**Chemoselective and Tandem Reduction of Arenes Using a Metal–Organic Framework-Supported Single-Site Cobalt Catalyst**

Neha Antil,‡ Ajay Kumar,‡ Naved Akhtar, Wahida Begum, Manav Chauhan, Rajashree Newar, Manhar Singh Rawat, and Kuntal Manna*

**ABSTRACT:** The development of heterogeneous, chemoselective, and tandem catalytic systems using abundant metals is vital for the sustainable synthesis of fine and commodity chemicals. We report a robust and recyclable single-site cobalt-hydride catalyst based on a porous aluminum metal–organic framework (DUT-5 MOF) for chemoselective hydrogenation of arenes. The DUT-5 node-supported cobalt(II) hydride (DUT-5-CoH) is a versatile solid catalyst for chemoselective hydrogenation of a range of nonpolar and polar arenes, including heteroarenes such as pyridines, quinolines, isoquinolines, indoles, and furans to afford cycloalkanes and saturated heterocycles in excellent yields. DUT-5-CoH exhibited excellent functional group tolerance and could be reusable at least five times without decreased activity. The same MOF-Co catalyst was also efficient for tandem hydrogenation–hydrodeoxygenation of aryl carbonyl compounds, including biomass-derived platform molecules such as furfural and hydroxymethylfurfural to cycloalkanes. In the case of hydrogenation of cumene, our spectroscopic, kinetic, and density functional theory (DFT) studies suggest the insertion of a trisubstituted alkene intermediate into the Co–H bond occurring in the turnover limiting step. Our work highlights the potential of MOF-supported single-site base–metal catalysts for sustainable and environment-friendly industrial production of chemicals and biofuels.

**INTRODUCTION**

Cycloalkanes and saturated heterocycles are common structural motifs in pharmaceutical and biologically active molecules and have a range of applications as fuel, solvent, and starting materials in the synthesis of polymers, resins, and fine chemicals.¹⁻⁴ The reduction of aromatic rings is the most facile pathway to prepare cycloalkanes and saturated heterocycles as aromatic compounds are naturally occurring and essential feedstock for chemical synthesis. However, arenes, especially heteroarenes, are generally difficult to reduce due to aromatic stabilization and inhibition by heteroatoms. Among many methods for reducing arenes,¹⁻¹⁴ catalytic hydrogenation is very attractive in petrochemical and pharmaceutical industries both economically and environmentally due to its 100% atom efficiency and the usage of H₂ as a cost-effective reductant.¹⁰,¹³,¹⁶ Chemoselective hydrogenation of lignin-derived phenolic compounds could be applied to produce cyclohexanols from biomass, an alternative synthetic route to the petroleum-based process. Besides, tandem arene hydrogenation–hydrodeoxygenation has also been drawing much attention for the upgradation of lignocellulosic biomass to fuels and chemicals with reduced oxygen content. Efficient catalysts for arene hydrogenation have largely been developed based on late transition metals¹³,¹⁷⁻³⁶ Due to their low abundance, high cost, and toxicity, the development of hydrogenation catalysts has been focused in recent years primarily on abundant metals such as Zr,³⁷,³⁸ Fe,³⁹,⁴⁰ Co,⁴¹–⁵³ Ni,⁵⁴–⁶² and Cu.⁶³ However, many of these base–metal catalysts lack chemoselectivity and recyclability and have limited substrate scope. Recently, some heterogeneous but poorly defined earth-abundant metal catalysts have been reported, which show excellent activity and chemoselectivity in arene hydrogenation.⁴³,⁴⁵,⁴⁶,⁴⁸,⁵¹ Despite recent progress, the development of highly active and chemoselective single-site heterogeneous base–metal catalysts is crucial for studying mechanistic pathways and industrial processes.

