

Heterogeneous Cobalt-Catalyzed Direct *N*-Formylation of Isoquinolines with CO₂ and H₂

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Isoquinolines (IQs) are an abundant feedstock, and *N*-formyl-1,2,3,4-tetrahydroisoquinolines (FTHIQs) are valuable fine chemicals and key intermediates. Herein, we report for the first time the Co⁰/ZnCl₂-catalyzed direct *N*-formylation of IQs by using CO₂ with H₂ to produce FTHIQs. It was discovered that the Co catalyst and ZnCl₂ worked synergistically in catalyzing

the *N*-formylation reactions, and moderate to high yields of the desired products could be obtained, depending on the nature of the substrates. The Co⁰ catalyst could be reused at least five times without a notable decrease in activity. A possible reaction mechanism is proposed on the basis of control experiments.

Introduction

N-formyl-1,2,3,4-tetrahydroisoquinoline and its derivatives (FTHIQs) are important fine chemicals and key intermediates for the synthesis of medical intermediates and alkaloids.^[1] Generally, classical approaches for the synthesis of FTHIQs involve *N*-formylations of 1,2,3,4-tetrahydroisoquinolines (THIQs) with C₁ sources, such as CO, CO₂, CH₃OH, HCHO, or DMF.^[2] Synthesis of FTHIQs directly from isoquinolines (IQs) is attractive^[3] because IQs are abundant, are present in coal and oil shale, and are the byproducts of petroleum refining processes.^[4] The transformation of IQs into value-added products is an attractive route for efficient utilization of carbon resources.^[5]

 CO_2 is an economical, abundant, and renewable C_1 building block for the production of value-added chemicals.^[6] *N*-Formylation of various amines has been studied widely with CO_2 as the C_1 source and H_2 or PhSiH₃ as the reducing agent in recent years.^[7] Hydrogen is a commonly used reducing agent because it is abundant, economical, and non-toxic and the only byproduct is H_2O . Ding and co-workers have reported the *N*-formylation of a series of saturated amines with H_2 and CO_2 catalyzed by a ruthenium-based homogeneous catalyst.^[71] Shi and coworkers have found that a heterogeneous palladium catalyst was also active for this kind of reactions.^[7] The *N*-formylation of IQs with CO_2 and H_2 would be an ideal route for the

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synthesis of FTHIQs that would involve selective hydrogenation of IQs and *N*-formylation of THIQs; however, it has not been reported. The selective hydrogenation of the heteroaromatic compounds, isoquinolines, is difficult because of the high resonance stability of these substrates and the potential poisoning of the catalysts by either the substrates or the hydrogenated products. To improve the reaction, various strategies have been developed,^[8] including the activation of *N*-heteroaromatic compounds by formation of their salts over various homogeneous precious Ir metal complex catalysts.^[9] In addition, several heterogeneous catalysts have also been developed for the selective hydrogenation of IQs.^[10]

Herein, we report the direct *N*-formylation of IQs to form FTHIQs by using CO_2 and H_2 for the first time. It was found that a Co^0 catalyst, which is abundant and relatively low cost,^[11] could catalyze the reaction efficiently in the presence of ZnCl₂. A detailed study indicated that the Co^0 catalyst and ZnCl₂ work synergistically in promoting the reaction by the coordination of ZnCl₂ and the nitrogen atom of the IQs.

Results and Discussion

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We initially studied the *N*-formylation of isoquinoline (**1 a**) with CO_2 and H_2 to form *N*-formyl-1,2,3,4-tetrahydroisoquinoline (**3 a**) and screened the catalytic system. The Co^0 catalyst was prepared by reduction of Co_3O_4 with H_2 at 400 °C for 2 h (the details are given in the Experimental Section). The reduction temperature for catalyst preparation was determined by temperature-programmed reduction (TPR) measurement (Figure 1a), in which the peaks at around 231 and 357 °C could be attributed to the reduction of Co_3O_4 to CoO and CoO to Co, respectively.^[12] The results indicated that, after reduction, the Co species had been reduced to Co^0 , which was confirmed by characterization with X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS), as illustrated in Figure 1. In the XRD patterns (Figure 1c) of the Co_3O_4 catalyst, the peaks at 19,



Figure 1. a) TPR test of Co_3O_4 . c) XRD patterns of Co_3O_4 , Co^0 catalyst, and Co^0 catalyst after reuse five times. b) and d) XPS spectra of the Co^0 catalyst and Co_3O_4 , respectively. e) TEM image of the Co^0 catalyst. f) TEM image of the Co^0 catalyst after reuse five times.

