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Rhenium-Loaded TiO_2: A Highly Versatile and Chemoselective Catalyst for the Hydrogenation of Carboxylic Acid Derivatives and the *N*-Methylation of Amines Using H_2 and CO_2

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Abstract

Herein, we report a heterogeneous TiO_2-supported Re catalyst (Re/TiO_2) that promotes various selective hydrogenation reactions, e.g. hydrogenation of esters to alcohols, hydrogenation of amides to amines, and *N*-methylation of amines using H_2 and CO_2. Initially, Re/TiO_2 was evaluated in the context of the selective hydrogenation of 3-phenylpropionic acid methyl ester to afford 3-phenylpropanol (p_{H2} = 5 MPa, T = 180 ºC), where revealed a superior performance relative to other catalysts explored in this study. In contrast to other typical heterogeneous catalysts, Re/TiO_2 did not produce dearomatized byproducts. DFT studies suggested that the high selectivity for the formation of alcohols in favor of the hydrogenation of aromatic rings, should be ascribed to the higher affinity of Re toward the $–COOCH_3$ group relative to the benzene ring. Moreover, Re/TiO_2 shows a wide substrate scope for the reaction (19 examples). Subsequently, Re/TiO_2 was applied to the hydrogenation of amides and the *N*-methylation of amines with H_2 and CO_2. Furthermore, Re/TiO_2 promotes the *N*-alkylation of amines with carboxylic acids or esters in the presence of H_2.

Introduction

The discovery and development of efficient methods for the selective reduction of challenging functional groups such as carboxylic acids, amides, and esters have for many years presented formidable challenges, despite their importance and the high demand for a variety of applications in the pharmaceutical and fine-chemical industry, as well as in biomass conversion.[1] The challenges are associated predominantly with the fact that these carboxylic acid derivatives are usually thermodynamically stable and kinetically inert due to the low electrophilicity of the carbonyl carbon atom.[2] Although stoichiometric quantities of strong reducing agents have conventionally been used for this process,[3] the inevitable workup procedures, which include a hazardous quenching step, filtration, and repeated extractions, as well as the concomitant formation of undesirable waste are problematic, especially on an industrial scale. These issues could potentially be overcome by catalytic hydrogenations that use molecular hydrogen, as this would be an environmentally benign alternative.[4] It is therefore hardly surprising that substantial effort has been devoted to the development of such hydrogenation processes in order to realize environmentally more friendly systems, and some of these processes have already become industrial viable. However, since those carboxylic acid derivatives are among the most difficult carbonyl substrates to be hydrogenated, harsh reaction conditions are usually required to transform these substrates.[5] For instance, a conventional copper-chromite-based catalytic system requires very severe conditions (p_{H2} > 20 MPa, T = 250 ºC) and high catalyst loadings (~20 wt%).[6] The harsh conditions typically required for heterogeneous catalytic systems often go hand in hand with low selectivity and efficiency,[7] and the yields of these processes are frequently limited by over-reductions. Especially when aromatic rings and carboxylic acid groups are present in the substrates, the preferential hydrogenation of the former relative to the latter represents a severe problem for most catalytic systems.[8] Since aromatic rings are frequently encountered in many organic molecules including natural compounds, this restriction seriously limits the utility of such hydrogenation processes in synthetic chemistry, both on an academic and industrial scale.

In recent years, substantial progress has been made to promote the selective hydrogenation of carboxylic acid derivatives using homogeneous catalytic systems. Efforts have especially been devoted to the selective hydrogenation of carboxylic acids,[9] of esters to alcohols,[10] and of amides to amines.[11] It is worth pointing out that the homogeneous catalysts used in these reductions selectively hydrogenate the targeted functional groups, while they do not compromise any aromatic rings in the substrates, and that these processes thus represent highly important contributions to the toolkit of selective hydrogenations of carboxylic acid derivatives. However, the homogeneous catalysts used in these cases generally suffer from product separation issues and limited potential for catalyst recycling. This is especially problematic with respect to sustainability considerations and large-scale applications, and ideally, catalysts employed for selective hydrogenations should be heterogeneous and readily recyclable. Another shortcoming of the aforementioned homogeneous catalysts is that they are often highly substrate specific and frequently require stoichiometric amounts of additives. Consequently, a highly versatile heterogeneous catalyst for the reduction of a broad variety of carboxylic and carbonic acid derivatives represents a highly desirable research target in order to develop a flexible platform for the transformation of diverse functionalities. It is therefore not surprising that substantial efforts have been made to realize selective hydrogenations promoted by heterogeneous catalysts.[12] Even though various types of catalysts have been proposed,[8,12] heterogeneous catalysts normally suffer from competitive product formation, i.e., dearomatization of aromatic rings and/or over-reductions to alkanes diminish the chemoselectivity compared to homogeneous catalysts. The selective hydrogenation of carboxylic acid derivatives with heterogeneous catalysts in the absence of dearomatization remains challenging and represents a long-standing research objective with benefits in academic organic synthesis and the industrial production of bulk chemicals. A few heterogeneous catalytic systems can promote such selective hydrogenations of carboxylic acid derivatives in the absence of dearomatizations. For instance, a German patent claims the selective hydrogenation of amides using activated Co and Ni catalysts.[13] Broadbent *et al.* have reported the selective hydrogenation of carboxylic acid derivatives including carboxylic acids, esters, and amides catalyzed by rhenium black, which was prepared *in situ* from Re oxides.[14] Although these seminal contributions are undoubtedly remarkable, these catalytic systems typically require high pressures and temperatures (p_{H2} > 20 MPa; T > 200 ºC), especially for the transformation of esters and amides. In addition, their substrate scopes remained limited for each reaction. More recently, heterobimetallic Ru/Sn catalysts loaded on Al_2O_3 have been reported to promote the hydrogenation of carboxylic acids that contain aromatic rings.[15] Furthermore, Lu *et al.* have reported Cu/ZnO-Al_2O_3-based catalysts that convert amino acid esters without dearomatization into the corresponding amino alcohols.[16] However, in these reports, the substrate scope and the applicability toward various carboxylic acid derivatives of these hydrogenations is limited, and thus, the development of more general and efficient systems is strongly desirable. In this context, we have very recently reported that a heterogeneous TiO_2-supported Re catalyst (Re/TiO_2) promotes the selective hydrogenation of various carboxylic acids that contain aromatic moieties to the corresponding alcohols under relatively mild conditions (p_{H2} = 5 MPa, T = 140–180 ºC; 22 examples; yield ≤ 97%), whereby additives are not required.[17] It should be noted here that this heterogeneous catalytic system does not produce any dearomatized byproducts, despite the difficulty of hydrogenating the –COOH group.[18] The high chemoselectivity of the Re/TiO_2 catalytic system toward the selective hydrogenation of carboxylic acids to alcohols under concomitant compatibility of aromatic rings are features rarely seen for both homogeneous and heterogeneous hydrogenation catalysts. Although selective hydrogenations of carboxylic acids that contain aromatic groups to alcohols over heterogeneous catalysts have been developed, a highly versatile heterogeneous catalyst for the reduction of a broad variety of carboxylic acid derivatives would be desirable in order to meet the demand for the development of a general catalytic system for these challenging transformations.[9a]

This study is concerned with the selective hydrogenation of carboxylic acid esters and amides that contain aromatic moieties using the aforementioned Re/TiO_2 catalyst. In contrast to previously developed catalysts for these reactions, Re/TiO_2 is heterogeneous and can accordingly be recovered and recycled with relative ease, while the synthesis of the catalyst is straightforward using a facile impregnation method. Even under relatively mild conditions, Re/TiO_2 displays high activity and does not require additives. Density functional theory (DFT) calculations suggested that the high selectivity for the generation of alcohols, which leaves aromatic rings unaffected, should be attributed to the higher affinity of Re toward the –$COOCH_3$ group than to aromatic rings. In addition to the simple hydrogenation of esters and amides, the *N*-alkylation of amines via hydrogenation was also accomplished. The latter reaction involves the hydrogenation of carboxylic acid esters to the corresponding alcohols in the presence of H_2, followed by *N*-alkylation of the amines with the generated alcohol. Furthermore, the *N*-methylation of amines using H_2 and CO_2 has been achieved using Re/TiO_2. The broad range of organic transformations, based on the selective hydrogenation of carboxylic acid derivatives promoted by Re/TiO_2 should render this catalyst system a highly desirable tool for synthetic organic chemistry.

