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ARTICLE

One-pot, chemoselective synthesis of secondary amines from aryl nitriles using PdPt–Fe_3O_4 nanoparticle catalyst†

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We have developed a new catalytic method for the one-pot, cascade synthesis of unsymmetrical secondary amines via the reductive amination of aryl nitriles with nitroalkanes using a PdPt–Fe_3O_4 nanoparticles (NPs) catalyst. The use of a bimetallic catalyst resulted in enhanced reactivity and selectivity compared to that of either monometallic Pd–Fe_3O_4 or Pt–Fe_3O_4 NPs catalyst. Using this bimetallic catalytic system, we were successful in the synthesis of various unsymmetrical secondary amines under mild conditions. However, aryl nitriles containing an electron-donating substituent were rather resistant to the reductive amination, and when hexafluoroisopropanol (HFIP) was used as a co-solvent, the reaction selectivity and yield for unsymmetrical secondary amines increased dramatically. Using the catalyst system, one-pot, gram-scale synthesis of indole was possible from 2-nitrophenylacetonitrile. Due to the magnetic property of the Fe_3O_4 support, the bimetallic catalyst could easily be recyled using an external magnet at least four times.

Introduction

Secondary amines are crucial intermediates in the synthesis of natural products, drug molecules, and industrial materials.[1] Among them, *N*-alkylated unsymmetrical secondary amines play particularly important roles in pharmaceutical industry.[2] They are embedded as structurally important units in drug molecules. Some selected examples of drug molecules containing secondary *N*-alkylamines such as Cinacalcet,[3] Clobenzorex,[4] Ambroxol,[5] Fluoxetine,[6] and Protriptyline[7] and Pexidartinib[8] are listed in Fig. 1. Conventional methods of synthesizing secondary amines include direct mono-*N*-alkylation,[9] alkylative amination,[10] and reductive amination of carbonyl compounds.[11] However, these methods have limitations such as over-alkylation, employment of expensive starting materials, low selectivity, or harsh reaction conditions. Among many methods of preparing secondary amines, catalytic hydrogenation of nitriles is an efficient one-step approach, which represents an alternative way to remove the need to use alkyl halides or carbonyl compounds.[12] However, a key problem with the nitrile hydrogenation is its selectivity, since a mixture of primary, secondary, tertiary amines and imines can be formed (Scheme 1a). Many research groups have shown that the selectivity for hydrogenation of nitriles can be achieved using transition metal catalysts under various reaction conditions.[12a] Although metal-catalyzed formation of secondary amines from nitriles has been studied to a much lesser extent than that of primary amines,[13] there have been some successful

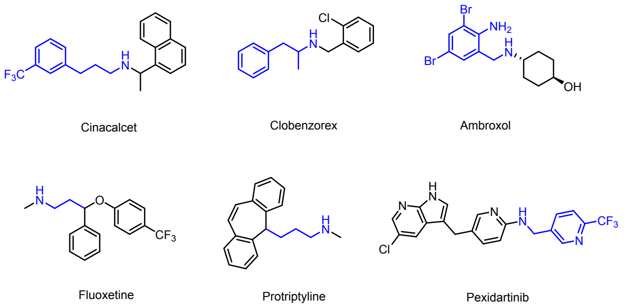
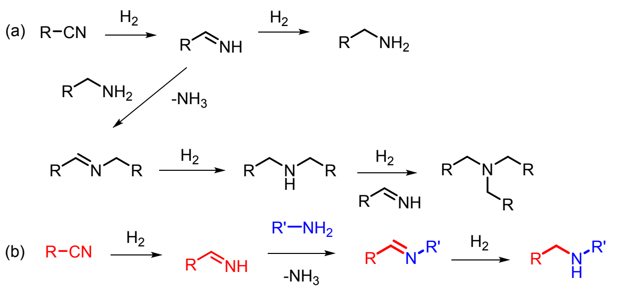


Fig. 1 Selective examples of drug molecules embedding *N*-alkylated secondary amines.



Scheme 1 (a) Probable reaction process for hydrogenation of nitrile. (b) Reaction pathway of reductive amination of nitrile with amine for unsymmetrical secondary amine.

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reports on the reactions employing Pd,[14] Rh,[15] Ru,[16] Pt,[17] PtMo alloy,[18] and Pd-FeCu NP[19] catalysts.

For the formation of unsymmetrical secondary amines, the reductive amination of nitriles with amines in the presence of homogeneous or heterogeneous catalysts has also been investigated (Scheme 1b). As a successful example of the homogeneous catalysis systems, Liu *et al*. reported the preparation of unsymmetrical secondary amines from nitriles and amines using a cobalt catalyst and ammonia borane in HFIP.[20] Recently, Punji *et al.* reported that (Xantphos)$CoCl_2$ catalyzed reductive amination of nitriles with diethylamine borane could produce unsymmetrical secondary amines.[21] As an approach utilizing a heterogenous catalysis system, Sajiki *et al*. reported Pd/C catalyzed hydrogenation of aliphatic nitriles in the presence of an amine or a nitro compound to obtain unsymmetrical secondary amines.[22] However, aromatic nitriles were not applicable to this catalytic system since benzonitrile was quickly reduced to benzylamine under their reaction condition. In another case, Pt nanowire catalyst has been used for the selective hydrogenation of aromatic nitriles in the presence of 1-pentanamine to yield unsymmetrical secondary amines under 1-4 bar pressure of hydrogen.[17] Williams *et al.* reported the synthesis of secondary amines through reductive amination from nitriles using Pt/C catalyst in a continuous flow multichannel microreactor.[23]

Despite the aforementioned catalysts' successful applications, heterogeneous systems still require high pressure of hydrogen or high temperatures for efficient synthesis of unsymmetrical secondary amines from nitriles.[17, 23] In particular, it is difficult to control reactivity and selectivity of nitrile reduction in heterogeneous catalysis system. Therefore, the development of heterogeneous catalytic system with high activity and selectivity remains to be a challenge. Given the importance of various amine synthesis in industrial application, it is crucial to develop efficient heterogeneous catalytic system that can produce secondary amines selectively from the hydrogenation of nitriles under the mild conditions.

Bimetallic NPs have shown remarkable achievement as a catalyst in organic reactions. They often present unique synergistic catalytic activity when compared to the corresponding monometallic NPs.[24] In this regard, we have reported extremely efficient catalytic reduction of nitroarenes,[25] silylation of aryl halides,[26] and continuous flow hydrogenation for reductive amination[27] using a magnetically recyclable PdPt–Fe_3O_4 catalyst. This bimetallic PdPt–Fe_3O_4 catalyst exhibited enhanced catalytic activity when compared to either monometallic Pd–Fe_3O_4 or Pt–Fe_3O_4 in the reactions mentioned above. Moreover, the catalyst could be easily recovered and reused with the assistance of an external magnet for 250 cycles in the nitroarene reduction and 20 cycles in the aryl silylation reaction, without the need for filtration or centrifugation. In addition, researchers have used bimetallic PdPt nanoparticles to enhance the reactivity of the catalyst by synthesizing various types of core-shell,[28] alloy,[29] and nanotube.[30] Both Pd and Pt catalysts have been utilized for the hydrogenation of nitriles,[14,17] however, no report exists on the use of PdPt alloy catalyst system. We envisioned that the use of alloyed PdPt NPs would have a distinctive synergistic effect on the hydrogenation of nitriles.

