entry 6). In order to study the difference of the two kinds of catalysts in more detail, less active substrates such as phenyl esters[5] were tested. Surprisingly, we found that when the AuNP catalyst was used, phenyl indole-2-carboxylate (**1e**) could react with **2c** at room temperature (25 °C) to afford desired product **3ac** in 85% yield, whereas no product formation was observed with the $Pd(OAc)_2$ catalyst at the same temperature (entry 7). When the temperature was raised to 115 °C, the yield of the AuNP-catalyzed reaction did not increase, and not only that, the difference between the homogeneous- and heterogeneous-catalyzed systems disappeared. Likewise, when phenyl benzoate (**1f**) was used as the ester source to compare the two kinds of catalysts, the same result was obtained (entry 8). In summary, although the catalytic performance of AuNPs was inferior to $Pd(OAc)_2$ at high temperature, AuNPs could perform the catalytic aminolysis reaction at room temperature, whereas $Pd(OAc)_2$ could not. We postulated that this is attributed to abundant low-coordinated atoms and the high d[10] energy of small gold nanoparticles, which results in the formation of active sites.[8]

To demonstrate the synthetic utility of the energy-efficient green catalysis, the scope of the present transformation was examined using **2c** as a model substrate to react with various esters **1** at 25 °C. As shown in Table 3, except for ethyl indole-2-carboxylate (**1n**), all of the carboxylic esters tested, including benzoate, picolinate, pyrazine-2-carboxylate, and pyridin-2-yl 4-cyanobenzoate, reacted with **2c** to give the corresponding amides in 61−94% yield. The results further proved that the catalyzed aminolysis reaction applies only to aryl and heteroaryl esters and not to alkyl esters whether homogeneous or heterogeneous catalysis is used. It is clear that having electron-withdrawing groups on the benzene ring of the aryl ester is more beneficial to this reaction, as the yields with **1b**−**i** were higher than 90% (entries 1−6). Furthermore, comparison of phenyl 4-cyanobenzoate (**1j**) (entry 7) with phenyl benzoate (**1f**) (Table 2, entry 8) shows that the cyano group (a typical electron-withdrawing group) on the benzoyl of the aryl ester increased the yield of the amide as well. Further experiments showed that naphthalen-2-yl 4-cyanobenzoate (**1k**) underwent the aminolysis reaction expediently to give the same product as **1j**, namely, 4-(pyrrolidine-1-carbonyl)benzonitrile (**3hc**), in 74% yield (entry 8). However, when pyridin-2-yl 4-cyanobenzoate (**1l**) (a heteroaryl ester) was used as the ester source, the yield of **3hc** increased significantly to 84% (entry 9). This result indicates that the 2-pyridyloxy group is a very good leaving group and that the coordination of the nitrogen to the catalyst promotes cleavage of the acyl C−O bond of the ester.[9] Similarly, naphthalen-2-yl pyrazine-2-carboxylate (**1m**), which includes nitrogen atoms in the acyl part of the ester, underwent the aminolysis reaction to give **3mc** in higher yield than obtained with **1k** (entry 10). This was also the case in our earlier studies.[10] These results clearly show that the pyridine or benzene ring serves as a directing group for cleavage of the acyl C−O bond of the ester and that coordination of the nitrogen atom to the catalyst is favorable for the catalyzed reaction (Scheme 1).