As porous and tunable molecular materials, metal–organic frameworks (MOFs) have drawn much attention in developing earth-abundant metal-based single-site solid catalysts for various applications.⁶⁵–⁶⁷ Owing to their crystalline, isoreticular, and heterogeneous nature, MOFs offer the...
advantages of both homogeneous and heterogeneous catalysis. Unlike the metal-oxide supports, the metal-oxo cluster-based nodes or secondary building units (SBUs) of MOFs offer suitable support for the straightforward synthesis of well-defined earth-abundant metal species via active-site isolation. Benefiting from the presence of highly dispersed and uniform hydroxyl groups of their SBUs, single-site metal catalysts could easily be obtained via postsynthetic grafting or metalation. Furthermore, the chemoselectivity and stereoselectivity of the catalysts could be easily tuned by adjusting the pore sizes of the isoreticular MOFs.

Herein, we report straightforward postsynthetic metalation of an easily synthesizable aluminum MOF (DUT-5) with cobalt to afford a highly active single-site cobalt-functionalized MOF catalyst for chemoselective hydrogenation of a range of arenes including pyridines, quinolines, isoquinolines, indoles, and furans.

**RESULTS AND DISCUSSION**

**Synthesis and Characterization of Cobalt-Functionalized DUT-5 MOF.** The reaction of AlCl₃·6H₂O and 4,4′-biphenylidicarboxylic acid (H₂bpdc) in dimethylformamide (DMF) at 120 °C produced DUT-5 MOF as a white crystalline solid having a formula of [Al(OH)(bpdc)] with rhombic channels. The deprotonation of μ₂-OH of SBUs of DUT-5 by n-BuLi followed by reaction with CoCl₂ in tetrahydrofuran (THF) at room temperature gave SBU-supported cobalt chloride species (DUT-5-CoCl). The treatment of NaEt₂BH with DUT-5-CoCl at room temperature afforded the corresponding DUT-5 node-supported Co-hydride species (DUT-5-CoH) via a halide-hydride exchange. The cobalt loading of 29% with respect to bridged hydroxy groups at SBUs of DUT-5-CoH was determined by inductively coupled plasma optical emission spectroscopy (ICP-OES). The crystallinity and structure of MOF remained intact after metalation and the halide-hydride exchange as displayed by the similar powder X-ray diffraction (PXRD) patterns between pristine DUT-5, DUT-5-CoCl, and DUT-5-CoH (Figure 1b). The oxidation state and coordination environment of the cobalt ion in DUT-5-CoH were investigated previously using X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) at the Co K-edge. The cobalt(II) ion in DUT-5-CoH adopts a distorted square pyramidal geometry, coordinating with two neutral carboxylate oxygens, one anionic μ₃-O⁻, one hydride, and one THF to give the [μ₃-O(carboxylate-O)₂CoH(THF)] species. Scanning electron microscopy (SEM)−energy-dispersive X-ray (EDX) mapping of DUT-5-CoH indicated the uniform distribution of both Co and Al throughout the spherical MOF-particles (Figure 1c,d).

**DUT-5-CoH-Catalyzed Hydrogenation of Arenes.** DUT-5-CoH was an active heterogeneous catalyst for the hydrogenation of arenes to the corresponding cycloalkanes. The condition of the hydrogenation reaction was first optimized by varying temperature, H₂ pressure, catalyst loading, and solvent [Tables S1 and S2, Supporting Information (SI)]. The highest turnover frequency (TOF) was observed when hydrogenation was performed at 150 °C under 30 bar H₂ in n-heptane using 0.1 mol % DUT-5-CoH. At 0.1 mol % Co loading, p-xylene was completely hydrogenated in 12 h under the optimized condition to give 1,4-dimethylcyclohexane in 99% gas chromatography (GC) yield (Scheme 1). Importantly, a turnover number (TON) of 7000 was obtained for the hydrogenation of neat p-xylene. A wide range of nonpolar substituted arenes was completely hydrogenated under identical reaction conditions. Monosubstituted benzenes such as toluene and ethylbenzene, disubstituted benzenes such as xylene and cymene, and trisubstituted benzene such as mesitylene were reduced to the corresponding...
The hydrogenation of fused benzenes such as naphthalene and anthracene afforded decahydronaphthalene (10) and tetradehydroanthracene (11), respectively, in quantitative yields. Less volatile products (10 and 11) were isolated in excellent purity by centrifugation of solid MOF followed by removing the volatiles under vacuum.