Herein, we report the first use of a bimetallic PdPt–Fe_3O_4 catalyst in the one-pot reductive amination of aryl nitriles with nitroalkanes toward the synthesis of various unsymmetrical secondary amines. Unique in this study is that we used nitro compounds instead of amines, and studied the formation of secondary amines by simultaneously reducing nitroalkanes and aryl nitriles. To the best of our knowledge, this is the first example of the direct use of aryl nitriles and nitroalkanes toward the synthesis of unsymmetrical secondary amines without employing high pressure and high temperature.

Results and discussion

Catalyst characterization (PdPt–Fe_3O_4 NPs)

The bimetallic PdPt–Fe_3O_4 catalyst was prepared via a one-pot hydrothermal method from palladium(II) chloride ($PdCl_2$) and potassium(II) tetrachloroplatinate (K_2PtCl_4) in the presence of Fe_3O_4 NPs in polyvinylpyrrolidone (PVP) and ethylene glycol (EG). The deposition of PdPt alloy NPs resulted onto the surface of the Fe_3O_4 NPs. High resolution transmission electron microscopy (HR-TEM), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) analyses of the PdPt–Fe_3O_4 NPs confirmed well-defined morphology (Fig. 2 and S1-S3). Mapping images from SEM-EDS showed that the Pd

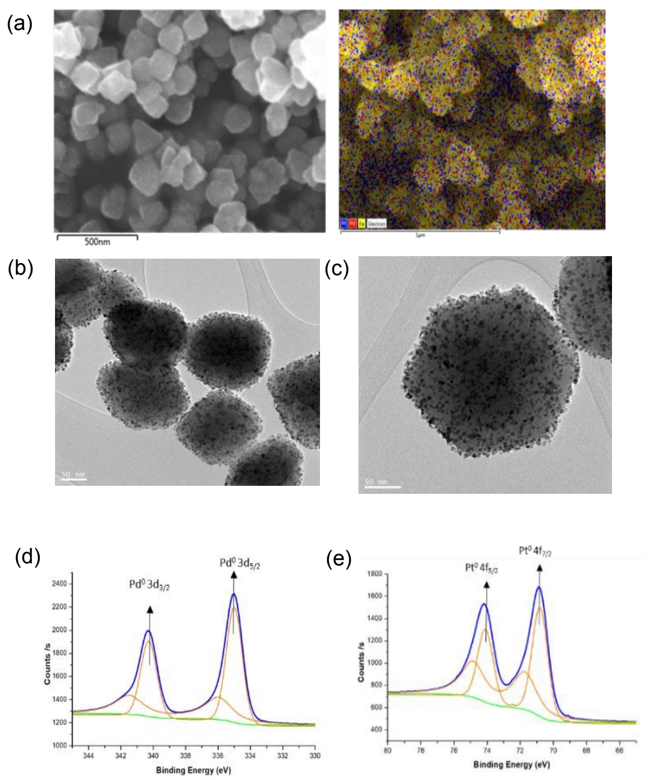


Fig. 2 (a) SEM-EDS image of PdPt–Fe_3O_4 NPs; (b) and (c) HR-TEM image of PdPt–Fe_3O_4 NPs; The XPS data of PdPt–Fe_3O_4 NPs (d) Pd 3d region and (e) Pt 4f region.

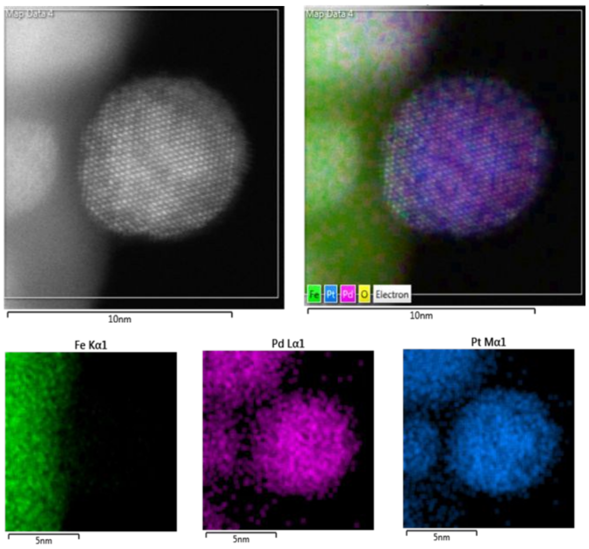
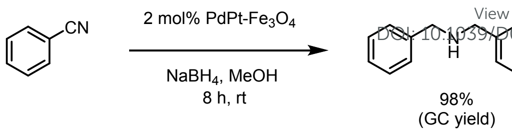


Fig. 3 STEM-EDS mapping image of alloyed PdPt NPs.

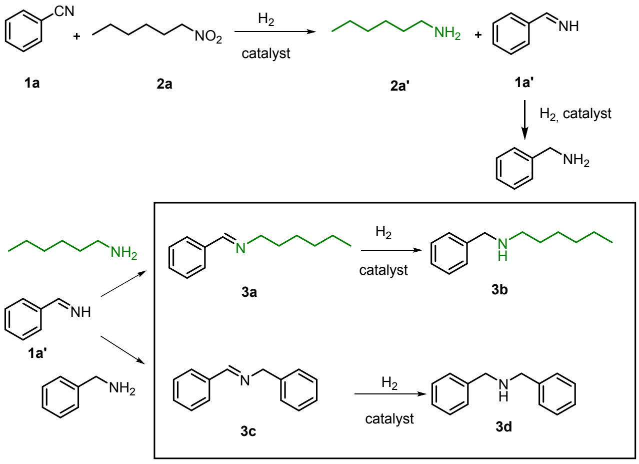
and Pt atoms were well distributed on the surface of Fe_3O_4 NPs in the same region (Fig. 2a). To examine the physical properties of PdPt NPs more closely, we explored high angle annular dark field (HAADF) scanning transmission electron microscopy (STEM) and bright field (BF)-STEM (Fig. 3 and S4-S5). We confirmed that a homogeneous contrast of nanoparticles in STEM images are clearly observable due to the different mass contrast (Z) of Pd and Pt (Fig. 3). The brighter area of the STEM image correspond to the heavier atom (Pt) and the darker area correspond to the lighter atom (Pd).[31] In this regard, we confirmed that Pd and Pt are randomly alloyed and bimetallic PdPt NPs have homogeneous structure with an average size of 5.5 nm. (Fig. 3 and S6). To further confirm the alloy structure, we conducted EDS line scan analysis on single nanoparticle. As shown in the Fig. S9, the EDS line scan profile shows the both intensity of Pd and Pt in the same region. Therefore, we concluded that PdPt NPs are not core-shell type, but rather homogeneous structure. We examined X-ray photoelectron spectroscopy (XPS) to determine the electronic conditions and oxidation states of Pd and Pt (Fig. 2d-e and S8). Two Pd 3d peaks were identified at 340.2 eV and 334.9 eV, respectively. These two binding energies correspond to a Pd(0) species. The binding energies of Pt $4f_{7/2}$ and $4f_{5/2}$ peaks were detected at 70.8 and 74.1 eV's, respectively, which indicated Pt(0) species. When we compared the XPS data of bimetallic PdPt-Fe_3O_4 NPs with monometallic NPs (Pd– and Pt–Fe_3O_4) , Pt $4f_{2/7}$ peak (70.8 eV) slightly shifted toward a lower binding energy in the PdPt–Fe_3O_4 NPs compared with that of the monometallic Pt–Fe_3O_4 NPs (71.0 eV). Inductively coupled plasma atomic emission spectroscopic (ICP-AES) analysis showed that PdPt–Fe_3O_4 NPs consist of 3.94 wt% palladium and 6.06 wt% platinum (Fig. S7).