Results and Discussion

The Re/TiO_2 catalyst was prepared using a facile impregnation method based on NH_4ReO_4 and TiO_2. The catalyst was characterized by X-ray diffraction (XRD) analysis and transmission electron microscopy (TEM) (**Figures S1** and **S2**). The XRD patterns of Re/TiO_2 exhibited peaks that arise exclusively from TiO_2, while peaks associated with Re species were not observed. TEM measurements showed that the Re clusters on TiO_2 exhibit particle sizes below 2 nm. These results suggest that the Re species are highly dispersed on TiO_2, similar to our previous study.[19] The X-ray photoelectron spectroscopy (XPS) analysis revealed the oxidation states of the Re species on TiO_2. **Figure 1** shows the XPS spectra of the Re 4f region of Re/TiO_2 before and after reduction with H_2 at T = 700 ˚C. It should be noted that the reduced samples were measured directly after the H_2 reduction without any exposure to air by using a glove box that was connected to the XPS chamber. The obtained spectra include signals due to both $4f_{7/2}$ and $4f_{5/2}$ core levels. The spectrum of Re/TiO_2 prior to the H_2 reduction showed two Re components that contain $4f_{7/2}$ peaks at ~46.1 eV, which is assigned to Re^{+VII} species with an atomic concentration of 56%, and at ~44.0 eV, which is attributed to Re^{+VI} species with an atomic concentration of 44% (**Fig. 1(a)**). On the other hand, a strong peak at ~40.7 eV assignable to a $4f_{7/2}$ peak of Re^0 species was observed for Re/TiO_2 after the reduction, as shown in **Fig. 1(b)**. The result suggests that the major part of the Re species were reduced to a metallic state after the reduction. Minor contributions from oxidized Re species such as Re^{+III} and Re^{+IV} could also be observed even after the H_2 reduction.[20] These results indicate that the H_2 reduction induces the formation of low-valent Re species that include the metallic state.

The ring-stretching region of the FT-IR spectra for pyridine adsorbed both on Re/TiO_2 and pristine TiO_2 is shown in **Figure 2**. Consistent with previous FT-IR studies,[21] the spectra for both Re/TiO_2 and TiO_2 exhibit a strong band at 1445 cm^{-1}, which is due to pyridine that coordinates to the Lewis-acidic sites, whereas a band at 1540 cm^{-1}, which should be due to the pyridinium ion (PyH^+), was not observed in significant intensity. This result indicates that both samples contain Lewis but not Brønsted acid sites. The spectra furthermore revealed that the intensity of the band at 1445 cm^{-1} is higher for Re/TiO_2 than for TiO_2, which suggests that the introduced Re species contain Lewis acid sites.

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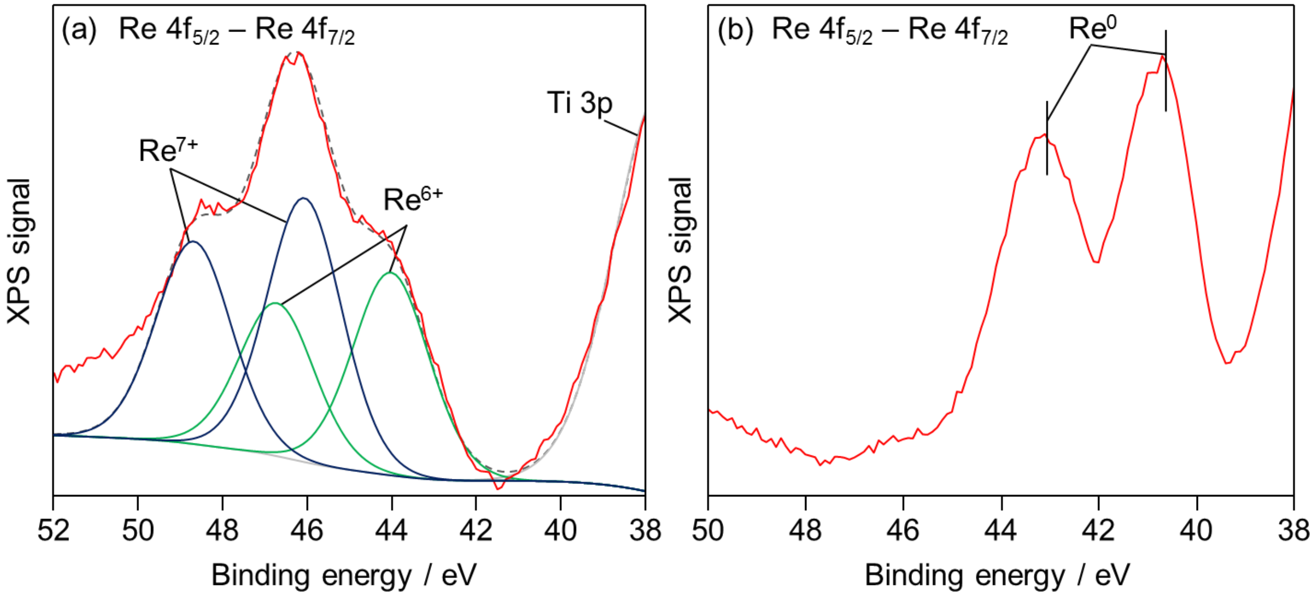


Figure 1. XPS spectra of the Re 4f region of Re/TiO_2 (a) before and (b) after the reduction with H_2 at *T* = 700 ˚C. Red line: raw spectra; dark gray line (dashed): total; pale gray line: Ti 3p; green line: Re^{6+}; navy blue line: Re^{7+}.

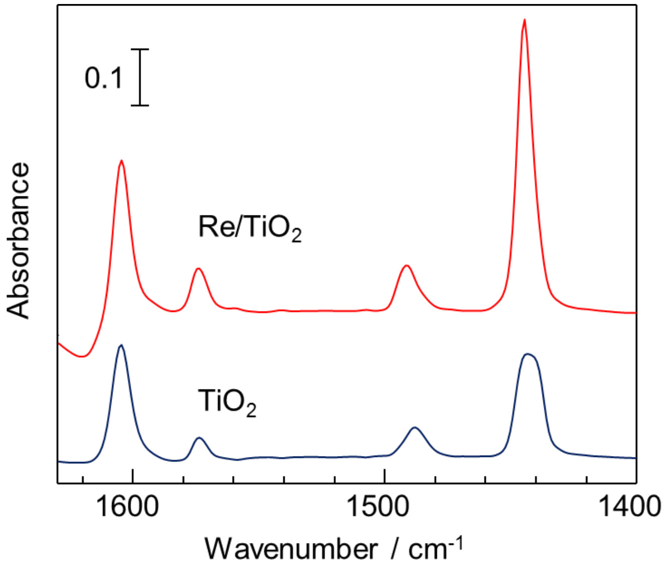
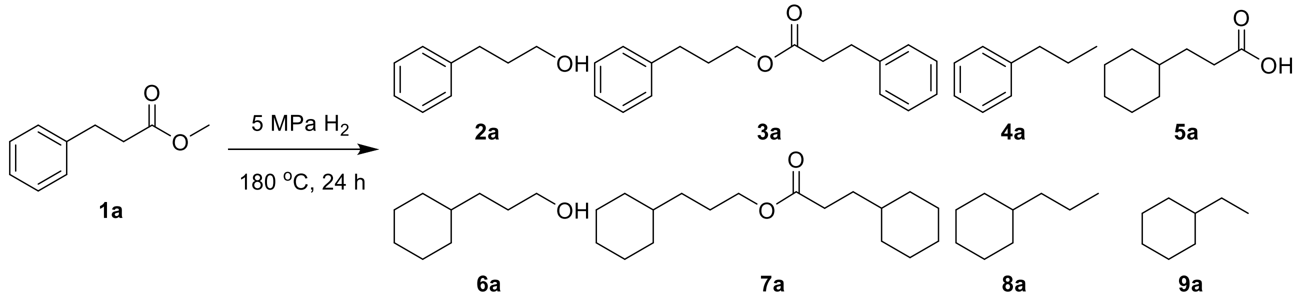


Figure 2. Ring-stretching region of the FT-IR spectra of pyridine adsorbed on Re/TiO_2 and TiO_2 after the H_2 reduction. Measurements were carried out at *T* = 100 °C under a He flow.