DUT-5-CoH was also tolerant with various functional groups during the hydrogenation of arenes. Polar arenes bearing hydroxy, methoxy, or amine were efficiently reduced to their respective cycloalkanes keeping the functional groups intact (Scheme 1). At a 0.1 mol % Co loading, aminooarenes such as aniline, \(N,N\)-dimethylaniline, benzyl amine, 1-phenylethalamine, and 2-naphthylamine were reduced to cyclohexylamine (12), \(N,N\)-dimethycyclohexylamine (13), cyclohexanemethylamine (19), 1-cyclohexylethylamine (20), and decahydronaphthalen-2-amine (21) in 87–99% yields. Several methoxy and hydroxy-functionalized cyclohexane derivatives (14–17) were also obtained from the respective arenes in excellent yields. Lignin-derived guaiacol was also converted to 2-methoxycyclohexanol (16) selectively. Notably, under identical reaction conditions, the rate of hydrogenation of p-methoxyphenol was at least 5.7 times faster than the analogous bulky substrate, 2,6-disopropyl-4-methoxycyclohexanol, presumably due to the facile diffusion of smaller p-methoxyphenol and the corresponding product (17) through the MOF channels (Figure S3, SI). Interestingly, in the case of hydrogenation of benzyl alcohol and \(p\)-methy lacetoph enone, both the reduction of the aromatic ring and the deoxygenation of carbonyl were observed to furnish methycyclohexanol (22) and \(1\)-ethyl-4-methylcyclohexane (23), respectively.

Reduction of cumene at 150 °C under 30 bar H\(_2\) in the absence of DUT-5-CoH did not produce any isopropylycyclohexane suggesting DUT-5-Co as the catalyst for arene hydrogenation (Section S3.6, SI). In addition, at 0.1 mol % Co loading, the catalytical activity of DUT-5-Co was unaffected in the presence of metallic mercury, precluding the role of any leached cobalt particles in catalysis (Section S3.7, SI). DUT-5-CoH was recycled and reused at least five times for the hydrogenation of cumene without any apparent decrease of TOF, supporting the heterogeneity and robustness of the MOF catalyst (Figure 2a). Leaching of Co and Al in the supernatant during the recycling experiments, as calculated by ICP-OES, was 0.02 and 0.004%, after run 2, and 0.05 and 0.002%, respectively, after run 4.