31, 36.9, 38.5, 44.8, 55.6, 59.2, and 65.2° can be assigned to the (111), (220), (1111), (2212), (400), (422), (511), and (440) indices of Co_3O_4 (powder diffraction file no. 43-1003), respectively. The peaks at 41.6, 44.4, 47.4, and 75.9 $^{\circ}$ for the Co⁰ catalyst can be attributed to the (100), (002), (101), and (110) indices of Co⁰ (powder diffraction file no. 05-0727).^[6e, 13] These results indicated that the Co species was reduced to Co⁰. The XRD spectrum of the Co⁰ catalyst after it had been reused five times indicated that the main crystalline phase did not change significantly. Broad peaks appeared at around 23° because of the amorphous structure. In the XPS spectrum of Co_3O_{4r} the peak at 780 eV is attributed to the Co^{3+} $2p_{3/2}$ configuration and a small peak at around 781.5 eV is ascribed to the Co^{2+} $2p_{3/2}$ configuration. The other spin-orbit component, $2p_{\scriptscriptstyle 1/2}\!,$ appears at 794.9 and 796.8 eV for Co^{3+} and Co^{2+} , respectively. The two peaks at 786.5 and 803.3 eV are Co²⁺ shake-up satellite peaks of Co_3O_4 (Figure 1 d). In Figure 1 b, the peaks at 779.2 and 794.6 eV can be assigned to the Co⁰ 2p_{3/2} and Co⁰ 2p_{1/2} configurations, respectively.^[14] The results indicated that, after reduction with hydrogen at 400 °C, the Co⁰ species was formed. The Co^{II/III} species were a result of oxidation during the catalyst preparation and characterization. The transmission electron microscopy (TEM) image showed

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that the particle size of the catalyst was in the range of 20–100 nm (Figure 1 e).

The conversion of 1a was very low and the main product was 1,2,3,4-tetrahydroisoquinoline (2 a) if only Co⁰ catalyst was used (Table 1, entry 1). Desired product 3a was not detected if pure ZnCl₂ was used as the catalyst (Table 1, entry 2). With a combination of Co⁰ catalyst and ZnCl₂ (Co⁰/ZnCl₂), the conversion of 1a and the yield of 3a could reach 97 and 94%, respectively (Table 1, entry 3). If MnCl₂ was used, the conversion of 1a was 85% with a 30% yield of 3a (Table 1, entry 4). The conversions of 1a were 52 and 58% in the presence of KCl and LiCl, respectively (Table 1, entries 5 and 6), which were higher values than that observed with pure Co⁰ catalyst. However, in these cases, the yields of 3a were still low. Addition of NiCl₂, CuCl₂, or AlCl₃ resulted in lower conversions than that with pure Co⁰ catalyst, which indicated that these salts inhibit the reaction remarkably (Table 1, entries 7-9). The substrate conversion could reach up to 96 and 95% in the presence of $Zn(acac)_2$ and $Zn(NO_3)_2$, respectively, and the yields of **3a** were 69 and 51%, respectively (Table 1, entries 10 and 11). The results indicated that Zn(acac)₂ and Zn(NO₃)₂ could promote the selective hydrogenation of 1 a effectively, whereas their promotion effect for the *N*-formylation was weaker than that of ZnCl₂ (Table 1, entries 3, 10, and 11). If Znl₂ was used, the conversion of 1a and the yields of 2a and 3a were all low (Table 1, entry 12), which indicated that the reaction was remarkably suppressed by the iodine ion. The poor performance was possibly a result of strong coordination between I⁻ ions and the