We also examined the possibility of recycling the AuNP catalyst in the reaction of perfluorophenyl indole-2-carboxylate

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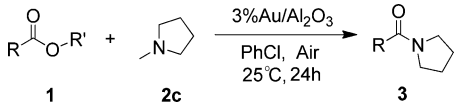
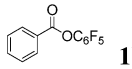
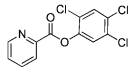
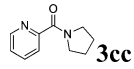
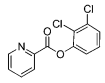
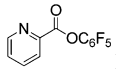
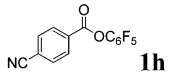
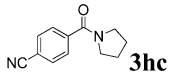
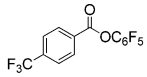
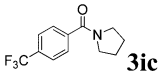
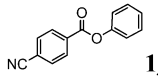
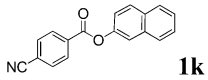
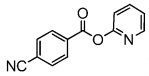
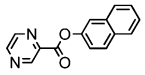
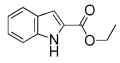
Table 3. Reactions of Various Esters 1 with 2c at Room Temperature[a]

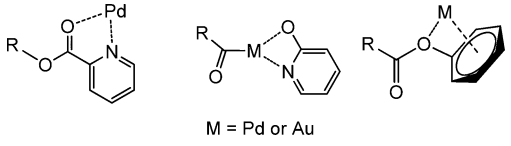


1 2c 3

entry	ester	product	yield(%)[b]
1	 1b	3fc	90
2	 1c	 3cc	92
3	 1d	3cc	93
4	 1g	3cc	91
5	 1h	 3hc	94
6	 1i	 3ic	92
7	 1j	3hc	72
8	 1k	3hc	74
9	 1l	3hc	84
10	 1m	 3mc	81
11	 1n	NP	

[a]Reaction conditions: **1** (0.2 mmol), **2** (2 equiv), and catalyst (10 mol %) in PhCl (1.5 mL) for 24 h. [b]Isolated yields.

Scheme 1. Directing Effect of Pyridine and Benzene Rings



(**1a**) with 1-methylpyrrolidine (**2c**). The results showed that the catalytic performance of the AuNPs did not apparently decline even after recycling five times (see the Experimental Section). Therefore, this AuNP-catalyzed aminolysis reaction is more aligned with green catalysis than the homogeneous catalysis is.

In order to get information on the eventual state of Au on the surface of the catalyst, AuNPs with three gold loadings (1.0, 2.0, and 3.0 wt %) on γ-Al_2O_3 were studied by transmission electron microscopy (TEM), UV−vis spectroscopy, and X-ray photoelectron spectroscopy (XPS). TEM images of Au/Al_2O_3 showed that the gold existed on Al_2O_3 as nanoparticles of about 2.4 nm in size (Figure 1). The UV−vis spectra of AuNPs on the Al_2O_3 support as well as the support alone are shown in Figure 2a. An absorption band at about 520 nm is observed in the

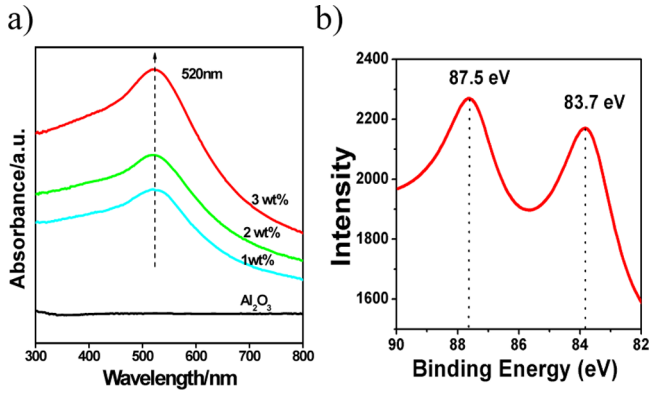


Figure 2. (a) UV−vis diffuse reflectance spectra of the Al_2O_3 support and 1−3 wt % Au/Al_2O_3. (b) The XPS spectrum of the supported AuNPs.

UV−vis spectra of the catalysts, which is the characteristic surface plasmon resonance absorption by AuNPs. The XPS spectra of the supported AuNPs with different gold contents all showed the same pattern. The binding energies of Au $4f_{7/2}$ and Au $4f_{5/2}$ electrons were found to be 83.7 and 87.5 eV, respectively (Figure 2b). These values are identical to those for metallic gold, which suggests that catalysts exist in the metallic state.