**Mechanism of DUT-5-CoH-Catalyzed Hydrogenation of Aremes.** We next investigated the mechanism of DUT-5-CoH-catalyzed hydrogenation of arenes by spectroscopic, kinetic, and computational methods using cumene as a model substrate. The framework of DUT-5-Co was robust compared to that of pristine DUT-5-CoH (Figure 1b). No characteristic peaks of cobalt(0) particulates at higher 2θ angles were observed, precluding the role of any cobalt nanoparticles formed during hydrogenation as the potential catalyst. SEM−EDX mapping of recovered DUT-5-Co after hydrogenation of cumene displayed the uniform distribution of Co and Al throughout the MOF particle (Figure 2d). Furthermore, X-ray absorption near-edge spectroscopy (XANES) of the recovered MOF indicated the presence of Co\(^{II}\) species after catalysis (Figure 2b). Therefore, we infer that the SBU-supported Co\(^{II}\) hydride was the catalytic species for the hydrogenation of arenes. Kinetic analysis of DUT-5-CoH-catalyzed hydrogenation of cumene at 150 °C indicates an empirical rate law first order in [Co] and zero order in both [H\(_2\)] and [cumene]. Based on the above spectroscopic and kinetic data, we propose the catalytic cycle for arene hydrogenation, as shown in Figure 2e. The coordination of arene to cobalt followed by hydride transfer gives intermediate-1 (INT-2). The subsequent hydrogenolysis of the Co–C bond leads to the formation of INT-3. Then, similar alkene insertion into the Co–H bond followed by Co–C hydrogenolysis of cyclohexadiene and cyclohexene furnish Co-cyclohexyl species.
Finally, the $\sigma$-bond metathesis of the Co–C bond and H$_2$ produces isopropylcyclohexane and regenerates DUT-5-CoH. Density functional theory (DFT) modeling was carried out to obtain further insight into DUT-5-CoH-catalyzed hydrogenation of cumene and the reaction kinetics. The Gibbs free energy profile shown in Figure 3 indicated that cumene coordination to the Co center is exergonic by 16.5 kcal/mol. The hydride transfer step leading to the formation of INT-2 is associated with a barrier of 16.1 kcal/mol. The subsequent intermediate INT-3 is also endergonic by 8.2 kcal/mol formed via the Co–C bond hydrogenolysis of INT-2. The second hydride transfer and Co–C hydrogenolysis occur in a similar manner to give INT-5 but lie at lower energies. The

Figure 2. (a) % GC yield of isopropylcyclohexane in the recycling and reuse experiments of DUT-5-CoH for hydrogenation of cumene. (b) Co K-edge XANES spectra of CoCl$_2$ (black) and DUT-5-Co after hydrogenation of cumene (red). (c) Plots of initial rates $-\langle\text{d}[\text{substrate}]/\text{d}t\rangle$ for hydrogenation of cumene versus initial concentrations of cobalt and cumene for the first 5 min. (d) SEM–EDX mapping of DUT-5-Co after catalysis: SEM image (left) and Co and Al distribution (right). (e) Proposed catalytic cycle of hydrogenation of arenes.

Figure 3. DFT-calculated energy profile diagram of DUT-5-CoH-catalyzed arene hydrogenation using the B3LYP method and a basis set of 6–311G(d,p) on Gaussian 09.
transformation of INT-5 to INT-6 requires an activation barrier of 50.3 kcal/mol, which is the highest among all of the steps and, therefore, the rate-determining one. The DFT calculation identifies TS-3 as the turnover-limiting transition state involving the insertion of trisubstituted alkene, 1-isopropylcyclohex-1-ene, into the Co–H bond. The DFT-calculated turnover limiting step (TLS) is also in agreement with the aforementioned experimental rate law that is first order in [Co] and zero order in both [H₂] and [arene]. Compared to the insertion of arene and disubstituted alkene into Co–H in TS-1 and TS-2, respectively, the insertion of bulky trisubstituted cyclohexene requires higher activation energy. Indeed, 1-isopropylcyclohex-1-ene was detected by GC–MS during the incomplete hydrogenation of cumene (Figures S8 and S9, SI).

Chemoselective Hydrogenation of Heteroarenes. DUT-5-CoH was also efficient for catalytic dearomatization of various heteroarenes such as pyridines, quinolines, isoquinolines, indoles, and furans to the corresponding saturated heterocyclic compounds (Table 1). Piperidine and its derivatives are important bioactive alkaloids and building blocks in many drug molecules.²⁹ At a 0.4 mol % Co loading, pyridine and methyl- and methyl-functionalized pyridines were hydrogenated in complete conversion at 150 °C under 30 bar H₂ in n-heptane to produce piperidine (24) and substituted piperidines (25–27) with TON up to 250 (entries 1–4, Table 1). The formation of any ring-cleavage products was not observed. Interestingly, the hydrogenation of quinolines and isoquinolines reduced only the pyridyl rings chemoselectively under similar reaction conditions. Several 1,2,3,4-tetrahydroquinoline and 1,2,3,4-tetrahydroisoquinoline derivatives were afforded upon semihydrogenation of various quinolines and isoquinolines bearing alkyl, alkoxy, and amino groups (entries 6–12, Table 1). Substituted derivatives of tetrahydroquinoline are common motifs in many bioactive molecules such as oxamniquine, dynamycin, vibramycin, and nicainoprol.³⁰–³² Indole derivatives were also hydrogenated chemoselectively to the corresponding indolines with excellent yields and TON (entries 13–15, Table 1). Further, the synthesis of saturated O-heterocycles such as 3-tetrahydrofurfurylamine (39) and dodecahydro-1H-xanthene (41) was also explored using DUT-5-CoH (entries 16 and 18, Table 1). Again, complete deoxygenation and arene hydrogenation occurred in the hydrogenation of heterocycles bearing the carbonyl group (entries 5 and 17, Table 1).