Table 1. N-Formylation of isoquinoline with CO2 and H2 over various catalysts. ^[a]						
$ \begin{array}{c} \hline \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ $						
1a		2a		3a	4a	
Entry	Cat.	Additive	Conversior	n	Yield ^[b] [%]	
-			[%]	2 a	3 a	4a
1	Со	_	39	34	5	0
2	-	ZnCl ₂	0	0	0	0
3	Со	ZnCl ₂	97	2	94	<1
4	Со	MnCl ₂	85	54	30	1
5	Со	KCI	52	44	8	0
6	Co	LiCl	58	49	9	0
7	Со	NiCl ₂	18	6	12	0
8	Co	CuCl ₂	13	7	6	0
9	Со	AICI ₃	11	7	4	0
10	Co	Zn(acac) ₂ ^[c]	96	26	69	1
11	Co	Zn(NO ₃) ₂	95	44	51	0
12	Co	Znl ₂	40	26	14	0
13 ^[d]	Co	ZnCl ₂	74	42	32	0
14	CoO	ZnCl ₂	0	0	0	0
15	Co ₃ O ₄	ZnCl ₂	0	0	0	0
16	Fe	ZnCl₂	12	9	3	0
17	Mn	ZnCl ₂	0	0	0	0
18	Cu	ZnCl ₂	0	0	0	0
19	In	ZnCl ₂	0	0	0	0
20	Co/ZnO	-	84	31	53	0
21	Со	ZnCl₂· <i>n</i> H₂O	88	40	48	0
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[a] Reaction conditions: substrate (0.5 mmol), catalyst (5 mg), additive (0.02 mmol), CO_2 (2 MPa), H₂ (8 MPa), THF (2 mL), 170 °C, 16 h. [b] Yield was determined by GC with toluene as an internal standard. [c] acac: acetyl acetone. [d] $ZnCI_2$ (0.01 mmol).

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active Co sites and/or Zn^{2+} ions. These results demonstrated that the counterions of zinc salts affected the catalytic performances greatly; this is probably related to their different coordination abilities and was proved by the ¹H NMR spectra in Figures S1–S3 in the Supporting Information. The above results showed that Co⁰ and ZnCl₂, and/or isoquinolines, had an excelent synergistic effect for catalyzing the direct *N*-formylation of isoquinolines by using CO₂ with H₂.

The ZnCl₂ loading affected the reaction dramatically. If 2 mol% of ZnCl₂ was added, 32% yield of **3a** was obtained, which was increased to 94% by increasing the loading to 4 mol% (Table 1, entries 13 versus 3). No product was detected over CoO or Co₃O₄ (Table 1, entries 14 and 15), which indicated that the Co⁰ species was the active component for the reaction. Combinations of ZnCl₂ with Fe⁰, Cu⁰, Mn⁰, and In⁰ species were checked as well. However, they all exhibited poor catalytic performances in the reaction (Table 1, entries 16-19). The activity of Co/ZnO was higher than that of the Co catalyst alone: the conversion of 1a was 84% and the yield of 3a was 53% (Table 1, entries 20 versus 1). The results indicated that Zn was important to the reaction. However, the interaction of ZnO and 1 a was weaker than that of ZnCl₂ and 1 a, which made the activity of Co/ZnO lower than that of Co/ZnCl₂ (Table 1, entries 20 versus 3). If hydrated zinc chloride was used, 88% conversion was exhibited and the yield of 3a was 48% (Table 1, entry 21). The results indicated that the hydrogenation and N-formylation over the Co⁰/ZnCl₂ catalytic system proceeded independently. The hydrated water affected the hydrogenation of isoquinolines slightly but mainly suppressed the N-formylation step, possibly as a result of the effect of water on the coordination of zinc chloride and isoquinoline (Table 1, entry 21).

The results above indicated that $Co^0/ZnCl_2$ was the best candidate for the *N*-formylation of isoquinoline with CO_2 and H_2 . The effect of reaction conditions on the reaction was studied, and the results are given in Table S1 in the Supporting Information and Table 2. The optimized temperature was 170 °C and the best solvent among those checked was THF (for details, see Table S1 the Supporting Information). The pressures of CO_2 and H_2 were also important parameters for the reaction.

Table 2. Effect of reaction conditions on $Co^0/ZnCl_2$ -catalyzed direct <i>N</i> -formylation of isoquinoline with CO_2 and H_2 . ^[a]						
Entry	$P_{\rm CO_2}/P_{\rm H_2}$	t	Conversion		Yield ^[b] [%	b]
	[MPa]	[h]	[%]	2 a	3 a	4a
1	0/8	16	98	98	0	0
2	0.5/8	16	99	56	43	0
3	1/8	16	97	26	71	0
4 ^[c]	2/8	16	97	2	94	<1
5	2/4	16	53	6	47	0
6	2/6	16	71	12	59	0
7	2/10	16	98	2	95	1
8	2/8	4	32	20	12	0
9	2/8	8	95	28	67	0
10	2/8	12	98	12	86	0
[a] Reaction conditions: substrate (0.5 mmol), catalyst (5 mg), ZnCl ₂ (0.02 mmol), THF (2 mL), 170 °C. [b] Yield was determined by GC with toluene as an internal standard. [c] From Table 1, entry 3 for comparison.						