On the basis of GC−MS analysis results (see the Experimental Section) and the commonly accepted mechanism from the literature, the proposed reaction pathway is shown in Scheme 2. Initially, AuNPs undergo an oxidative addition with the acyl C−O bond in aryl ester **1**, generating the acylgold alkoxide. Then the highly Lewis acidic gold species coordinates

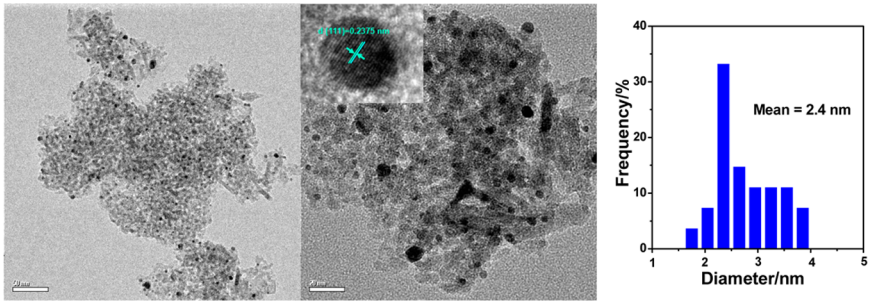


Figure 1. (left, center) TEM images of AuNPs on a γ-Al_2O_3 support. The lengths of the scale bars in the images are 50 and 20 nm, respectively. (right) Histogram showing the AuNP size distribution.

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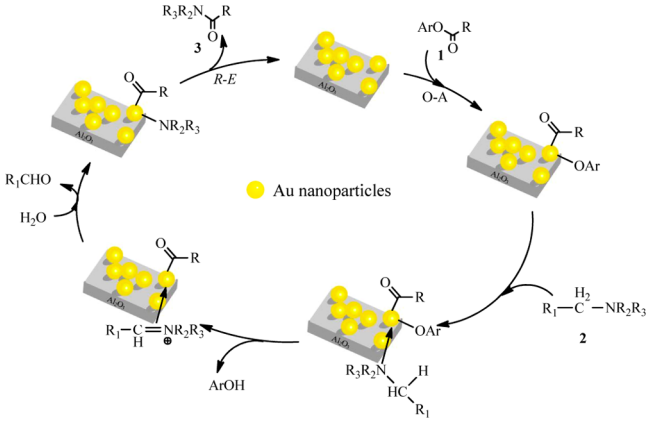
Scheme 2. Proposed Mechanism for the AuNP-Catalyzed Aminolysis Reaction



to the nitrogen of tertiary amine **2** and reacts with it to give the iminium-type intermediate by elimination of phenol via the generally accepted mechanism.[11] The complex is then hydrolyzed to be converted into the acylgold amino salt by elimination of aldehyde.[4c] Reductive elimination from this salt results in the desired tertiary amide **3** and regenerates Au^0 to complete the catalytic cycle.

In conclusion, it was found for the first time that supported gold nanoparticles can catalyze the aminolysis reaction between various aryl esters and inert tertiary amines to form tertiary amides via C−O and C−N bond activations. Compared with the homogeneous catalyst $Pd(OAc)_2$, the most outstanding feature of the AuNP catalyst is its superior ability to catalyze the aminolysis reaction at room temperature. The experimental results indicated that the activity order of esters in the aminolysis reaction is pyridin-2-yl carboxylates > phenyl carboxylates. Also, electron-withdrawing groups in either the alkyl part or the acyl part of the ester are more beneficial for this reaction. This study opens the door to heterogeneous catalysis of esters by C−O activation and inspires the application of the catalyzed aminolysis reaction.