Hydrogenation of benzonitrile with PdPt–Fe_3O_4 NPs

We first evaluated the catalytic activity of the PdPt–Fe_3O_4 NPs in the reduction of benzonitrile. Benzonitrile was selectively



Scheme 2 The formation of dibenzylamine from benzonitrile



Scheme 3 The possible reaction pathways for the one-pot reductive amination using benzonitrile and 1-nitrohexane.

converted to dibenzylamine in the presence of the bimetallic catalyst in 98% yield with $NaBH_4$ in MeOH (Scheme 2, Table S1). Under these conditions, the formation of *N*-benzylidene-benzylamine and benzylamine in 1% yield each was observed with no tribenzylamine formation. We compared this result with those of monometallic Pd– or Pt–Fe_3O_4 catalysts. The yield of dibenzylamine in Pd–Fe_3O_4 catalyzed reaction was 60%. However, reactions using Pt–Fe_3O_4 catalyst produced only *N*-benzylidenebenzylamine as the major product (54%) with no hint of dibenzylamine formation. Under the same conditions, the bimetallic PdPt catalyst showed much better conversion and selectivity than those of monometallic Pd– or Pt–Fe_3O_4 catalyst. Compared to the previously reported heterogeneous catalysts,[14a, 15a, 17-19] the bimetallic PdPt–Fe_3O_4 catalyst showed very high selectivity, without high temperature and high pressure (Table S2).

One-pot reductive amination of benzonitrile with 1-nitrohexane

We then investigated one-pot cascade reaction of benzonitrile in the presence of 1-nitrohexane. In order for this reaction to be successful, three reductive steps should occur in an appropriate sequence (Scheme 3). Initially, the nitro group in compound **2a** should be rapidly reduced to the amine **2a'** followed by hydrogenation of nitrile **1a** to give unsubstituted imine **1a'**, which forms an unsymmetrical secondary imine **3a** upon reaction with the n-hexylamine (**2a'**). Finally, imine **3a** should be reduced to the desired secondary amine **3b**. To determine the

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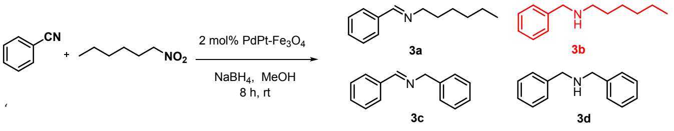
optimal reaction conditions, we ran the catalytic reaction using $NaBH_4$ as the stoichiometric reductant in methanol for 8 h at room temperature. First, we examined the catalytic activity of the Fe_3O_4 support and found that Fe_3O_4 did not catalyze the reduction (Table 1, entry 1). We then compared the catalytic activity of the bimetallic PdPt–Fe_3O_4 catalyst with either monometallic Pd–Fe_3O_4 or Pt–Fe_3O_4 catalysts. When the reaction was performed with 4 mol% Pd–Fe_3O_4, the desired product was obtained in 32% yield along with dibenzylamine in 13% yield. However, no imines were detected (Table 1, entry 2). When 4 mol% Pt–Fe_3O_4 was used, *N*-hexyl-1-phenylmethanimine (**3a**) was obtained as a major product instead of the desired product (Table 1, entry 3). When a reaction was performed using a combination of 2 mol% Pd–Fe_3O_4 and 2 mol% Pt–Fe_3O_4, the yield of the desired product increased slightly(36%) compared to those obtained with either Pd–Fe_3O_4 or Pt–Fe_3O_4 (Table 1, entry 4). Interestingly, the highest yield was obtained with the bimetallic alloy catalyst, PdPt–Fe_3O_4 (Table 1, entry 5). This indicates that high conversions for both benzonitrile and imine reduction can be achieved with the bimetallic catalyst. When the catalyst loading was reduced to 1 mol% PdPt–Fe_3O_4, the yield of the desired product was 28% and recovered benzonitrile and large portions of the intermediate imines (**3a** and **3c**) remained in the product mixture (Table 1, entry 6).

To investigate the effects of Fe_3O_4 support, we compared the catalytic activity of PdPt on different supports such as C, CeO_2, and TiO_2. Catalysts with these supports were synthesized by the one-pot hydrothermal method as in the case of PdPt–Fe_3O_4 NPs (Fig. S10-S12). In the reaction employing PdPt–C NP catalyst, the initial hydrogenation of benzonitrile did not progress at all (Table 1, entry 7). From the reaction employing PdPt–CeO_2 NPs catalyst, the conversion of benzonitrile was 40%, however, *N*-hexyl-1-phenylmethanimine and *N*-benzylidene-benzylamine were also obtained in 30% and 8%, respectively (Table 1, entry 8). The PdPt–TiO_2 catalyzed reaction provided the desired product in 37% yield (Table 1, entry 9). Among the supports examined, Fe_3O_4 showed the best results for the reduction of benzonitrile and the intermediate imine. Interestingly, our previous studies on hydroxymethylfurfural (HMF) oxidation[32] and reductive amination[33] have consistently revealed the enhanced catalytic activity of metal NP catalysts on Fe_3O_4 compared to other supports.

Table 1 Investigation of the various catalysts used for the synthesis of unsymmetrical amines via a cascade reductive amination of benzonitrile and 1-nitrohexane[a]



Entry	Catalyst	Conversion of benzonitrile[b]	Selectivity[b] (**3a:3b:3c:3d**)
1	Fe_3O_4	0	-
2	4 mol% Pd–Fe_3O_4	45	0 : 32 : 0 : 13
3	4 mol% Pt–Fe_3O_4	48	39 : 0 : 7 : 0
4	2 mol% Pd–Fe_3O_4 + 2 mol% Pt–Fe_3O_4	47	1 : 36 : 1 : 9
5	2 mol% PdPt– Fe_3O_4	100	4 : 62 : 1 : 27
6	1 mol% PdPt–Fe_3O_4	90	42 : 28 : 10 : 9
7	2 mol% PdPt–C	0	-
8	2 mol% PdPt–CeO_2	40	30 : 0 : 8 : 0
9	2 mol% PdPt–TiO_2	54	0 : 37 : 0 : 17

[a] Reaction conditions: benzonitrile (0.3 mmol),1-nitrohexane (0.3 mmol), MeOH (1.8 mL), $NaBH_4$ (0.6 mmol), room temperature, 8 h. [b] Yields were determined via GC analysis using anisole as an internal standard.

Since the production of a symmetrical diamine is always a competing reaction in the synthesis of unsymmetrical secondary amines, we examined the ratio of benzonitrile and 1-nitrohexane to improve the yield and selectivity for the unsymmetrical secondary amines (Table S3). As $NaBH_4$ is required as a reducing agent to reduce both nitrohexane and benzonitrile, we searched for an optimum amount of $NaBH_4$. When the benzonitrile/1-nitroheaxne ratio was 1.5 and 2 equiv of $NaBH_4$ was employed, the yield of the desired unsymmetrical secondary amine was highest (86%) (Table S3, entry 1).