Hydrogenations of 3-phenylpropionic acid methyl ester (**1a**) were carried out in order to screen the properties of various catalysts. Following pretreatment of the catalysts with H_2 at 700 °C, reactions were carried out using 1 mmol of **1a** and 2 mol% of catalyst in a stainless autoclave (V = 10 cm^3; p_{H2} = 5 MPa; T = 180 ºC; t = 24 h). The obtained results are summarized in **Table 1**. Re/TiO_2 produced 3-phenylpropanol (**2a**) and 3-phenylpropyl 3-phenyl-propionate (**3a**) in yields of 96% and 3%, respectively. It was expected that **3a** is formed via a transesterification between the starting ester and the alcohol generated during the reaction, but it should also be noted that methanol was also detected as a product. In contrast, merely low yields of the alcohol were observed when other precious metal (Ru, Pt, Ir, Rh, or Pd) catalysts were used (**entries 2-6**). This should mainly be attributed to the formation of byproducts such as propyl-benzene (**4a**), 3-cyclohexyl-propionic acid (**5a**), 3-cyclohexyl-propan-1-ol (**6a**), 3-cyclohexyl-propionic acid 3-cyclohexyl-propyl ester (**7a**), propyl-cyclohexane (**8a**), and ethyl-cyclohexane (**9a**) via the competitive hydrogenation of benzene rings and over-reduction to alkanes. Such side reactions should be expected, as the hydrogenation of the aromatic ring should proceed easier than the far more demanding reduction of the ester group. The reaction was not promoted by Ag-, Cu-, Ni-, or Co-loaded TiO_2 catalyst systems (**entries 7-10**). In addition, no reaction occurred when pristine TiO_2 was used as the catalyst (**entry 11**). Moreover, we observed that Re/TiO_2 afforded **2a** and **3a** much more efficiently than other Re-based catalysts on other supports (**entries 13-24**). In a control experiment, we confirmed that NH_4ReO_4, as well as non-supported Re metal and its oxides (e.g. ReO_2 and Re_2O_7) did not catalyze this hydrogenation reaction (**entries 25-28**). These results clearly demonstrate that the combination of Re as the catalytically active species and TiO_2 as the support leads to an efficient catalyst system that selectively promotes the hydrogenation of esters to form alcohols, whereby the generation of undesired products such as alkanes and dearomatized compounds is minimized.

Table 1. Heterogeneous catalytic hydrogenation of 3-phenylpropionic acid methyl ester.[a]



Entry	Catalysts	Conv. [%]	Yield [%]							
			2a	**3a**	**4a**	**5a**	**6a**	**7a**	**8a**	**9a**
1	Re/TiO_2	99	96	3	0	0	0	0	0	0
2	Ru/TiO_2	83	0	0	4	0	44	18	0	16
3	Pt/TiO_2	82	50	0	0	0	2	27	2	0
4	Ir/TiO_2	39	10	28	0	0	0	0	1	0
5	Rh/TiO_2	36	2	0	0	22	0	5	0	9
6	Pd/TiO_2	34	0	0	4	6	5	19	0	0
7	Ag/TiO_2	3	1	2	0	0	0	0	0	0
8	Cu/TiO_2	0	0	0	0	0	0	0	0	0
9	Ni/TiO_2	0	0	0	0	0	0	0	0	0
10	Co/TiO_2	0	0	0	0	0	0	0	0	0
11	TiO_2	0	0	0	0	0	0	0	0	0
12[b]	Re/TiO_2	18	10	8	0	0	0	0	0	0
13	Re/Carbon	90	74	0	16	0	0	0	0	0
14	Re/θ-Al_2O_3	60	39	20	1	0	0	0	0	0
15	Re/γ-Al_2O_3	57	39	16	1	0	0	0	0	0
16	Re/ZrO_2	16	15	1	0	0	0	0	0	0
17	Re/HZSM-5(22)	29	12	10	4	0	0	0	0	0
18	Re/SiO_2	16	10	4	0	0	0	0	0	0
19	Re/SiO_2-Al_2O_3	31	8	23	1	0	0	0	0	0
20	Re/HY(5.5)	35	7	18	4	0	0	0	0	0
21	Re/Nb_2O_5	15	6	9	0	0	0	0	0	0
22	Re/CeO_2	6	3	0	3	0	0	0	0	0
23	Re/MgO	1	0	0	0	0	0	0	0	0
24	Re/SnO_2	0	0	0	0	0	0	0	0	0
25[c]	NH_4ReO_4	7	6	0	0	0	0	0	0	0
26	Metallic Re	1	1	0	0	0	0	0	0	0
27	ReO_2	2	2	0	0	0	0	0	0	0
28	Re_2O_7	1	1	0	0	0	0	0	0	0

[a] Reaction conditions: 2 mol% catalyst, 1 mmol phenylpropionic acid methyl ester, 3 mL octane, p_{H2} = 5 MPa, T = 180 °C, t = 24 h. Yields were determined by GC using *n*-dodecane as the internal standard. [b] The reaction was performed after calcination at T = 500 °C in air. [c] The reaction was performed without pretreatment.

DFT calculations were conducted in order to identify the origin of the high selectivity of Re/TiO_2 toward the formation of alcohols relative to the dearomatization of benzene rings. We have previously reported that the selectivity of the hydrogenation of carboxylic acid derivatives strongly depends on the relative adsorption affinities of their functional groups, specifically on the benzene rings and the –COOH groups.[17] Accordingly, we examined the relative adsorption affinities of –$COOCH_3$ and benzene moieties on the catalyst surfaces, employing methyl acetate and benzene as probe molecules. In addition to Re, metals that promote the hydrogenation of aromatic rings rather than that of –$COOCH_3$ groups such as Pd and Rh were examined for comparison. It should be noted that the most stable and common planes for each metal were used for this investigation. The most stable adsorption structures of methyl acetate adsorbed on the Re(0001), Pd(111), and Rh(111) surfaces are displayed in **Figures S3-5**. As shown in **Figure 3**, the adsorption energy of benzene on Re(0001) is lower than that on Pd(111) or Rh(111). In contrast, the adsorption energy of methyl acetate on Re(0001) is higher than that on Pd(111) or Rh(111). To rationalize this trend, we calculated the projected density of states (PDOS), which is shown in **Figure 4**. The HOMO-like (highest occupied Kohn-Sham orbital) states of both methyl acetate and benzene are broadened (*cf.* blue line in **Figure 4**), indicating that all systems exhibit a forward-donation from the HOMO of methyl acetate and benzene to the metal surfaces. As Re(0001) has more unoccupied d band than Pd(111) and Rh(111),[22] the adsorption energy on the Re(0001) surface should be higher than that on the Pd(111) or Rh(111) surfaces. This more open d band feature, which is located just above the Fermi level (0 eV in the figures), should thus be responsible for the strong adsorption of methyl acetate on Re(0001) relative to the other surfaces. In contrast to methyl acetate, benzene adsorbs weaker on the Re(0001) surface than on the Pd(111) or Rh(111) surfaces. This should be due to the weaker back-donation from the occupied d-band of the metal surface to the empty π* orbitals (LUMOs) of benzene.[23] This feature can be observed in the PDOS as follows. Upon the adsorption on the surface, the peaks for the LUMO-like (lowest unoccupied Kohn-Sham orbital) state of benzene are significantly broadened relative to the position observed for benzene in the gas phase, indicating a strong back-donation from the metal surfaces to the LUMO of benzene (*cf.* blue line in **Figure 3**). In addition, adsorbed benzene molecules are more negatively charged than adsorbed methyl acetate molecules on each metal surface (**Table S1**). Furthermore, benzene adsorbed on the Re(001) surface is less negatively charged in comparison to benzene adsorbed on the Pd(111) or Rh(111) surfaces, indicating a weaker back-donation from the Re(001) surface to benzene compared to Pd(111) and Rh(111). These results reasonably explain why the Re surface exhibits a higher affinity toward the $–COOCH_3$ group and a lower affinity toward the benzene moiety relative to the other metal surfaces, and consequently the high selectivity of Re/TiO_2 for the hydrogenation of 3-phenylpropionic acid methyl ester. This relatively high affinity of Re toward $–COOCH_3$ should be one reason to explain the high selectivity of Re/TiO_2 for the hydrogenation of 3-phenylpropionic acid methyl ester. We also considered geometric factors of the adsorbates as well as the aforementioned electronic structures. These features can be evaluated by the adsorption modes and the C–C bond distances of the optimized structures of benzene on the surfaces and in the gas phase (**Figure 5**). The calculated C–C bond distances for benzene in the gas phase (1.40-1.41 Å) are consistent with those obtained from previous DFT studies.[24] On the Re(0001) surface, the adsorption mode where the center of the aromatic ring is located above the hollow position has been identified as the most favorable. Although the calculated C–C bond distances of benzene on the Re(0001) surface (1.44-1.45 Å) increase upon adsorption, the six C–C bonds remain almost equivalent, which is similar to the gas phase. Conversely, the bridge site was found to be most favorable adsorption site for benzene on the Pd(111) and Rh(111) surfaces.[25] Moreover, the six C–C bonds are no longer equivalent and consist of two short (*cf.* C–C bonds 2 and 5 in Figure 4) and four long bonds (C–C bonds 1, 3, 4, and 6 in Figure 4). This result indicates that the adsorption of benzene on Pd(111) and Rh(111) leads to a sp^2 to sp^3 rehybridization, which transforms the adsorbate from an aromatic planar mode to a 1,4-cyclohexadiene-like conformation.[26] Specifically, benzene distorts to a higher degree on the Pd(111) and Rh(111) surfaces compared to the Re(0001) surface, which represents another important factor explaining the higher affinity of the former to aromatic rings, and why Pd and Rh metals hydrogenate benzene rings, while Re does not.