EXPERIMENTAL SECTION

1. Catalyst Preparation. AuNPs on γ-Al_2O_3 and other supports were prepared by the impregnation−reduction method. For example, 3 wt % Au/γ-Al_2O_3 was prepared by the following procedure: γ-Al_2O_3 powder (1.0 g) was dispersed into 50 mL of 3.3×10^{-3} $HAuCl_4$ aqueous solution with magnetic stirring, and 0.1 M NaOH aqueous solution was added to the mixture to adjust the pH to 6. Next, 4 mL of 0.03 M lysine was added with vigorous stirring. To this suspension, 4 mL of 0.35 M $NaBH_4$ solution was added dropwise over 10 min. The mixture was left to stand for 24 h and then filtered, and the residue was washed with water and ethanol and dried at 80 °C. The residue was used directly as the catalyst. Catalysts on other supports were prepared in a similar manner.

2. Catalyst Characterization. TEM images were recorded with a JEOL JEM-1210 transmission electron microscope employing an accelerating voltage of 200 kV. The samples were suspended in ethanol and dried on holey carbon-coated Cu grids. The compositions of samples were determined using the energy-dispersive X-ray spectroscopy attachment of the transmission electron microscope. The XPS spectra were measured with an ESCALAB210 spectrometer (British VG Co.). All of the binding energies were referenced to the C 1s hydrocarbon peak at 285.00 eV. The UV−vis spectra were obtained using a Shimadzu UV-2550 spectrophotometer in the range of 200−800 nm at room temperature with $BaSO_4$ as the reference.

3. Preparation of Esters (1a−n). A mixture of the carboxylic acid (10 mmol), phenol or pyridine-2-ol (10 mmol), DMAP (1 mmol), and 1-ethyl-3-(3-(dimethylamino)propyl)carbodiimide hydrochloride (EDC·HCl, 10 mmol) in THF (50 mL) was stirred overnight at 25 °C. The resulting mixture was filtered, and the filtrate was evaporated in vacuo. The residue was purified by flash column chromatography (silica gel, ethyl ether/petroleum ether = 1:2−1:5 as the eluent), affording the corresponding aryl ester **1a−n**.

4. Aminolysis Reaction for Synthesis of Versatile Amides. The general procedure for the aminolysis reaction was as follows: A mixture of ester **1** (0.20 mmol), tertiary amine **2** (0.30 mmol), and 3% Au/Al_2O_3 (15 mg, 0.02 mmol, 10 mol %) in PhCl (1.5 mL) was sealed in a 30 mL vial. The reaction mixture was stirred at 115 or 25 °C for 24 h. After cooling to room temperature, the mixture was filtered, and the filtrate was evaporated in vacuo. The residue was purified by flash column chromatography (silica gel, ethyl acetate/petroleum ether = 1:2−1:5 as the eluent) to afford the desired amide **3**.

*N,N-Diethylindole-2-carboxamide (**3aa**).* Liquid. Yield: 91% (39.3 mg). ^{1}H NMR (500 MHz, $CDCl_3$): δ 10.10 (s, 1H), 7.66 (d, J = 7.7 Hz, 1H), 7.46 (d, J = 8.0 Hz, 1H), 7.32−7.19 (m, 1H), 7.19−7.04 (m, J = 7.1 Hz, 1H), 6.81 (s, 1H), 3.97−3.45 (m, 4H), 1.47−1.24 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 162.3, 135.5, 129.8, 127.9, 124.2, 121.9, 120.3, 111.8, 104.3, 43.4, 39.4, 14.1, 12.8. MS (ESI): m/z 433.02 $[2M + H]^+$. Anal. Calcd for $C_{13}H_{16}N_2O$: C, 72.19; H, 7.46; N, 12.95%. Found: C, 72.15; H, 7.51; N, 13.04%.

*N,N-Diethylbenzamide (**3ba**).*[12] Yield: 85% (30.1 mg). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.46−7.30 (m, 5H), 3.55 (s, 2H), 3.26 (s, 2H), 1.34−1.02 (m, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.7, 136.8, 129.2, 128.4, 126.2, 43.4, 39.4, 14.1, 12.8. MS (ESI): m/z 178.10 $[M + H]^+$.