Effect of metal ratio of bimetallic Pd_xPt_y–Fe_3O_4 catalyst

To establish the effect of the alloy metal composition, we compared the catalytic activities of Pd_xPt_y–Fe_3O_4 using different proportions of Pd and Pt (x/y = 2.3:1, 1:0.97, and 1:1.7), under otherwise the same reaction conditions (Table S4 and Fig. S14). Interestingly, the reactions performed using the catalysts containing a large proportion of the Pd component (Pd–Fe_3O_4 and $Pd_{2.3}Pt_1$–Fe_3O_4) showed high reactivity in the imine reduction steps. In the case of $Pd_{2.3}Pt_1$–Fe_3O_4, the desired amine product was produced in 78% yield and the yields of the side product imines were low. On the other hand, the reactions performed with catalysts containing a large proportion of the Pt component (Pt– Fe_3O_4 and Pd_1 $Pt_{1.7}$–Fe_3O_4) did not produce the desired product at all due to the poor reactivity in the imine reduction step. In the reaction using the $Pd_1Pt_{1.7}$–Fe_3O_4 catalyst, the predominant production of *N*-hexyl-1-phenylmethanimine (55%) was observed. The $Pd_1Pt_{0.97}$–Fe_3O_4 catalyst showed both the best selectivity and reactivity, furnishing the highest yield (86%) of the desired product. Overall, the alloyed PdPt NP catalyst increased the reactivity toward the reduction of the nitrile when compared to the monometallic catalysts. In addition, the higher the proportion of Pd, the more favorable the imine reduction reaction becomes. Among the reactions employing catalysts with different metal compositions, the system using an almost equal ratio of Pd/Pt (1:0.97) gave the highest turnover number (TON) (Table S4).

Substrate scope

With the optimized reaction conditions for the production of secondary amines in hand, we investigated the substrate scope

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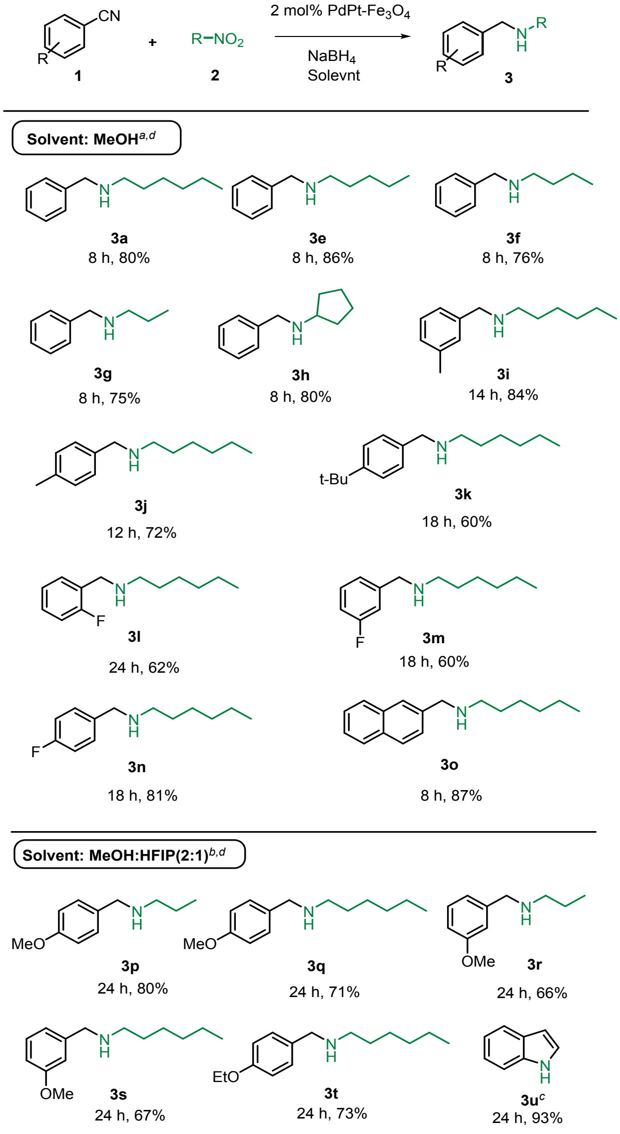
of the reaction with a variety of aryl nitriles and nitroalkanes (Scheme 4). Reductive amination of benzonitrile with various 1-nitroalkanes (n = 3-6) gave the desired secondary amines (**3g, 3f, 3e** and **3a**) in 75, 76, 86, and 80% yields, respectively. The reaction with nitrocyclopentane gave the corresponding product **3h** in 80% yield. The duration of the reaction was adjusted for each aryl nitrile derivative since a mixture of amine and imine was formed after 8 h. The reactions performed using *m*- and *p*-tolunitrile proceeded to give the corresponding amines **3i** and **3j** in 84 and 72% yield, respectively. However, the reaction with *o*-tolunitrile did not furnish the desired amine presumably due to steric hindrance. When 4-*tert*-butylbenzonitrile was used, a 60% yield of the desired amine **3k** was produced. The reactions using 2-, 3-, and 4-fluorobenzonitriles with 1-nitrohexane afforded their corresponding unsymmetrical amine products **3l–n** in 62, 60, and 81% yield, respectively. The reaction of naphthalene-2-carbonitrile with 1-nitrohexane gave the desired unsymmetrical secondary amine **3o** in 87% yield. When 4-methoxybenzonitrile was used as a starting material in the reductive amination reaction with 1-nitropropane, the conversion of the nitrile was low and the reaction stopped at the imine stage. Further reduction of the unsymmetrical secondary imine to the amine did not proceed under the previously optimized reaction conditions. Then we screened various acidic additives to increase the reactivity of the intermediate imine to favor the desired secondary amine (Table S5). Among the conditions examined, the highest yield was obtained for the desired *N*-(4-methoxybenzyl)-propan-1-amine product with the use of HFIP as a co-solvent (Table S6). Recently, HFIP has been a popular solvent in various reactions due to its unique properties.[34] Since HFIP is a protic solvent exhibiting strong hydrogen-bonding capability, it is used to activate various organic functional groups, including carbonyls,[35] imines,[36] and C-H bonds.[37] Using HFIP as a co-solvent, we examined the reductive amination of benzonitriles substituted with an electron-donating group (i.e. methoxy and ethoxy groups) with 1-nitroalkanes, which were reluctant to proceed further than the intermediate imine under our standard reaction conditions. With the use of HFIP, the catalytic reactions proceeded smoothly and the results can be seen in Scheme 4. The reactions of 4-methoxybenzonitrile with 1-nitropropane or 1-nitrohexane afforded the desired amines **3p** and **3q** in 80 and 71% yields, respectively. In addition, the reductive amination of 3-methoxybenzonitrile with 1-nitropropane and 1-nitrohexane furnished secondary amines **3r** and **3s** in 66% and 67% yield, respectively. The reaction of 4-ethoxybenzonitrile gave the corresponding secondary amine **3t** in 73% yield. It was gratifying to accomplish an efficient synthesis of indole **3u** via the intramolecular reductive amination of 2-nitrophenylacetonitrile. It is of particular note that the synthesis of the indole did not proceed in methanol, however, with the addition of HFIP as a co-solvent an excellent yield (93%) of indole was obtained at 50 °C.



Scheme 4. The PdPt–Fe_3O_4 catalyzed reductive amination of different nitriles with nitroalkanes. [a] Reaction conditions: nitrile (1.5 mmol), nitroalkane (1.0 mmol), PdPt–Fe_3O_4 (2.0 mol% based on Pd), $NaBH_4$ (2.0 mmol), methanol (6 mL), RT. [b] Reaction conditions: nitrile (1.5 mmol), nitroalkane (1.0 mmol), PdPt–Fe_3O_4 catalyst (2.0 mol% based on Pd), $NaBH_4$ (3.0 mmol), methanol (4 mL) and HFIP (2 mL), RT. [c] 50 °C. [d] Yields of isolated products.