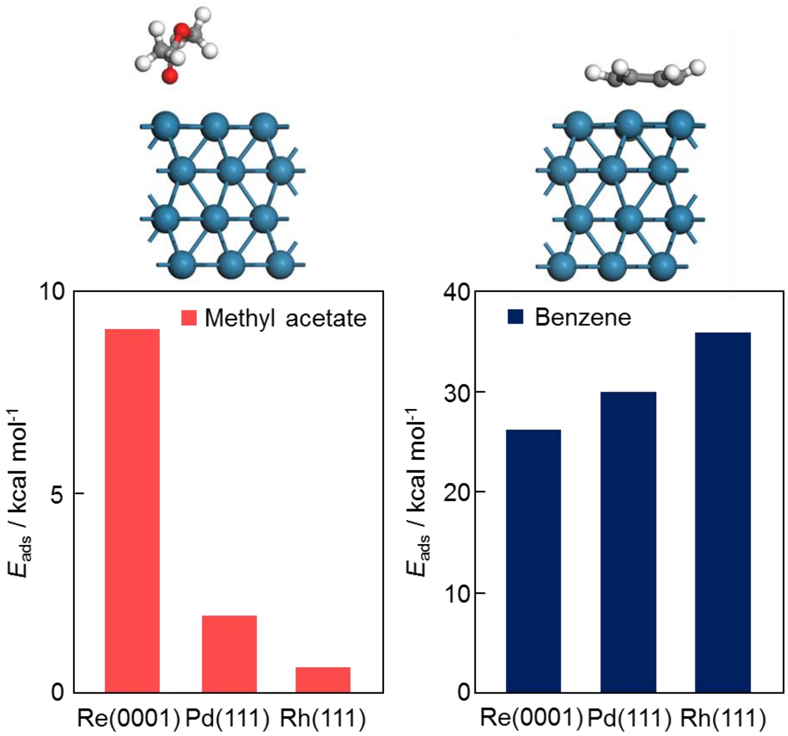


Figure 3. Adsorption energies of benzene and methyl acetate on Re(0001), Pd(111), and Rh(111). The most stable adsorption structures of benzene and methyl acetate adsorbed on Re(0001) are shown (side view).

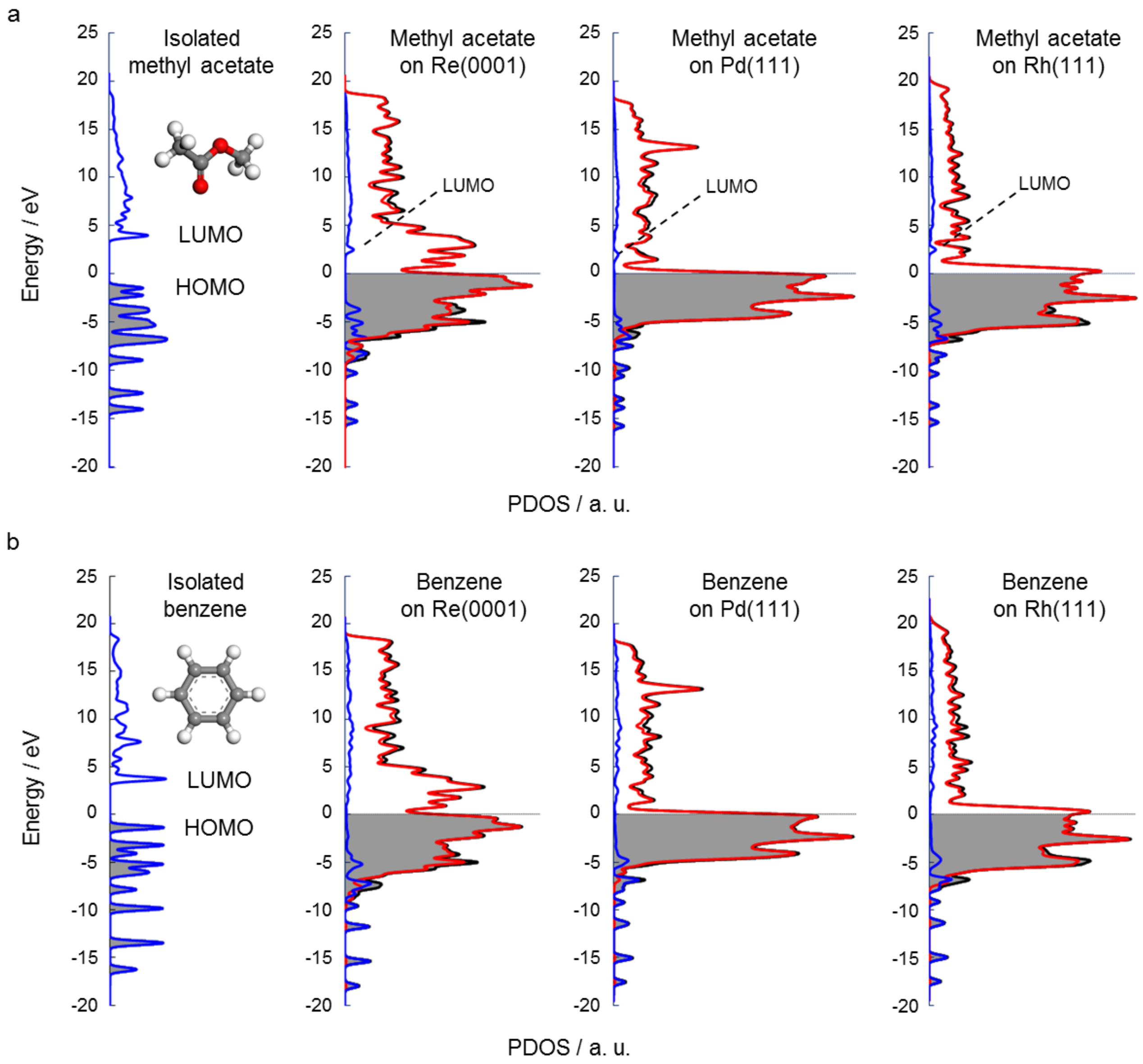


Figure 4. PDOSs of (a) isolated methyl acetate and methyl acetate adsorbed on the Re(0001), Pd(111), and Rh(111) surfaces; (b) isolated benzene and benzene adsorbed on the Re(0001), Pd(111), and Rh(111) surfaces; black line: total PDOS; blue line: PDOS of the adsorbates; red line: PDOS of the slabs; in all plots: $E_F = 0$. The PDOS calculations for isolated methyl acetate and benzene were performed by placing the molecules at the center of the vacuum space on top of the Re(0001) slab.