*N,N-Diethylpicolinamide (**3ca**).*[5] Yield: 79% (28.1 mg). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.58 (d, J = 4.7 Hz, 1H), 7.89−7.68 (m, 1H), 7.55 (d, J = 7.8 Hz, 1H), 7.40−7.30 (m, 1H), 3.57 (q, J = 7.1 Hz, 2H), 3.36 (q, J = 7.1 Hz, 2H), 1.27 (t, J = 7.0 Hz, 3H), 1.14 (t, J = 7.1 Hz, 3H). MS (ESI): m/z 379.15 $[2M + Na]^+$.

*N-Ethyl-N-phenylindole-2-carboxamide (**3ab**).*[5] Yield: 48% (25.3 mg). ^{1}H NMR (300 MHz, $CDCl_3$): δ 9.40 (s, 1H), 7.55−7.46 (m, 3H), 7.40−7.28 (m, 4H), 7.25−7.16 (m, 1H), 7.05−6.94 (m, 1H), 5.18 (d, J = 1.1 Hz, 1H), 3.97 (q, J = 7.1 Hz, 2H), 1.27 (t, J = 7.1 Hz, 3H). MS (ESI): m/z 265.05 $[M + H]^+$.

*N-Ethyl-N-phenylpicolinamide (**3bb**).*[5] Yield: 36% (16.3 mg). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.37 (s, 1H), 7.69−7.53 (m, 1H), 7.37 (d, J = 5.7 Hz, 1H), 7.23−6.92 (m, 6H), 4.01 (q, J = 6.5 Hz, 2H), 1.25 (t, J = 8.4 Hz, 3H). MS (ESI): m/z 227.05 $[M + H]^+$.

*(1H-Indol-2-yl)(pyrrolidin-1-yl)methanone (**3ac**).*[13] Yield: 93% (39.8 mg). ^{1}H NMR (500 MHz, $CDCl_3$): δ 10.07 (s, 1H), 7.68 (d, J = 8.0 Hz, 1H), 7.49 (d, J = 8.3 Hz, 1H), 7.29 (t, J = 7.6 Hz, 1H), 7.13 (t, J = 7.5 Hz, 1H), 6.90 (s, 1H), 3.90 (t, J = 6.7 Hz, 2H), 3.78 (t, J = 6.8 Hz, 2H), 2.14−2.02 (m, 2H), 2.02−1.92 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 161.0, 135.6, 130.8, 128.1, 124.4, 122.0, 120.3, 111.9, 105.3, 48.3, 47.5, 26.7, 24.0.

*Phenyl(pyrrolidin-1-yl)methanone (**3fc**).*[14] Yield: 90% (31.5 mg). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.56−7.44 (m, 2H), 7.44−7.31 (m, 3H), 3.64 (t, J = 7.0 Hz, 2H), 3.41 (t, J = 6.6 Hz, 2H), 2.07−1.90 (m, 2H), 1.90−1.77 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 169.8, 137.2, 129.8, 128.3, 127.1, 49.6, 46.2, 26.4, 24.5.

*Pyridin-2-yl(pyrrolidin-1-yl)methanone (**3cc**).* Liquid. Yield: 92% (32.4 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.59 (d, J = 4.6 Hz, 1H), 7.87−7.73 (m, 2H), 7.42−7.31 (m, 1H), 3.74 (t, J = 6.5 Hz, 2H), 3.69 (t, J = 6.6 Hz, 2H), 2.02−1.83 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 166.6, 154.5, 148.0, 136.9, 124.7, 123.9, 49.1, 46.9, 26.6, 24.1. HRMS (ESI): m/z $[M + H]^+$ calcd for $C_{10}H_{12}N_2O$ 177.1028, found 177.1028.