In addition to the one-pot hydrogenation of nitriles in the existence of a nitro compound, we anticipated that direct use of an amine as a nucleophile would also proceed to produce secondary amines under the same reaction conditions with the PdPt–Fe_3O_4 catalyst. We carried out the reactions of a variety of nitriles in the presence of various primary amines and obtained good to excellent yields of the desired secondary amine products, as shown in Scheme 5. Under the optimized reaction condition (Table S7), reaction of benzonitrile with 1-hexylamine or cyclohexylamine produced the desired amine **5a** or **5b**, in 80% and 64% yields, respectively. When the reactions employing 4-methylbenzylamine, 4-*tert*-butylbenzylamine and 4-methoxybenzylamine were carried out with benzonitrile in the presence of the bimetallic catalyst, 81, 78 and 92% yields of the corresponding

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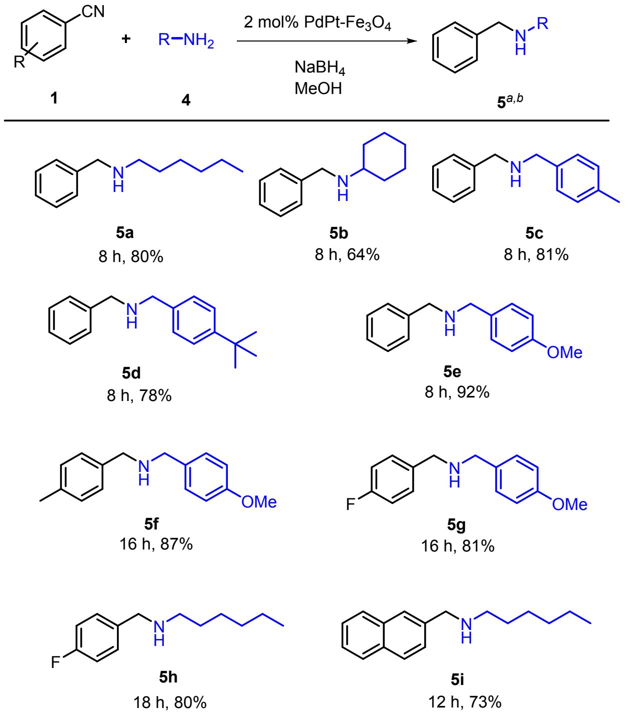
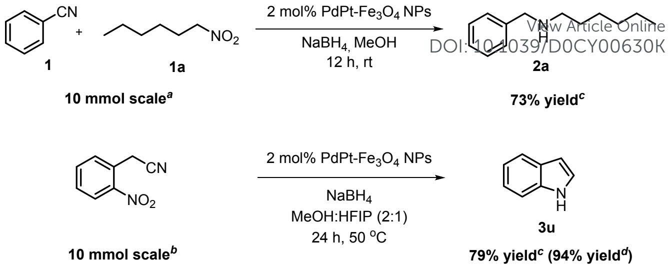
products (**5c-e**) were obtained, respectively. The reductive amination of *p*-tolunitrile with 4-methoxy-benzylamine proceeded smoothly to yield the unsymmetrical secondary amine **5f** (87%).



Scheme 5. The PdPt–Fe_3O_4 catalyzed reductive amination of nitrile derivatives with various amine compounds for the synthesis of unsymmetrical secondary amines. [a] Reaction conditions: nitrile (0.5 mmol), amine (0.75 mmol), PdPt–Fe_3O_4 (2.0 mol% based on Pd), $NaBH_4$ (1.0 mmol), methanol (3 mL), RT. [b] Isolated yield.

Reaction of 4-fluorobenzonitrile with either 4-methoxy-benzylamine or 1-hexylamine gave the corresponding product **5g** or **5h** in 81 and 80% yields, respectively. The reaction of naphthalene-2-carbonitrile with 1-hexylamine afforded the desired amine **5i** in 73% yield. However, when aniline was used as a nucleophile, only dibenzylamine was produced as a sole product. This is presumably because aniline's nucleophilicity is considerably lower than that of its competitor, benzylamine. Finally, we compared reaction conditions of synthesizing unsymmetrical secondary amines with the bimetallic PdPt–Fe_3O_4 catalyst system and those using previously reported heterogeneous catalysts (Table S8). Previously Pd and Pt monometallic catalysts have been used,[17, 22-23] however, the use of aryl nitrile has not been explored to the synthesis of unsymmetrical secondary amines with heterogeneous Pd catalysts, and high temperature and pressure were required for the synthesize the desired amines in the case of Pt catalysts. Use of bimetallic PdPt–Fe_3O_4 catalyst ensured successful synthesis of unsymmetrical secondary amines without high temperature and hydrogen pressure. These results are summarized in Table S8.

Gram-scale synthesis



Scheme 6. Gram-scale synthesis of secondary amine using PdPt-Fe_3O_4 NPs. [a] Reaction conditions: benzonitrile (15 mmol), 1-nitrohexane (10 mmol), PdPt–Fe_3O_4 (2.0 mol%), $NaBH_4$ (20 mmol), methanol (60 mL), RT. [b] Reaction condition: 2-nitrophenylaceotnitrile (10 mmol), PdPt–Fe_3O_4 (2.0 mol%), $NaBH_4$ (50 mmol), methanol (40 mL) and HFIP (20 mL). [c] Isolated yield. [d] Determined by ^1H NMR analysis.

To demonstrate the practicality and scalability of the catalytic process, we carried out the gram-scale synthesis of secondary amines using bimetallic PdPt–Fe_3O_4 NPs catalyst. We performed the scale-up experiment using benzonitrile and 1-nitrohexane as starting materials under the standard condition (Scheme 6). The reaction gave 1.44 g (73% isolated yield) of *N*-benzylhexan-1-amine (**2a**). In addition, a large-scale synthesize of indole from 2-nitrophenylacetonitrile was also performed. We confirmed that the indole was produced in 94% yield thorough ^1H NMR analysis. After isolation, 0.93 g (79% yield) of indole was obtained. Thus, we demonstrated that the bimetallic PdPt-Fe_3O_4 NPs catalyst could be successfully applied to large-scale synthesis of amines.

Reusability Test

One of the attractive features of a heterogeneous catalyst with Fe_3O_4 is the reusability due to its superparamagnetic property.[38] There was a report on recycled catalyst on the formation of unsymmetrical secondary amine from the reductive amination of nitrile in the presence of a primary amine,[17] however, recycling on the formation of unsymmetrical secondary amines from nitriles and nitroalkanes has not been documented. When a reaction was complete, the bimetallic catalyst can be easily separated using an external magnet. To evaluate the recyclability of the catalyst, we recovered and reused the PdPt–Fe_3O_4 catalyst with fresh benzonitrile and 1-nitrohexane (Fig. S15). The catalyst showed considerable activity up to four cycles. However, the yield dropped sharply after the 5th run. The ICP-AES, XPS, and HR-TEM data obtained for the recovered catalyst from the 5th reaction showed considerable agglomeration of the PdPt NPs, which presumably caused the reduced catalytic activity (Fig. S7, S8, and S16).