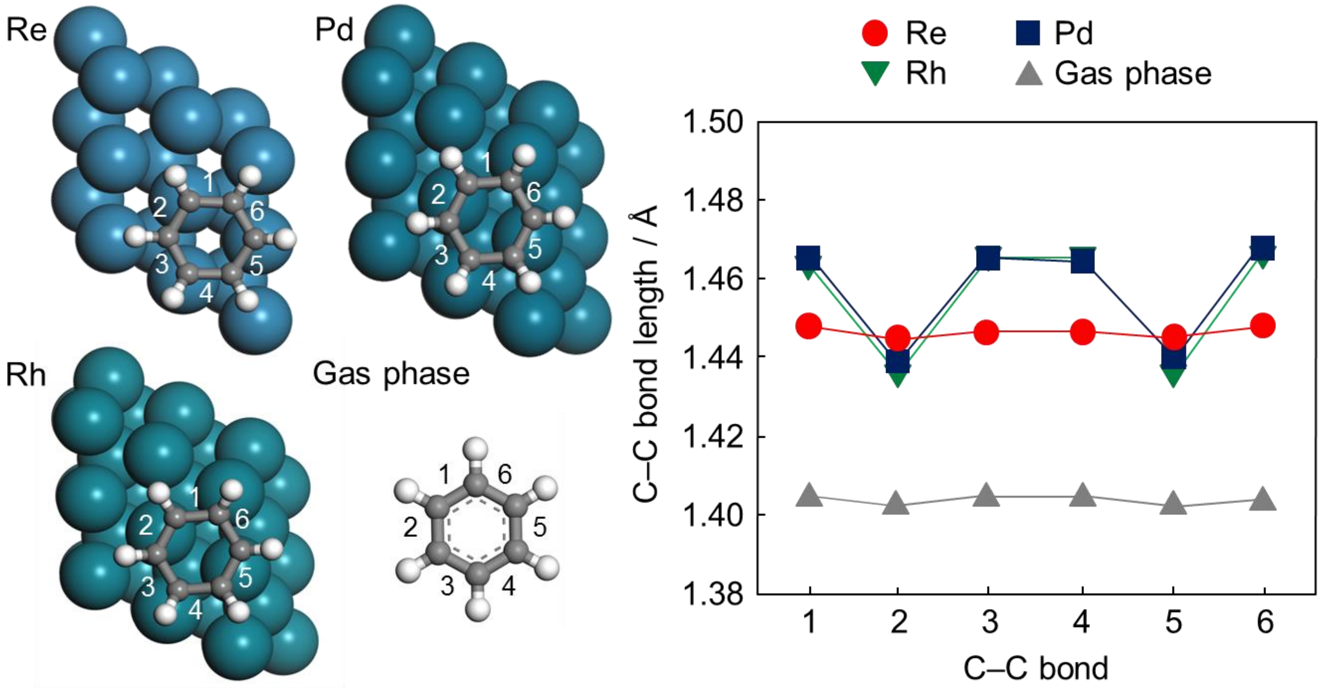


Figure 5. C–C bond distances in the optimized structures of benzene on the Re(0001), Pd(111), and Rh(111) surfaces, as well as for benzene in the gas phase. Color code: gray: C; white: H; blue: metal atoms.

The Re/TiO_2 catalyst system and the reaction conditions for the hydrogenation of 3-phenylpropionic acid methyl ester were further investigated. In particular, the effects of the Re loading, the pretreatment temperature, and the H_2 pressure were explored. The results (**Tables S2-4**) show that the catalytic activity reached a maximum for a catalyst loading of 5 wt% of Re. The yield of alcohol **2a** increase with increasing pretreatment temperature and H_2 pressure, which level at T = ~ 500 ºC and p_{H2} = 5 MPa, respectively. It should be noted that the yield of **2a** was only 10% when the reaction was performed after calcination at T = 500 °C in air without an H_2 reduction pretreatment (**entry 12**, **Table 1**). The effects of the reaction solvent and temperature were also investigated (**Table S5 and S6**). The reaction proceeds efficiently to afford alcohols (yield: > 90%) in a variety of solvents including hexane, octane, *p*-xylene, *o*-xylene, 1,4-dioxane, THF, and dimethoxyethane (DME). We found that the reaction proceeds at lower temperature, but that temperatures of at least 180 °C are required to obtain an alcohol yield of > 90% under the applied conditions.

The time-course plot of the hydrogenation of 3-phenylpropionic acid methyl ester in (**Figure 6**) shows that 3-phenylpropanol (**2a**) was efficiently generated from 3-phenylpropionic acid methyl ester (**1a**). It is noteworthy here, that **3a** was formed as an intermediate from the transesterification of **1a** and **2a**. The yield of **2a** reached 96% after t = 24 h. However, 3-phenylpropionaldehyde, which would be an anticipated intermediate in this process together with other over-reduced products, was not observed even after t = 24 h. In order to examine the reaction kinetics, a hydrogenation reaction employing **3a** as the starting material was carried out, and the obtained time-course plot is shown in **Figure S6**. An inspection of the time-course plot shows that the hydrogenation of **3a** is a slightly slower than that of **1a**. In addition, a recycling test of Re/TiO_2 was carried out to evaluate the potential reusability of this heterogeneous catalyst system. Following the reaction, Re/TiO_2 was separated, washed with isopropanol, dried in air, reduced with H_2 at T = 700 °C, and subsequently reused for an ensuing reaction. In this second run, the desired alcohol was obtained in excellent yield (97%), indicating that the Re/TiO_2 catalyst is recyclable. However, we found that the product alcohol yield gradually decreased after the 4th recycling experiment. It should also be noted that a second run without the reduction step using H_2 afforded **2a** in 75% yield, which is lower than the yield obtained with an H_2 reduction, indicating that the H_2 reduction is necessary for optimal recycling.[27] In order to further confirm the heterogeneous nature of the Re/TiO_2 system, a leaching test was performed (**Figure S8**), which revealed that the removal of the catalyst after *t* = 3 h caused the hydrogenation to cease, indicating that only supported-Re species act as catalytically active sites.

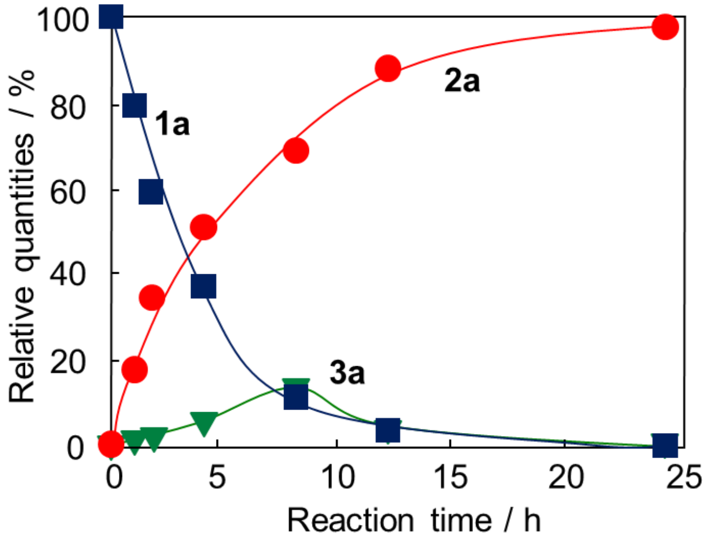
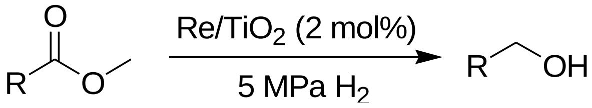


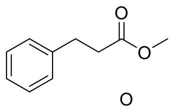
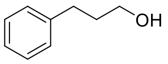
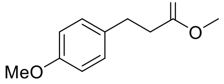
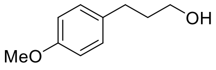
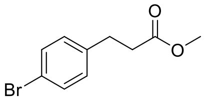
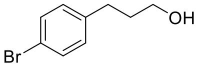
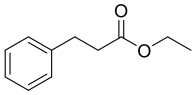
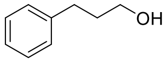
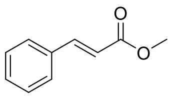
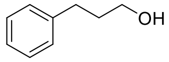
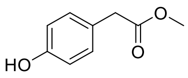
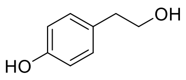
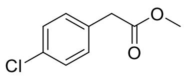
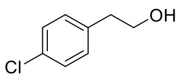
Figure 6. Time-course plot of the hydrogenation of 3-phenylpropionic acid methyl ester catalyzed by Re/TiO_2; **1a**: 3-phenylpropionic acid methyl ester; **2a**: 3-phenylpropanol; **3a**: 3-phenylpropyl 3-phenyl-propionate. Reaction conditions: 2 mol% Re, 1 mmol phenylpropionic acid methyl ester, 3 mL octane, p_{H2} = 5 MPa.

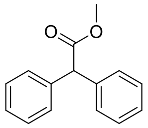
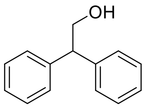
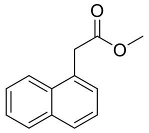
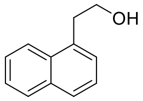
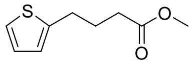
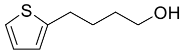
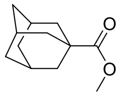
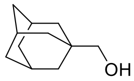
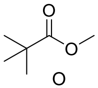
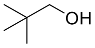
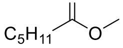
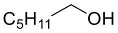
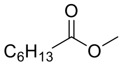
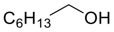
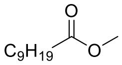
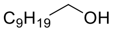
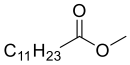
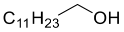
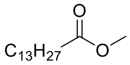
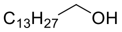
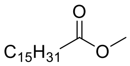
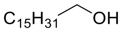
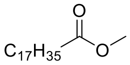
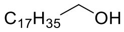
The substrate scope of the reaction was explored in order to assess the potential versatility of the Re/TiO_2-catalyzed hydrogenation process. The results (**Table 2**) show that Re/TiO_2 is capable of promoting the hydrogenation of a wide range of carboxylic acid esters to alcohols. Notably, substrates containing chlorine- or bromo-substituted benzene rings underwent the selective hydrogenation with these functional groups remaining intact (**entries 3**, **7**). Moreover, Re/TiO_2 can be used for the hydrogenation of substrates containing heterocyclic compounds to yield the corresponding alcohols (**entry 10**). At present, this process is still somewhat limited by e.g. olefin moieties in the substrates, which are reduced under the applied reaction conditions (**entry 5**). Moreover, methyl benzoate was hydrogenated to toluene (97% yield) over Re/TiO_2 at *T* = 180 °C and p_{H2} = 5 MPa after 24 h through an undesired over reduction. However, the high chemoselectivity of the Re/TiO_2-catalyzed hydrogenation and its concomitant compatibility with aromatic rings are rarely encountered features, especially for heterogeneous hydrogenation catalysts.