None of the desired product 3a was detected in the absence of CO₂, which indicated that CO₂ was the C₁ source for the reaction (Table 2, entry 1). If the H₂ pressure was 8 MPa, the yield of 3a increased remarkably from 43 to 71% with an increase in CO₂ pressure from 0.5 to 1 MPa, respectively (Table 2, entries 2 and 3). In addition, the pressure of H_2 had a great impact on the conversion of 1 a and the yield of 3 a, both of which increased with increasing H₂ pressure (Table 2, entries 5, 6 and 4). The effect of reaction time on the catalytic performance was studied as well. Only 12% yield of 3a was generated with a time of 4 h. This yield increased to 67 and 86% after the time was extended to 8 and 12 h. At the same time, the hydrogenated product 2a increased from 20 to 28% and then reduced to 12% (Table 2, entries 8-10). The results revealed that 2a could be transformed into 3a, and the 3a yield was thus increased by prolonging the reaction time. Based on the above results, we speculated that the N-formylation of isoquinoline with CO₂ and H₂ occurs in two steps, that is, the selective hydrogenation of 1 a to 2 a and the N-formylation of 2 a with CO₂ and H₂ to **3a**. Fortunately, no *N*-formyl-decahydroisoquinoline or decahydroisoquinoline were detected under the reaction conditions we studied. The results indicated that Co⁰/ ZnCl₂ exhibited high selectivity for the N-formylation of isoquinoline.

To test the versatility of the Co⁰/ZnCl₂ catalytic system, some typical substituted IQs with electron-donating and electronwithdrawing groups were studied and the results are given in Table 3. The IQs with electron-donating groups, namely 5-methoxy- and 5- and 6-methylisoquinolines, were effectively converted into the desired products, with yields of 98, 88, and 92%, respectively (Table 3, entries 1-3). 3-Methyl-isoquinoline (1 e) was converted into 3 e with 79% yield, whereas 1-methyl isoquinoline (1 f) afforded 3 f with a relatively lower yield even after 48 h (Table 3, entry 5), which can probably be attributed to steric hindrance from the methyl group at the 1 position. The chlorine-substituted IQs 1g and 1h could be formylated to form the corresponding products after 36 h with yields of 83 and 63%, respectively (Table 3, entries 6 and 7). The results indicated that the Co⁰/ZnCl₂ catalytic system was compatible for substituted IQs with electron-donating and electron-withdrawing groups. The isoquinoline-N-oxide (1i) was converted into 3a with a high yield of 99% (Table 3, entry 8), which indicated that the oxidized substrate did not affect the catalytic performance and this approach is not sensitive to oxygen. However, the activity of $Co^0/ZnCl_2$ for the direct *N*-formylation of quinoline was very low, and only 7.8% yield of N-formyl-1,2,3,4-tetrahydroquinoline (3 j) was obtained, which is lower than that of isoquinoline (Table 3, entry 9).

To find out the intermediate of CO_2 conversion in the *N*-formylation reaction, other C_1 sources, namely CO, HCOOH, and HCOONa, were checked with **1a** as the starting material (Table 4). If CO was employed, **1a** gave a rather low yield of **3a** (1%; Table 4, entry 1). Notably, the hydrogenation activity of **1a** to form **2a** was poor in this case, which was probably a result of catalyst poisoning by CO. With consideration of the fact that HCOOH can dissolve the Co⁰ catalyst, HCOONa was also surveyed. However, only a small amount of **3a** was

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[[]a] Reaction conditions were the same as those for entry 3 in Table 1, unless mentioned otherwise. [b] Determined by GC-FID with toluene as an internal standard. Yields of isolated products are given in brackets. [c] t=48 h. [d] t=36 h.

Table 4. Control experiments for <i>N</i> -formylation of $1a$ and $2a$ with other C_1 sources. ^[a]							
Entry	C ₁ source	Conversion [%]	2 a	Yield ^[b] [%] 3 a	4a		
1	СО	12	11	1	0		
2	HCOOH	15	5	10	0		
3	HCOONa	8	3	5	0		
[a] The reaction conditions were same as those for entry 3 of Table 1, except that CO_2 was replaced by another C_1 source (3 equiv., relative to the substrate). [b] CO pressure was 2 MPa.							

produced by using HCOONa or HCOOH as the C₁ source (Table 4, entries 2 and 3). These results demonstrated that the above C₁ sources were probably not the intermediates for the *N*-formylation of **1 a** with CO₂ and H₂. Additionally, our experiments showed that CO and HCOOH were not detected in the reaction of CO₂ and H₂ over the Co⁰/ZnCl₂ catalytic system.