Conclusion

In summary, we developed a bimetallic PdPt–Fe_3O_4 catalyst system for unsymmetrical secondary amine synthesis via one-pot cascade hydrogenation of aryl nitriles with nitroalkanes or alkylamines. This catalytic system provides a straightforward

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way to synthesize secondary amines from nitriles under mild conditions. With the use of the catalyst, benzonitrile was converted to dibenzylamine in 98% yield with PdPt–Fe_3O_4 NPs and $NaBH_4$ in methanol. The PdPt bimetallic catalyst was proven to be superior to its corresponding monometallic Pd and Pt catalysts in terms of both its reactivity and selectivity. Especially, the employment of PdPt NPs has shown to be effective in producing unsymmetrical secondary amines from the reactions of aryl nitriles and nitroalkanes. When monometallic Pt–Fe_3O_4 NPs were used, the major product of the nitrile reduction was imine. However, when Pt was alloyed with Pd to form the bimetallic PdPt–Fe_3O_4, the desired amines were obtained due to their synergetic effect. Solvent proved to be critical in the nitrile and imine reduction steps particularly for nitriles possessing an electron-donating group since the conversion rate and the selectivity dramatically increased when HFIP was used as a co-solvent. Compared to the bimetallic PdPt NPs prepared on other supports such as C, CeO_2 and TiO_2, the PdPt on Fe_3O_4 exhibited the best reactivity and selectivity. Also, the almost equal ratio of the Pd and Pt metals in the catalyst system proved to be critical for the optimal reduction performance. Particularly, through the use of the bimetallic PdPt–Fe_3O_4 catalyst one-pot synthesis of indole in 93% yield was possible.

Experimental

Materials

All commercially available chemicals were used as received without further purification. Palladium chloride (99% purity) and potassium tetrachloroplatinate (99.9 % purity) were purchased from Alfa-Aesar. Polyvinylpyrrolidone (PVP, Mw ~ 10,000) was purchased from Sigma-Aldrich. Iron oxide nanoparticle (Fe_3O_4 NPs) was purchased from DK nanomaterials.

Characterization methods

All products were confirmed through comparison with authentic compounds and quantified through gas chromatography/mass spectrometry (GC-Mass) analyses (Hewlett Packard 5890 Gas Chromatograph and Agilent 5793 Mass Selective Detector) with the use of anisole as an internal standard. All Transmission Electron Microscopy (TEM) images were performed using JEM-3010 microscope at an accelerating voltage of 300 kV. The Energy Disperse Spectroscopy (EDS) map sum spectrum pattern was acquired using Oxford Instruments X-Maxn (software: Aztex). Sonication was performed in 120 W ultrasonic bath (Branson, B-3210).

Synthesis of PdPt–Fe_3O_4 NPs

Palladium(II) chloride ($PdCl_2$, 0.102g), potassium tetrachloroplatinate (K_2PtCl_4, 0.240 g) and polyvinylpyrrolidone (PVP) (Mw ~10,000, 1.2 g) were placed in 26 mL of EG in a 100 mL round-bottom flask. This mixture was sonicated for 10 min and stirred for 1 hour at 100 °C. Meanwhile, Fe_3O_4 (100 nm, 0.300 g) was placed in EG (100mL) in a two-necked 250 mL round-bottom flask. Then, the heated solution of $PdCl_2$, K_2PtCl_4 and PVP was added dropwise to the Fe_3O_4 suspension with syringe pump. Resulting mixture was heated at 100 °C for 24 h. The product was washed with ethanol. Finally, PdPt-Fe_3O_4 (0.250 g) was obtained from drying on a rotary evaporator for 30 min at 50 °C.

Synthesis of Pd–Fe_3O_4 NPs

Palladium(II) chloride ($PdCl_2$, 0.102 mg) and polyvinylpyrrolidone (PVP) (Mw ~ 10,000, 1.2 g) were placed in ethylene glycol (26 mL). This solution was thoroughly mixed using a sonicator for 10 min and heated for 1 hour at 100 °C. Fe_3O_4 (0.300g) NPs in EG (100 mL) was prepared in a 250 mL round bottom flask. The preheated $PdCl_2$ mixture was added dropwise with syringe pump to Fe_3O_4 suspension then the mixture was stirred for 24 h at 100 °C. The resulting Pd–Fe_3O_4 was washed in the same way as in the preparation of PdPt–Fe_3O_4. Finally, Pd-Fe_3O_4 (0.270 g) was obtained from drying on a rotary evaporator for 30 min at 50 °C.

Synthesis of Pt–Fe_3O_4 NPs

Potassium(II) tetrachloroplatinate (K_2PtCl_4,0.080g) and polyvinylpyrrolidone (PVP) (Mw ~10,000, 0.150 g) were placed in 9 mL of EG in a 50 mL round-bottom flask. This mixture was sonicated for 10 min and stirred for 1 hour at 100 °C. Meanwhile, commercially available Fe_3O_4 (0.100 g) was placed in 20 mL of EG in a two-necked 100 mL round-bottom flask. Then, prepared platinum precursor solution was added dropwise. Stirring of the mixture was continued for 24 h at 100 °C. The resulting Pt–Fe_3O_4 was washed in the same way as in the preparation of PdPt–Fe_3O_4. Finally, Pt–Fe_3O_4 (0.240 g) was obtained from drying on a rotary evaporator for 30 min at 50 °C.

Synthesis of Pd_xPt_y–Fe_3O_4 NPs

Pd_xPt_y–Fe_3O_4 NPs were synthesized in the same method as for PdPt-Fe_3O_4 with changing quantities of Pd and Pt metals. For the synthesis of Pd_2Pt_1–Fe_3O_4 NPs, $PdCl_2$ (0.068 g) and K_2PtCl_4 (0.080 g) together with PVP (Mw ~10000, 0.300 g) and Iron oxide (0.100g) were used. In the case of Pd_1Pt-Fe_3O_4 NPs, $PdCl_2$ (0 .034 g) and K_2PtCl_4 (0.160 g) together with PVP (Mw ~10,000, 0.300 g) and iron oxide (0.100 g) were used.

Synthesis of PdPt–C NPs, PdPt–CeO_2 NPs, and PdPt–TiO_2 NPs

Catalysts with different supports (C, CeO_2, and TiO_2) were synthesized in the same method as for PdPt-Fe_3O_4 with changing supports. For the synthesis of PdPt–C NPs, $PdCl_2$ (0.034 g) and K_2PtCl_4 (0.080 g) together with PVP (Mw ~10000, 0.300 g) and activated carbon (DARCO®, -100 mesh particle size, 0.100 g) were used. In the case of PdPt–CeO_2 NPs, $PdCl_2$ (0.034 g) and K_2PtCl_4 (0.080 g) together with PVP (Mw ~10000, 0.300 g) and cerium(IV) oxide (< 50 nm particle size, 0.100 g) were used. When synthesizing PdPt–TiO_2 NPs, we used $PdCl_2$ (0.034 g) and K_2PtCl_4 (0.080 g) together with PVP (Mw ~10000, 0.300 g) and titanium (IV) oxide (<100 nm particle size, 0.100 g).

A general procedure for reductive amination of nitriles with nitroalkanes.

PdPt–Fe_3O_4 NPs (2 mol %) catalyst, a nitrile (R-CN, 1.5 mmol), a nitroalkane (R-NO_2, 1 mmol) and sodium borohydride ($NaBH_4$, 2 mmol) were introduced in a 55 mL glass vial. Methanol (6 mL) was added to the vial and the mixture was stirred at room temperature for a specified period. After the reaction was terminated, the catalyst was recovered with an external magnet. The resulting mixture was diluted with 10 mL dichloromethane. The mixture was placed into a separatory funnel and the organic layer was washed with water. It was dried ($MgSO_4$) and concentrated to give a crude mixture, which was purified by flash column chromatography on silica gel with DCM/methanol to give the desired product.