Driven by the desire to replace fossil fuel sources, much attention has been given to the conversion of biomass materials into fuels and chemicals.[28] Selective hydrogenations of carboxylic acid esters are important methods in this context, as these can be employed to generate fatty alcohols, which are widely used in the production of surfactants, polymers, and solvents.[29] To evaluate the applicability of the Re/TiO_2 catalyst for the generation of fatty alcohols, hydrogenation reactions of various fatty acid esters were explored. Fatty acid esters with long or short aliphatic chains underwent efficient hydrogenation to produce the corresponding alcohols in 67-92% yield under the previously established optimal conditions (**Table 2**). These observations suggest that Re/TiO_2 should also be applicable for the hydrogenation of bio-relevant carboxylic acid esters.

Table 2. Catalytic hydrogenation of carboxylic acid esters to alcohols using Re/TiO_2.[a]



Entry	Substrate	Product	Temperature [°C]	Time [h]	Yield [%]
1			180	24	96 (93)
2			180	24	97 (93)
3			200	24	71 (57)
4			180	24	97 (92)
5			180	24	95 (90)
6			200	24	94 (91)
7			200	24	82 (76)

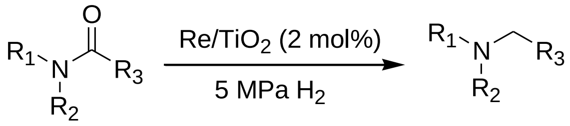
8			180	24	97 (94)
9			180	24	89 (85)
10			200	48	85 (81)
11			200	48	92 (86)
12			200	48	94
13			180	24	90 (87)
14			180	24	89 (85)
15			180	36	92 (90)
16			180	24	67 (62)
17			180	36	90 (86)
18			180	36	90 (88)
19			180	36	76 (73)

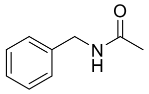
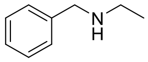
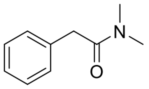
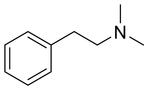
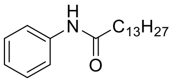
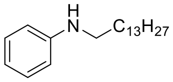
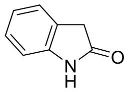
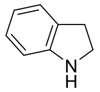
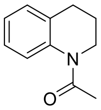
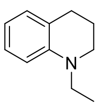
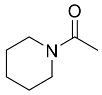
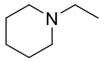
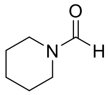
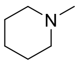
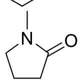
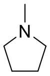
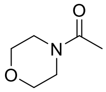
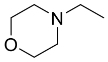
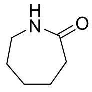
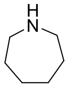
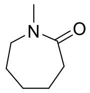
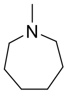
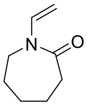
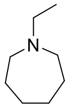
^{a}Reaction conditions: 2 mol% Re, 1 mmol ester, 3 mL octane, p_{H2} = 5 MPa. Yields were determined by GC using *n*-dodecane as the internal standard. Yields of isolated products are given in parenthesis.

In order to show the potentially extended utility of the Re/TiO_2 catalytic system, we examined the hydrogenation of amides to amines. This reaction has recently attracted much interest, as it is as important for academic and industrial applications as it is challenging. In addition, the selective hydrogenation of amides that contain aromatic moieties is considered particularly difficult over heterogeneous catalysts.[12d] Prior to the exploration of the substrate scope, a catalyst screening was carried using some promising catalysts based on the results from the ester and carboxylic hydrogenation reactions. The hydrogenation of *N*-benzylacetamide (**1b**) was selected, and p_{H2} = 5 MPa and T = 180 °C were employed for this purpose. The results, summarized in **Table S7** in the supporting information, show that Re/TiO_2 exhibited the best activity and selectivity, and yielded *N*-ethylbenzylamine (**2b**) in 86% yield. The results of the hydrogenation of various amides to amines using Re/TiO_2 (p_{H2} = 5 MPa, T = 180-200 °C) is summarized in **Table 3**. Re/TiO_2 enabled the selective hydrogenation of various substrates that contain aromatic and aliphatic moieties. Importantly, Re/TiO_2 does not lead to the formation of dearomatized byproducts when aromatic rings are present in the substrate. It is also noteworthy that the required conditions to promote this transformation are similar to the previously reported systems using precious metals such as Pt, Ru, or Rh.[8,12d,30] Although some instances were observed, where olefin moieties were reduced (**entry 11**), similar to the case of the ester hydrogenation, the wide substrate scope that includes in particular amides that contain aromatic rings, can hardly be accessed with conventional heterogeneous catalysts. The selective hydrogenation of the primary amide 2-phenylacetamide was tested using the Re/TiO_2 catalyst under p_{H2} = 5 MPa and T = 180 °C. After 24 h, diphenylamine and *N*-phenethyl-2-phenylacetoamide were obtained in 38% and 45% yield, respectively. The formation of these products could be feasible attributed to coupling reactions of the starting 2-phenylacetamide and/or 2-phenyethylamine, which is a well-known difficulty in the hydrogenation of primary amides.[12d] For the suppression of such coupling reactions, further studies are required.

Depending on the type of catalyst, the hydrogenation of amides to amines can proceed via two principal pathways: i) an initial reduction of the amide carbonyl group to a hemiaminal, which leads to the formation of an alcohol and amine via cleavage of the C–N bond, followed by an amination of the alcohol with the amine,[31] or ii) a simple deoxygenation of the amide. In order to determine the reaction pathway operative in the present system, the time-course plots of the hydrogenation of *N*-benzylacetamide (**1b**) were recorded (**Fig. S9**). The plots show that **1b** is consumed under concomitant formation of *N*-ethylbenzylamine (**2b**), which is obtained in 86% yield after *t* = 24 h. It should be noted that the corresponding alcohol and amine were not observed during the hydrogenation. This result indicates that the reaction should proceed via the deoxygenation of the amide over the Re/TiO_2 catalyst.

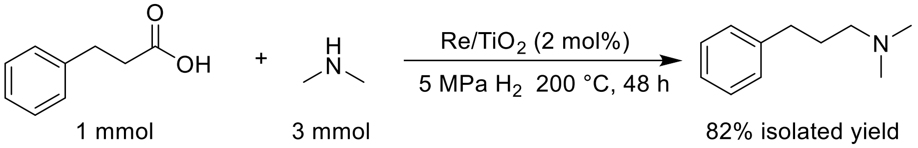
Table 3. Catalytic hydrogenation of various amides to amines using Re/TiO_2.[a]



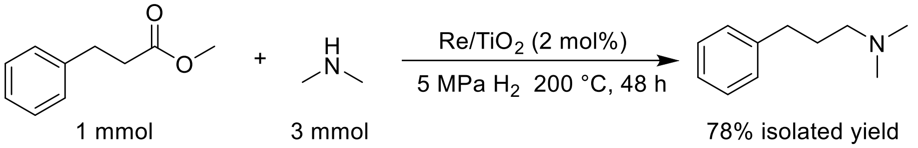
Entry	Substrate	Product	Temperature [°C]	Time [h]	Yield [%]
1			180	24	86 (78)
2			200	24	83
3			200	20	91
4			180	24	54
5			180	24	85
6			180	24	99
7			180	24	99
8			180	24	94
9			180	24	94
10			200	36	56
11			200	24	87
12			180	36	70

[a]Reaction conditions: 2 mol% Re, 1 mmol amide, 3 mL octane, p_{H2} = 5 MPa. Yields were determined by GC using *n*-dodecane as the internal standard. Yields of isolated products are given in parenthesis.