*4-(Pyrrolidine-1-carbonyl)benzonitrile (**3hc**).* Liquid. Yield: 94% (37.6 mg). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.71 (d, J = 8.2 Hz, 2H), 7.61 (d, J = 8.1 Hz, 2H), 3.65 (t, J = 6.9 Hz, 2H), 3.37 (t, J = 6.6 Hz, 2H), 2.03−1.94 (m, 2H), 1.94−1.87 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 167.6, 141.4, 132.3, 127.8, 118.2, 113.5, 49.5, 46.4, 26.4, 24.4. HRMS (ESI): m/z $[M + H]^+$ calcd for $C_{12}H_{12}N_2O$ 201.1028, found 201.1030.

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*Pyrrolidin-1-yl(4-(trifluoromethyl)phenyl)methanone (**3ic**).* Liquid. Yield: 92% (44.7 mg). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.63 (dd, J = 21.8, 8.2 Hz, 4H), 3.64 (t, J = 6.7 Hz, 2H), 3.37 (t, J = 6.4 Hz, 2H), 2.01−1.92 (m, 2H), 1.92−1.83 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 168.2, 140.7, 131.6 (q, J_{C-F} = 32.6 Hz), 127.5, 125.4 (q, J_{C-F} = 3.8 Hz), 123.8 (q, J_{C-F} = 272.3 Hz), 49.5, 46.3, 26.4, 24.4. HRMS (ESI): m/z $[M + H]^+$ calcd for $C_{12}H_{12}F_3NO$ 244.0949, found 244.0948.

*Pyrazin-2-yl(pyrrolidin-1-yl)methanone (**3mc**).* Liquid. Yield: 81% (28.7 mg). ^{1}H NMR (500 MHz, $CDCl_3$): δ 9.12 (s, 1H), 8.63 (s, 1H), 8.54 (s, 1H), 3.83−3.73 (m, 2H), 3.73−3.65 (m, 2H), 1.95 (dt, J = 6.8, 3.5 Hz, 4H). ^{13}C NMR (126 MHz, $CDCl_3$): δ 164.2, 149.5, 145.9, 145.4, 142.3, 49.0, 47.1, 26.7, 23.9. HRMS (ESI): m/z $[M + H]^+$ calcd for $C_9H_{11}N_3O$ 178.0980, found 178.0983.

5. Study of Recycling of the AuNP Catalyst. We examined recycling of the AuNPs catalyst in the reaction of perfluorophenyl indole-2-carboxylate (**1a**) with 1-methylpyrrolidine (**2c**) (Table 4).

Table 4. Catalyst Recycling Study

recycle no.	1	2	3	4	5
yield (%)	93	92	90	90	87

The catalyst was recycled five times after being used in a catalytic reaction. The catalyst was separated by centrifugation, washed twice with ethanol, and dried in an oven at 80 °C.

6. GC−MS Analysis of the Reaction Solution. To identify a byproduct formed by the cleavage of the C−N bond and the C−O bond, the reaction solution of **1d** with *N*-benzyl-*N*-ethylaniline **2d** (a higher-molecular-weight amine) was detected with GC−MS after the end of reaction (see the Supporting Information). Two kinds of aminated products, *N*-benzyl-*N*-phenylpicolinamide (**3dd**) and *N*-ethyl-*N*-phenylpicolinamide (**3dd′** = **3cb**), were detected in an almost 14:1 ratio, which indicated that cleavage of the sterically less hindered ethyl group is much more facile. The GC area % data showed that along with **3dd′**, a similar amount of benzaldehyde was obtained. Therefore, this aminolysis reaction proceeds via the formation of an iminium intermediate, which would cause the formation of an aldehyde.[15] In addition, 2,3-dichlorophenol, derived from the alkoxy group of the ester, was detected.

■ ASSOCIATED CONTENT

Supporting Information

^{1}H NMR, ^{13}C NMR, and HRMS spectra and analysis by GC−MS. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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