Procedure for gram-scale synthesis

The PdPt–Fe_3O_4 catalyst (2 mol%), 1-nitrohexane (10 mmol), benzonitrile (15 mmol) and methanol (60 mL) were introduced in round-bottom pressure flask (500 mL) with a magnetic stirrer bar. The reaction mixture was sonicated for 1 min. Then sodium borohydride ($NaBH_4$, 20 mmol) was added to the mixture and the flask was closed with a Teflon plug. The mixture was stirred for 1 min at 0 ºC and then stirring was continued for 12 h at room temperature. After completion of the reaction, the catalyst was separated from the reaction mixture using a magnet. The solvent was evaporated from rotary evaporator and the resulting reaction mixture was treated with water (50 mL). The mixture was extracted with dichloromethane (40 mL X 3), dried over $MgSO_4$, filtrated and concentrated in vacuum. The residue was purified by silica gel flash chromatography (DCM/MeOH) to afford 1.44 g of the desired product. The method of synthesizing indole (**3u**) was carried out in the same way as above. 2-Nitrophenylaceotnitrile (10 mmol), PdPt–Fe_3O_4 (2.0 mol%) in methanol (40 mL) and HFIP (20 mL) was placed in round-bottom pressure flask. Then, sodium borohydride ($NaBH_4$, 50 mmol) was added to the mixture in the same method as described above. The reaction was stirred at 50 °C for 24 h. Upon completion of the reaction, the catalyst was recoverd using a magnet and solvent was removed from a rotary evaporator. The mixture was quenched with water (50 mL) and extracted using DCM (40 mL X 3). The combined organic solution was dried over anhydrous $MgSO_4$, filtered, and concentrated using a rotary evaporator. The crude material was treated with silica gel and purified by flash column chromatography (hexane/ethyl acetate) to give 0.93 g (79 % yield).

Conflicts of interest

"There are no conflicts to declare"

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Notes and references

1 ((a) R. N. Salvatore, C. H. Yoon, K. W. Jung, *Tetrahedron,* 2001, **57**, 7785-7811; (b) O. I. Afanasyev, E. Kuchuk, D. L. Usanov, D. Chusov, *Chem Rev.,* 2019, **119**, 11857-11911.

2 (a) E. J. Barreiro, A. E. Kummerle and C. A. Fraga, *Chem. Rev.*, 2011, **111**, 5215-5246; (b) McGuire, J. L. *Pharmaceuticals: Classes, Therapeutic Agents, Areas of Application* Wiley–VCH: Weinheim, Germany, 2000.

3 G. A. E. Mostafa and A. A. Al-Badr, *Profiles of drug substances, excipients, and related methodology*, 2017, **42**, 1-90

4 J. T. Cody and S. Valtier, *J. Anal. Toxicol.,* 2001, **25**, 158-165.

5 B. F. Gibbs, W. Schmutzler, I. B. Vollrath, P. Brosthardt, U. Braam, H. H. Wolff and G. Zwadlo-Klarwasser, *Inflamm. Res.,* 1999, **48**, 86-93.

6 S. M. Cheer and K. L. Goa, *Drugs*, 2001, **61**, 81-110.

7 W. A. Conway, F. Zorick, P. Piccione and T. Roth, *Thorax*, 1982, **37**, 49-53.

8 Y. N. Lamb, *Drugs*, 2019, **79**, 1805-1812.

9 (a) R. N. Salvatore, A. S. Nagle, S. E. Schmidt, K. W. Jung, *Org. Lett.,* 1999, **1**, 1893-1896.; (b) M. Selva, P. Tundo and A. Perosa, *J. Org. Chem.*, 2001, **66**, 677-680; (c) G. Marzaro, A. Guiotto and A. Chilin, *Green. Chem*., 2009, **11**, 774-776; (d) M. C. Lubinu, L. D. Luca, G. Giacomelli and A. Porcheddu, Chem. Eur. J., 2011, **17**, 82–85; (e) C. Chiappe and D. Pieraccini, *Green Chem.,* 2003, **5**, 193-197.

10 (a) O. Saidi, A. J. Blacker, M. M. Farah, S. P. Marsden, J. M. Williams, *Angew. Chem. Int. Ed.,* 2009, **48,** 7375-7378; (b) M. M. Farah, S. P. Marsden, J. M. Williams, *Chem. Commun.,* 2010, **46**, 1541-1543; (c) X. Cui, Y. Deng, F. Shi, *ACS Catal.,* 2013, **3**, 808-811; (d) B. Emayavaramban, P. Chakraborty, E. Manoury, R. Poli, B. Sundararaju, *Org.Chem.Front.,* 2019, **6**, 852-857; (e) B. Emayavaramban, P. Chakraborty, B. Sundararaju, *ChemSusChem,* 2019, **12**, 3089-3093.

11 (a) A. F. Abdel-Magid, S. J. Mehrman, *Org. Process Res. Dev*., 2006, **10**, 971-1031; (b) A. F. Abdel-Magid, K. G. Carson, B. D. Harris, C. A. Maryanoff, R. D. Shah, *J. Org. Chem.,* 1996, **61**, 3849-3862; (c) R. Apodaca, W. Xiao, *Org. Lett.,* 2001, ***3,*** 1745-1748; (d) R. Tripathi, S. Verma, J. Pandey, V. Tiwari, *Curr. Org. Chem.,* 2008, **12,** 1093-1115; (e) J. S. Sapsford, D. J. Scott, N. J. Allcock, M. J. Fuchter, C. J. Tighe, A. E. Ashley, *Adv. Synth. Catal.,* 2018, **360**, 1066-1071.

12 (a) D. B. Bagal, B. M. Bhanage, *Adv. Synth. Catal.,* 2015, **357**, 883-900; (b) Werkmeister, K. Junge, M. Beller, *Org. Process Res. Dev*., 2014, **18**, 289-302; (c) J. Krupka, J. Pasek, *Curr. Org. Chem.,* 2012, **16**, 988-1004.

13 (a) A. Mukherjee, D. Srimani, S. Chakraborty, Y. Ben-David, D. Milstein, *J. Am. Chem. Soc.,* 2015, **137**, 8888-8891; (b) K. Tokmic, B. J. Jackson, A. Salazar, T. J. Woods, A. R. Fout, *J. Am. Chem. Soc.,* 2017, **139**, 13554-13561; (c) M. Vilches-Herrera, S. Werkmeister, K. Junge, A. Börner, M. Beller, *Catal. Sci & Technol.,* 2014, **4**, 629-632; (d) L. Hegedűs, K. Lévay, *Period. Polytech. Chem. Eng.,* 2018, **62**. 476-488; (e) Y.-F. Zen, Z. C. Fu, F. Liang, Y. Xu, D.-D. Yang, Z. Yang, X. Gan, Z.-S. Lin, Y. Chen, W.-F. Fu, *Asian J. Org. Chem.,* 2017, **6**, 1589-1593.

14 (a) Y. Li, Y. Gong, X. Xu, P. Zhang, H. Li, Y. Wang, *Catal. Commun.,* 2012, **28**, 9-12; (b) Z.-F. Jiao, J.-X. Zhao, X.-N. Guo, X.-L. Tong, B. Zhang, G.-Q. Jin, Y. Qin, X.-Y. Guo, *Catal. Sci & Technol*., 2019, **9**, 2266-2272.

15 (a) A. Galan, J. De Mendoza, P. Prados, J. Rojo, A. M. Echavarren, *J. Org. Chem.,* 1991, **56**, 452-454; (b) Y. Monguchi, M. Mizuno, T. Ichikawa, Y. Fujita, E. Murakami, T. Hattori, T.

Maegawa, Y. Sawama, H. Sajiki, *J. Org. Chem.,* 2017, **82**, 10939-10944.

16 (a) C. Ortiz-Cervantes, I. Iyañez, J. J. García, *J. Phys. Org. Chem.,* 2012, **25**, 902-907; (b) M. K. Sayantani Saha, Kuldeep Singh, Jitendra K. Bera, *J. Organomet. Chem.,* 2016, **812**, 87-94.