Schemes 1 and 2 demonstrate the potential applicability of Re/TiO_2 toward the *N*-alkylation of amines with carboxylic acids or esters in the presence of H_2. Traditionally, such transformations have been accomplished by using stoichiometric amounts of metal borohydrides.[32] Although recent efforts have enabled this challenging reaction to proceed catalytically, these processes still depend on homogeneous catalysts and co-catalysts such as trifluoromethanesulfonimide ($HNTf_2$), or on silanes as reducing agents, which generally suffer from a low atom efficiency and laborious workup procedures.[33] Herein, we report a heterogeneous catalytic system that enables the one-pot *N*-alkylation of amines with carboxylic acids or esters in the presence of H_2. The reaction involves the hydrogenation of carboxylic acids (or esters) to give the corresponding alcohols in the presence of molecular H_2, followed by an *N*-alkylation of the amines with the generated alcohols. The reaction with dimethylamine and 3-phenylpropionic acid under p_{H2} = 5 MPa and T = 200 ºC furnished 3-phenylpropyl-dimethylamine in 83% yield after t = 48 h. We moreover demonstrated that the *N*-Alkylation of dimethylamine with 3-phenylpropionic acid methyl ester proceeded efficiently under similar conditions, generating the desired product in 83% yield.



Scheme 1. *N*-Alkylation of dimethylamine with 3-phenylpropionic acid (p_{H2} = 5 MPa and T = 200 ºC) catalyzed by Re/TiO_2.



Scheme 2. *N*-Alkylation of dimethylamine with 3-phenylpropionic acid methyl ester (p_{H2} = 5 MPa and T = 200 ºC) catalyzed by Re/TiO_2.

Re/TiO_2 also promotes the *N*-methylation of various amines in the presence of CO_2 and H_2. The use of CO_2 as a renewable carbon resource for the production of chemicals such as methanol, formic acid, and other value-added chemicals has recently received substantial attention.[34] Among the various methods reported, especially the use of a CO_2/H_2 mixture as a methylation reagent for the synthesis of fine chemicals seems highly promising.[35] This reaction involves the initial formation of formate from CO_2 and H_2, a subsequent condensation with amines (or NH_3), and a hydrogenation of the generated amides to *N*-methylated amines.[36] Taking this reaction mechanism into consideration, Re/TiO_2, which is an effective catalyst for the hydrogenation of amides, may potentially also be applicable to this transformation. The feasibility of the catalytic system toward such *N*-methylation reactions was examined by performing the reaction with *N*-methylaniline (**1c**) under p_{CO2} = 1 MPa, p_{H2} = 5 MPa, and T = 200 °C. After t = 24 h, the desired product, *N,N*-dimethylaniline (**2c**), was generated in 98% yield (**Figure S10**). The effect of the reaction temperature was investigated (**Table S8**), and the results show that temperatures of at least 200 °C are necessary for the progression of the reaction under the applied conditions. A comparison of the catalytic performance was carried out under the same conditions (p_{CO2} = 1 MPa, p_{H2} = 5 MPa, T = 200 °C, and t = 24 h) and the results are summarized in **Table S9**. Among the catalysts explored in this study, the Re/TiO_2 catalyst afforded the highest yield for **2c**. The Re/TiO_2 catalyst was also compared to the supported Au catalyst (Au/Al_2O_3), which is the state-of-the-art heterogeneous catalyst.[34d] Using Re/TiO_2 under the same condition (0.5 mol% Re, p_{CO2} = 2 MPa, p_{H2} = 6 MPa, T = 140 °C, and t = 7 h) afforded **2c** in 25% yield, suggesting that further improvements regarding the activity are required for the future. However, compared to Au-based catalysts, Re-based catalysts would be more attractive from an economic perspective. The substrate scope for this system was also explored and is summarized in **Table 4**. Re/TiO_2 effectively catalyzes the *N*-methylation of various amines under the aforementioned conditions. Re/TiO_2 catalyzed not only the transformation of substituted anilines, but also that of tetrahydroquinolines (**entries 6**, **7**). Furthermore, aliphatic secondary amines were also converted to the corresponding tertiary amines in 70-99% yield.

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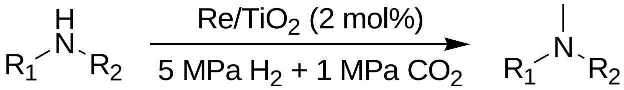
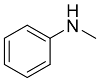
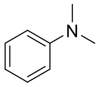
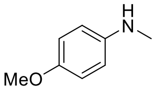
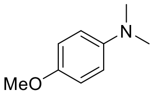
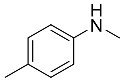
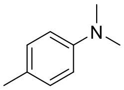
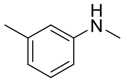
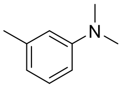
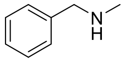
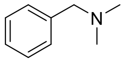
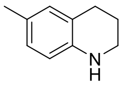
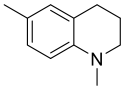
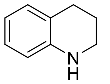
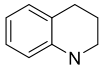
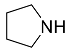
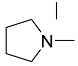
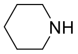
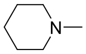
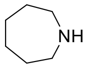
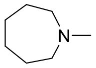
Table 4. Catalytic *N*-methylation of amines with CO_2 and H_2 over Re/TiO_2.[a]



Entry	Substrate	Products	Temperature [°C]	Time [h]	Yield [%]
1			200	24	98 (91)
2			200	24	78
3			200	24	92
4			200	36	84
5			200	24	85
6			180	24	66
7			200	36	85
8			200	24	99
9			200	24	99
10			200	24	70

[a] Reaction conditions: 2 mol% Re, 1 mmol amine, 3 mL octane, p_{CO2} = 1 MPa and p_{H2} = 5 MPa. Yields were determined by GC using *n*-dodecane as the internal standard. Yields of isolated products are given in parenthesis.

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Conclusions

We developed a heterogeneous catalytic system based on Re and TiO_2 that promotes the selective hydrogenation of esters to alcohols and of amides to amines. Most importantly, this Re/TiO_2 catalyst did not promote dearomatization reactions during the hydrogenations. The results of DFT calculations suggested that this high chemoselectivity of Re/TiO_2 should be ascribed to the high affinity of Re toward carboxylic acid derivatives relative to benzene rings. This result should provide an important design guideline for the development of advanced catalysts for this process. Re/TiO_2 also effectively catalyzed the *N*-alkylation of amines with carboxylic acids or esters in the presence of H_2 via an initial hydrogenation of carboxylic acids (or esters) to afford the corresponding alcohols, followed by *N*-alkylation of the amines with the generated alcohols. In addition, Re/TiO_2 efficiently catalyzed the *N*-methylation of amines using a H_2/CO_2 mixture. Given the importance of these processes for both academic organic synthesis and the industrial production of bulk chemicals, the presented system is a versatile and selective hydrogenation catalyst that should find widespread applications.

Experimental section

Materials and Catalyst Preparation

Organic and inorganic compounds were purchased from common commercial suppliers (Tokyo Chemical Industry, Kanto Chemical, Wako Pure Chemical Industries, Nacalai Tesque, and SigmaAldrich) and used without further purification. TiO_2 (ST-01) was obtained from Ishihara Sangyo Co., Ltd., while MgO (JRC-MGO-3) and SiO_2-Al_2O_3 (JRC-SAL-2, Al_2O_3 = 13.75 wt%) were supplied by the Catalysis Society of Japan. Conversely, γ-Al_2O_3 and θ-Al_2O_3 were prepared by calcination of γ-AlOOH (Catapal B Alumina, Sasol) for 3 h at T = 900 and 1100 °C, respectively. CeO_2 was prepared by calcination (T = 600 °C, t = 3 h, in air) of CeO_2 supplied from Daiichi Kigenso Kagaku Kogyo Co., Ltd (Type A). SiO_2 (Q-10) was supplied by Fuji Silysia Chemical Ltd., while Nb_2O_5 was prepared by calcination (T = 500 °C, t = 3 h) of niobic acid (CBMM). The standard carbon support, Vulcan XC72 (210 m^2g^{-1}), was commercially supplied by Cabot Carbon Black. ZrO_2 was prepared by calcination (T = 500 °C, t = 3 h) of a hydroxide of Zr. SnO_2 was prepared by calcination (T = 500 °C, t = 3 h) of H_2SnO_3 (Kojundo Chemical Laboratory Co., Ltd.). H-ZSM-5 (SiO_2/Al_2O_3 = 22) and HY (SiO_2/Al_2O_3 = 5.5) were obtained from TOSO Co., Ltd. NH_4ReO_4 and metallic Re were purchased from SigmaAldrich. ReO_2 and Re_2O_7 were supplied from Hydrus Chemical Inc. and Strem Chemicals Inc., respectively.