Based on the above experimental study, a possible reaction mechanism has been proposed for the *N*-formylation of IQs with CO₂ and H₂ over the Co⁰/ZnCl₂ catalytic system, and the catalytic cycle, with **1a** as an example, is shown in Scheme 1.

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Briefly, 1 a was transformed into 2 a by selective hydrogenation via the I-III species, and 2a then reacted with CO_2 and H_2 via IV to form **3a**. The Co^0 catalyst and ZnCl₂ work cooperatively, which results in high activity in the reaction. This synergy not only enhances the selectivity for the hydrogenation of 1 a to 2a but also the N-formylation of 2a to 3a. The high selectivity of hydrogenation of 1a to 2a is probably caused by coordination between ZnCl₂ and 1 a,^[15] which has been preliminarily proved by the ¹H NMR spectra in Figures S5–S7 in the Supporting Information. In the ¹H NMR spectrum of **1**a, the chemical shift of the H atom in the 1 position on 1 a can be observed at $\delta = 9.26$ ppm, which is shifted to $\delta = 9.52$ ppm after the introduction of ZnCl₂. Importantly, the anion acting as a ligand to the Zn^{2+} ion modulates the catalytic performance and affects the ¹H NMR spectrum of the H atom in the 1 position of isoquinoline remarkably, and the Cl- ion was the best one for the reaction. It is believed that the easily formed carbamic acid or carbamate^[16] formed from 2a with CO_2 may be an intermediate in the Nformylation and is then hydrogenated to the formyl amine over the $Co^0/ZnCl_2$ catalyst (Scheme 1). The high activity is related to the appropriate coordination abilities of ZnCl₂ and the Co⁰ catalyst. The coordination of ZnCl₂ and the nitrogen atom may not only be able to activate the N-heteroaromatic ring but also to eliminate the coordination of 1 a and/or 2a with the active catalyst sites, and it therefore promotes both the hydrogenation of 1a and the Nformylation of **2**a.

To determine whether Co leached into the solvent in the reaction, a hot filtration test was performed, and the result is shown in Figure 2a. The yield of **3a** was not changed after the Co^0 catalyst was



Scheme 1. Proposed reaction mechanism for *N*-formylation of isoquinoline with CO_2 and H_2 catalyzed by the $Co^0/ZnCl_2$ catalyst system.



Figure 2. a) Hot filtration test; \blacksquare : typical reaction, \bullet : the Co⁰ catalyst was filtered off. Reaction conditions were similar to those given in Table 1, entry 3. b) Reusability of the Co⁰ catalyst.

removed. This indicated that the Co⁰ catalyst was a highly efficient heterogeneous catalyst for *N*-formylation of IQs. Notably, the Co⁰ catalyst exhibited good stability in the reaction and could be reused at least five times without apparent loss of activity (Figure 2b), and these results further confirmed that the catalyst worked in a heterogeneous way. The XRD and TEM characterizations of the fresh and the five-times reused Co⁰ catalyst indicated that the main crystalline phase and morphology did not change significantly (Figure 1 c and f). Combined with the above results, it was determined that the Co⁰ species was the active site, and most of Co⁰ species was still in the Co⁰ state after the reaction.

Conclusions

In conclusion, we have demonstrated the first approach for direct *N*-formylation of IQs with CO₂ and H₂ to produce FTHIQs and the Co⁰/ZnCl₂ catalytic system has been found to be excellent for this kind of reaction. Moderate to very high yields of the desired products can be obtained, depending on the structures of the substrates. The Co⁰ catalyst and ZnCl₂ work cooperatively to catalyze the *N*-formylation of THIQs. The Co⁰ catalyst works in a heterogeneous manner and can be reused at least five times without a considerable decrease in activity. This work opens the way for the synthesis of formamides from feedstocks with pyridine structures.