17 S. Lu, J. Wang, X. Cao, X. Li, H. Gu, *Chem.Commun.,* 2014, **50**, 3512-3515.

18 S. Lu, P. Xu, X. Cao, H. Gu, *RSC Adv.,* 2018, **8**, 8755-8760.

19 L. Liu, Y. Liu, Y. Ai, J. Li, J. Zhou, Z. Fan, H. Bao, R. Jiang, Z. Hu, J. Wang, K. Jing, Y. Wang, Q. Liang, H. Sun, *iScience,* 2018, **8**, 61-73.

20 Z. Shao, S. Fu, M. Wei, S. Zhou, Q. Liu, *Angew. Chem. Int. Ed.,* 2016, **55**, 14653-14657.

21 D. M. Sharma, B. Punji, *Adv. Synth. Catal.,* 2019, **361**, 3930-3936.

22 (a) T. Ikawa, Y. Fujita, T. Mizusaki, S. Betsuin, H. Takamatsu, T. Maegawa, Y. Monguchi, H. Sajiki, *Org. Biomol. Chem.,* 2012, **10**, 293-304; (b) H. Sajiki, T. Ikawa, K. Hirota, *Org. Lett.* 2004, **6**, 4977-4980.

23 S. K. Sharma, J. Lynch, A. M. Sobolewska, P. Plucinski, R. J. Watson, J. M. J. Williams, *Catal. Sci. Technol.,* 2013, **3**, 85-88.

24 (a) A. K. Singh, Q. Xu, *ChemCatChem,* 2013, **5**, 652-676; (b) R. Ferrando, J. Jellinek, R. L. Johnston, *Chem. Rev.,* 2008, **108**, 845-910; (c) O. G. Ellert, M. V. Tsodikov, S. A. Nikolaev, V. M. Novotortsev, *Russ. Chem. Rev.,* 2014, **83,** 718-732.

25 S. Byun, Y. Song, B. M. Kim, *ACS Appl. Mater. Interfaces,* 2016, **8**, 14637-14647.

26 J. Jang, S. Byun, B. M. Kim, S. Lee, *Chem.Commun.,* 2018, **54**, 3492-3495.

27 H. W. Kim, S. Byun, S. M. Kim, H. J. Kim, C. Lei, D. Y. Kang, A. Cho, B. M. Kim and J. K. Park, *Catal. Sci. Technol*., 2020, **10**, 944-949.

28 (a) A. Goswami, A. K. Rathi, C. Aparicio, O. Tomanec, M. Petr, R. Pocklanova, M. B. Gawande, R. S. Varma and R. Zboril, *ACS Appl. Mater Interfaces*, 2017, **9**, 2815-2824; (b) K. J. Datta, K. K. Datta, M. B. Gawande, V. Ranc, K. Cepe, V. Malgras, Y. Yamauchi, R. S. Varma and R. Zboril, *Chem. Eur. J.,* 2016, **22**, 1577-1581;(c) C. Kim, J. Kim, S. Yang and H. Lee, *RSC Adv.,* 2014, **4**, 63677-63680; (d) J. Zhang, L. Wan, L. Liu, Y. Deng, C. Zhong and W. Hu, *Nanoscale*, 2016, **8**, 3962-3972; (e) A. Pekkari, Z. Say, A. Susarrey-Arce, C. Langhammer, H. Harelind, V. Sebastian and K. Moth-Poulsen, *ACS Appl. Mater. Interfaces*, 2019, **11**, 36196-36204.

29 (a) O. Rosseler, C. Ulhaq-Bouillet, A. Bonnefont, S. Pronkin, E. Savinova, A. Louvet, V. Keller and N. Keller, *Appl. Catal., B*, 2015, **166-167**, 381-392; (b) Y. Liu, M. Chi, V. Mazumder, K. L. More, S. Soled, J. D. Henao and S. Sun, *Chem. Mater.,* 2011, **23**, 4199-4203; (c) R. Esparza, A. Santoveña, A. Ruíz-Baltazar, A. Angeles-Pascual, D. Bahena, J. Maya-Cornejo, J. Ledesma-García and R. Pérez, *Mater. Res.,* 2017, **20**, 1193-1200.

30 (a) Y. Wang, Q. Li, P. Zhang, D. O'Connor, R. S. Varma, M. Yu and D. Hou, *J. Colloid Interface Sci*., 2019, **539**, 161-167; (b) Z. Huang, H. Zhou, F. Sun, C. Fu, F. Zeng, T. Li and Y. Kuang, *Chemistry*, 2013, **19**, 13720-13725.

31 C. A. Rodriguez-Proenza, J. P. Palomares-Baez, M. A. Chavez-Rojo, A. F. Garcia-Ruiz, C. L. Azanza-Ricardo, A. Santovena-Uribe, G. Luna-Barcenas, J. L. Rodriguez-Lopez, R. Esparza, *Materials,* 2018, **11**, 1882.

32 A. Cho, S. Byun, J. H. Cho, B. M. Kim, *ChemSusChem,* 2019, **12**, 2310-2317.

33 A. Cho, S. Byun, B. M. Kim, *Adv. Synth. Catal.,* 2018, **360**, 1253-1261.

34 I. Colomer, A. E. R. Chamberlain, M. B. Haughey, T. J. Donohoe, *Nat. Rev. Chem.,* 2017, **1**, 0088.

35 H. F. Motiwala, M. Charaschanya, V. W. Day, J. Aube, *J. Org. Chem.,* 2016, **81**, 1593-1609.

36 K. Kushwaha, B. Pinter, S. A. Shehzadi, C. C. Malakar, C. M. L. Vande Velde, F. de Proft, K. Abbaspour Tehrani, *Adv. Synth. Catal.,* 2016, **358**, 41-49.

37 S. K. Sinha, T. Bhattacharya, D. Maiti, *React. Chem. & Eng.,* 2019, **4**, 244-253.

38 (a) M. B. Gawande, P. S. Branco, R. S. Varma, *Chem. Soc. Rev.,* 2013, **42**, 3371-3393; (b) R. K. Sharma, S. Dutta, S. Sharma, R. Zboril, R. S. Varma, M. B. Gawande, *Green. Chem.,* 2016, **18**, 3184-3209.

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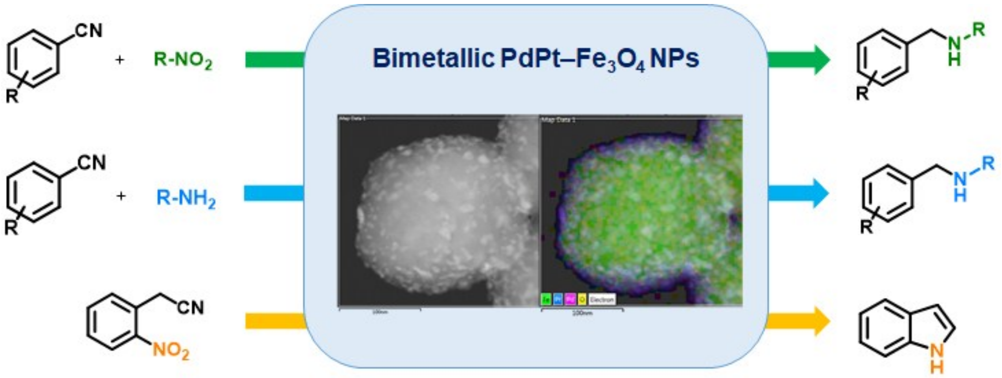

- ✓ Bimetallic synergistic effect
- ✓ One-pot, cascade reduction
- ✓ High chemoselectivity
- ✓ Magnetically recyclable catalyst