Precursors of M/TiO_2 (M = 5 wt% Re, Pt, Ir, Rh, Ru, Pd, Ag, Cu, Ni, or Co) and Re/MOx (5 wt% Re; MOx = metal oxides, zeolites, or carbon) were prepared by mixing the support material with the metal sources, i.e., an aqueous solution of NH_4ReO_4, nitrates of Ag, Ni, Cu, Co, $RuCl_3$ or $IrCl_3 \cdot nH_2O$, or aqueous HNO_3 solutions of $Pt(NH_3)_2(NO_3)_2$, $Rh(NO_3)_3$, or $Pd(NH_3)_2(NO_3)_2$. Typically, for the preparation of Re/TiO_2, 0.72 g of NH_4ReO_4 were added to a glass vessel (500 mL) containing 100 mL of deionized water ([Re] = 0.027 M). After sonication for 1 minute to completely dissolve the NH_4ReO_4, TiO_2 (9.5 g) was added to the solution, which was then stirred (200 rpm) for 15 min at room temperature. Subsequently, the reaction mixture was evaporated to dryness at T = 50 °C, followed by drying at T = 90 °C under ambient pressure for t = 12 h. The thus obtained material was calcinated (T = 500 °C, t = 3 h, in air). For each experiment, the active catalyst was prepared by reduction in a quartz tube (T = 700 °C, t = 0.5 h) under a flow of H_2 (20 cm^3min^{-1}). The other M/TiO_2 catalysts were prepared in the same manner as described above, except that the H_2 reduction of M/TiO_2 was carried out at T = 500 °C.

Characterization of the Catalysts

X-ray photoelectron spectroscopy (XPS) was carried out on an Omicron EA 125 X-ray photoelectron spectrometer, equipped with a modified UHV chamber using Mg Kα (1253.6 eV) radiation. Binding energies were calibrated based on the O1s peak energy of TiO_2 (532.0 eV). The reduced samples were measured after the reduction using H_2 in an N_2-filled glove box that was directly connected to the XPS chamber in order to avoid exposure of the samples to air.

FT-IR spectra were recorded on a JASCO FT/IR-4200 with an MCT (Mercury-Cadmium-Telluride) detector. Samples (40 mg) were pressed to obtain self-supporting pellets (ϕ = 2 cm), which were placed in the quartz FT-IR cell with CaF_2 windows connected to a conventional gas flow system. Prior to the measurements, the sample pellets were subjected to a pretreatment (T = 700 °C, t = 0.5 h) under a flow of H_2 (20 $cm^3 min^{-1}$), followed by cooling to T = 100 °C under He. Subsequently, 0.3 mmol liquid pyridine per g of catalyst were injected into the He flow, which was preheated to T = 150 °C, before the vaporized pyridine was fed into the FT-IR cell. Then, the FT-IR disk was purged with He for t = 600 s, and the IR measurement was carried out. Spectra were measured by accumulating 15 scans (resolution: 4 cm^{-1}). A reference spectrum was taken at T = 100 °C under a He flow, which was subtracted from each spectrum.

Catalytic Reactions

A following procedure for the hydrogenation reactions can be considered representative: after the reduction with H_2 at T = 700 °C (cf. Catalyst Preparation), the catalyst (2 mol% with respect to the Re loading), and a mixture of 3-phenylpropionic acid methyl ester (1.0 mmol), octane (3 mL), and *n*-dodecane (0.29 mmol) were added to a stainless steel autoclave (10 cm^3). The resulting mixture was magnetically stirred (T = 180 °C, p_{H2} = 5 MPa). The products were analyzed by GCMS (SHIMADZU GCMS-QP2010 with an Ultra ALLOY capillary column UA^+-1; Frontier Laboratories Ltd.) and GC (Shimadzu GC-14B with an Ultra ALLOY capillary column UA^+-1; Frontier Laboratories Ltd.). Yields were determined by GC analysis using *n*-dodecane as the internal standard relative to the starting esters. All products were subjected to column chromatography on silica gel 60 (spherical, 63-210 μm, Kanto Chemical Co. Ltd.; eluent:hexane/ethyl acetate = 90/10, v/v), and subsequently analyzed by GC and GCMS. ^1H and ^{13}C NMR analysis was carried out for those products that were isolated successfully. ^1H and ^{13}C NMR spectra were recorded at ambient temperature on a JEOL-ECX 600 spectrometer (^1H: 600.17 MHz, ^{13}C: 150.92 MHz), using tetramethylsilane as the internal standard. Isolated yields were determined relative to the starting esters.

Reactions for the recycling experiments were performed in a manner similar to that described above. Following the reaction (p_{H2} = 5 MPa, T = 180 ºC, t = 24 h), the catalyst was separated, washed with isopropanol, dried in air, reduced with H_2 at T = 700 °C and then reused for an ensuing reaction. It should be noted that the recycling reaction was carried out after H_2 reduction as in the case of the initial run. A leaching test was performed in a manner comparable to the recycling test. After t = 3 h, the catalyst was separated by centrifugation. Subsequently, the separated solution was transferred to the reactor, which was recharged with H_2 (p_{H2} = 5 MPa), followed by heating (T = 180 °C) and magnetic stirring for t = 21 h.

Computational Methods

All calculations were performed with the CASTEP code[37] in the Materials Studio of Accelrys Inc. The Perdew−Burke−Ernzerhof (PBE) generalized gradient functional[38] was employed for the exchange-correlation energy. The plane-wave basis set with a cutoff energy of 250 eV was used for the system with periodic boundary conditions. Ultrasoft pseudopotentials were used to describe the electron–ion interactions. The Brillouin zone was sampled with (3 × 3 × 1) Monkhorst–Pack[38] k-points. The Re(0001), Pd(111), and Rh(111) surfaces were modeled by a supercell slab that consists of a (3 × 3) surface unit cell with four atomic layers in accordance with previously reported procedures.[17] It should be noted that the most stable and common planes were used for each metal. The (0001) surface, which was used for Re, has a hexagonal-close-packed (hcp) structure, while the (111) surface, which was used for Pd and Rh, exhibits a face-centered-cubic (fcc) structure. The slab was separated in vertical direction by a vacuum space (height: 15 Å). The top two layers of the surface were fully relaxed, whereas the bottom two layers were fixed at the corresponding bulk positions. The adsorption energy (E_{ads}) was calculated as the difference in energy between the molecule absorbed on the surface ($E_{\text{molecule/surface}}$), the individual adsorbate molecule (E_{molecule}), and the surface (E_{surface}) according to:

$$E_{\text{ads}} = E_{\text{molecule}} + E_{\text{surface}} - E_{\text{molecule/surface}} \qquad (1)$$

It should be noted that the reliability of the models was confirmed in a previous study by considering the adsorption energy of benzene on Re(0001) with extended models [(4 × 4 × 2) k-point, 300 eV cutoff energy, (4 × 4) surface unit cell, and six surface layers].[17] We confirmed that the small quantitative differences do not affect the conclusions.

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Keywords

Rhenium • Selective hydrogenation •CO_2 utilization• *N*-methylation

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Note added in proof

During the reviewing process of our manuscript, a very interesting work describing selective hydrogenation of amides with retention of aromatic moieties catalyzed by a platinum-vanadium catalyst was reported by Mitsudome, *et al.* and has come to our attention. T. Mitsudome, K. Miyagawa, Z. Maeno, T. Mizugaki, K. Jitsukawa, J. Yamasaki, Y. Kitagawa, K. Kaneda, *Angew. Chemie Int. Ed.* **2017**, *8531*, 9381–9385.

Entry for the Table of Contents

FULL PAPER

A heterogeneous TiO_2-supported Re catalyst (Re/TiO_2) promotes various selective hydrogenation reactions, e.g. hydrogenation of esters to alcohols, hydrogenation of amides to amines, and *N*-methylation of amines using H_2 and CO_2. Re/TiO_2 shows a wide substrate scope for each reaction.

Takashi Toyao, S. M. A. H. Siddiki, Yoshitsugu Morita, Takashi Kamachi, Abeda S. Touchy, Wataru Onodera, Kenichi Kon, Shinya Furukawa. Hiroko Ariga, Kiyotaka Asakura, Kazunari Yoshizawa, Ken-ichi Shimizu,**

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Rhenium-Loaded TiO_2: A Highly Versatile and Chemoselective Catalyst for the Hydrogenation of Carboxylic Acid Derivatives and the *N*-Methylation of Amines Using H_2 and CO_2