DUT-5-CoH-Catalyzed Tandem Hydrogenation−Hydrodeoxygenation of Aromatic Carbonyl Compounds. Based on the observation of the incompatibility of the benzyl alcohol group and carbonyls during arene hydrogenation, we sought to explore DUT-5-CoH-catalyzed tandem hydrogenation−hydrodeoxygenation reactions to convert arene compounds bearing alcohol and carbonyl functionalities to cycloalkanes. Tandem hydrogenation−hydrodeoxygenation is an important catalytic chemical process for transforming biomass, particularly lignocellulose and hemicellulose to biofuel and chemicals.¹⁰³ A range of substituted acetophenones and benzophenones were converted to cycloalkanes via tandem deoxygenation of carbonyls and hydrogenation of aromatic rings at 150 °C under 30 bar H₂ using 0.5–1.0 mol % DUT-5-CoH (Table 2). No dissociation of functional groups such as alkyl, methoxy, hydroxy, and amino from the cyclohexyl ring was observed (entries 1–8, Table 2). Interestingly, hydrodeoxygenation of cyclohexanol did not

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occur, although the deoxygenation of hydroxyl located at the benzylic position of the alkyl chain proceeded smoothly (entries 4–6, Table 2). Benzophenone and 2-methylbenzophenone were converted to dicyclohexylmethane (51) and 1-(cyclohexylmethyl)-2-methylcyclohexane (52) in 93 and 75% yield, respectively. Biomass-derived platform molecules such as furfural and hydroxymethylfurfural were also successfully converted to 2-methyltetrahydrofuran (55) and 2,5-dimethyltetrahydrofuran (56), respectively, in excellent yields (entries 14–15, Table 2).

**CONCLUSIONS**

In conclusion, we have developed an easily synthesizable and highly active cobalt-hydride catalyst supported on DUT-5-MOF nodes for the hydrogenation of arenes and heteroarenes. A range of nonpolar and polar arenes and heteroarenes including pyridines, quinolines, isoquinolines, indoles, and furans were hydrogenated in good yields. Selective hydrogenation of only pyridyl and pyrrole rings in quinolines, isoquinolines, and indoles was achieved successfully with excellent productivity. DUT-5-MOF was tolerant with various functional groups such as alkyl, alkoxy, and amine, except the carbonyl groups. The mechanistic study for hydrogenation of arenes was performed using cumene as the model compound by spectroscopic, kinetic, and computational studies. In addition, one-pot synthesis of fully saturated cycloalkanes from arene carbonyl compounds was developed via tandem hydrogenation-hydrodeoxygenation reactions, which may find
application for conversion of biomass-derived platform molecules to higher-value chemicals and fuels. Our work features the potential importance of MOF-supported single-site base-metal catalysts for sustainable and eco-friendly industrial production of chemicals and biofuels.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.inorgchem.1c03098.

Synthesis and characterization of DUT-5-MOF and DUT-5-Co: experimental details for catalytic reactions; details for kinetics; and GC-analysis and DFT calculations (PDF).

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**Notes**

The authors declare no competing financial interest.

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