Experimental Section

Chemicals

Chemicals were sourced as follows: Co_3O_4 (99.5%, J&K Chemicals), CoO (99.0%, Sinopharm Chemical Reagent Co., Ltd), CuCl₂ (98.5%, J&K Chemicals, AlCl₃ (99%, J&K Chemicals), NiCl₂ (98%, J&K Chemicals), LiCl (99%, J&K Chemicals), Fe (98.0%, Sinopharm Chemical Reagent Co., Ltd), Cu (99.99%, Sinopharm Chemical Reagent Co., Ltd), In (99.99%, Alfa Aesar), Mn (99.6%, Alfa Aesar), HCOOH (98.0%, Sinopharm Chemical Reagent Co., Ltd), and HCOONa (97.0%, Sinopharm Chemical Reagent Co., Ltd). CO₂ (99.99%) and H₂ (99.99%) were provided by Beijing Analytical Instrument Company. All other chemicals were purchased from commercial sources and used without further purification.

Catalyst preparation and characterization

The Co^0 catalyst was prepared by reducing of Co_3O_4 with H₂ at a flow rate of 30 mLmin⁻¹ at 400 °C for 2 h. After the reduction, the catalyst was cooled to room temperature. The catalyst was then passivated in a flow of N₂ containing 1% O₂ (30 mLmin⁻¹). The Co/ZnO catalyst was prepared by impregnation-reduction of Co(NO₃)₂ on a ZnO support with NaBH₄ as the reducing agent. The catalyst was characterized by TPR, XRD, XPS, and TEM. The TPR test was performed in a conventional atmospheric quartz flow reactor (3 mm in diameter; AutoChem II 2950 HP Chemisorption Analyzer, MICROMERITICS) to detect the effluent gas with a thermal conductivity detector (TCD). Before the test, the catalyst was heated at 300 °C for 30 min in Ar at a flow rate of 50 mLmin⁻¹. The temperature was then reduced to 50 $^{\circ}$ C and 10% H₂/Ar mixed gas was passed through the catalyst at a flow rate of 30 mLmin⁻¹. The temperature was linearly raised from 50 to 800 °C at a heating rate of 10°Cmin⁻¹. The XRD experiment was performed on a Rigaku D/ max 2500 instrument with nickel-filtered $Cu_{\kappa\alpha}$ radiation ($\lambda =$ 0.154 nm) operated at 40 kV and 20 mA. The XPS spectra were measured by using an ESCALab 220I-XL electron spectrometer from VG Scientific with 300 W $\text{Al}_{\text{K}\alpha}$ radiation and a hemispherical energy analyzer. The binding energies were calibrated with the C1s level of adventitious carbon at 284.8 eV as the internal standard reference. The TEM images of the catalysts were measured by using a JEOL-1011 electron microscope operated at 120 kV.

N-Formylation of isoquinoline with CO₂ and H₂

The reaction was conducted in a Teflon-lined stainless-steel reactor of 16 mL volume with a magnetic stirrer. The pressure was determined by a pressure transducer (FOXBORO/ICT, Model 93), which is accurate to $\pm\,0.025$ MPa. In a typical experiment, suitable amounts of Co⁰, ZnCl₂, substrate, and solvent were loaded into the reactor. The reactor was sealed and purged with CO₂ to remove the air at ambient temperature and was then placed in an air bath at the desired temperature. CO₂ was charged to the desired pressure, H₂ was added to the final pressure, and then the stirrer was started at 800 rpm. Upon reaction completion, the reactor was placed in ice water and the gas was released slowly. The reaction mixture was analyzed by GC-MS and GC with toluene as an internal standard. GC analysis was performed on an Agilent Technologies 7890B system equipped with an HP-5 column. GC-MS analysis was conducted on an Agilent 7892B/MSD 5975C system equipped with a HP-5MS column. NMR spectra were obtained with a Varian INOVA 400 MHz spectrometer. Chemical shifts are reported in ppm relative to the deuterated solvent.

The reusability of the Co catalyst was tested. After the reaction, the reaction mixture was centrifuged and the solid catalyst was recovered and washed with THF (3×5 mL). The catalyst was reused directly for the next run after it had been dried at 60 °C for 5 h in a vacuum oven.

Under the optimized reaction conditions, a hot filtration experiment was carried out to study whether the catalyst worked in a heterogeneous way. In the experiment, the reaction was quenched after 4 h by placing the reactor in ice water, and the solid catalyst was separated by filtration. The filtrate was analyzed by GC and then treated under similar conditions for 12 h, and then the reaction mixture was analyzed again by GC.



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