RSC Advances

PAPER

View Article Online
View Journal | View Issue

Cite this: *RSC Adv.*, 2023, **13**, 29607

One-pot reductive amination of carbonyl compounds and nitro compounds *via* Ir-catalyzed transfer hydrogenation†

Renshi Luo,[ab] Jinghui Tong,[b] Lu Ouyang,[b] Liang Liu[b] and Jianhua Liao *[b]

The formation of C–N bond is a vital synthetic tool for establishing molecular diversity, which is highly sought after in a wide range of biologically active natural products and drugs. Herein, we present a new strategy for the synthesis of secondary amines *via* iridium-catalyzed one-pot reductive amination of carbonyl compounds with nitro compounds. This method is demonstrated for a variety of carbonyl compounds, including miscellaneous aldehydes and ketones, which are compatible with this catalytic system, and deliver the desired products in good yields under mild conditions. In this protocol, the reduction of nitro compounds occurs *in situ* first, followed by reductive amination to form amine products, providing a new one-pot procedure for amine synthesis.

Received 22nd August 2023
Accepted 25th September 2023

DOI: 10.1039/d3ra05736d

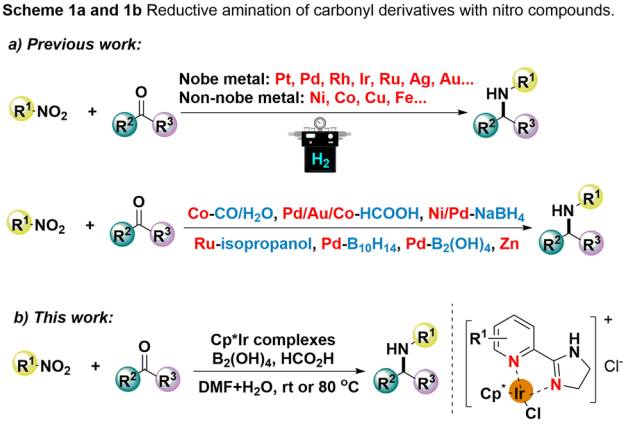
rsc.li/rsc-advances

Amines, particularly secondary amines, are not only prevalent in dyestuff, and chemosynthesis plants as important industrial materials, but also exist in a wide range of biologically active natural products and drugs.[1] Thus, the establishment of strategies to facilely form C–N bond is of longstanding significance in organic synthesis. A simple strategy to construct amines is the alkylation of amines with alkyl halides[2] or alcohols.[3] The successful preparation of C–N bond would also be realized by Buchwald-Hartwig[4] or Ullman-type cross-coupling reactions.[5] Notably, strategies of reductive amination[6] and addition reactions to imines[7] have been described as in the C–N bond synthesis. Additionally, the reduction of amides[8] also enables the formation of amine products. Given the simple and easy accessibility of raw materials, reductive amination undoubtedly enables the practical and direct formation of the C–N bond,[9] which is shown as a step and atomic economy.

Nitro compounds, as readily available feedstocks, have been extensively employed for reductive amination with carbonyl compounds, in which the nitro compounds are converted into primary amines in advance, thereby avoiding the additional purification steps.[10] In this context, a pioneering report on the reductive amination of carbonyl compounds with nitro compounds was described by Major's group in early 1931 with H_2 as the hydrogenation reagent.[11] Since this seminal work, extensive outstanding progress has been achieved over the past decades. In this regard, a heterogeneous catalytic system utilizing noble metals (such as platinum,[12] palladium,[13] rhodium,[14] iridium,[15] ruthenium,[16] silver,[17] and gold[18]) and non-noble metals (such as nickel,[19] cobalt,[20] copper,[21] and iron,[22]) as catalysts have been established (Scheme 1a). Similarly, strategies based on the catalytic system with the form of metals, oxides, and other compounds as catalysts have been developed as well for the reductive amination of carbonyl derivatives with nitro compounds (Scheme 1a). However, synthetic methods for this one-pot reductive amination of nitro compounds were limited to H_2 as the hydrogen donor, which is inevitably constrained in the use of high-pressure devices and possesses potential safety issues.

As a consequence, approaches for replacing hydrogen gas with other hydrogen donors, such as CO/H_2O,[23] HCO_2H,[24]

Scheme 1a and 1b Reductive amination of carbonyl derivatives with nitro compounds.



Scheme 1 Reductive amination of carbonyl derivatives with nitro compounds.

[a]College of Chemistry and Environmental Engineering, Shaoguan University, Shaoguan 512005, P. R. China

[b]School of Pharmaceutical Sciences, Gannan Medical University, Ganzhou 341000, Jiangxi Province, P. R. China. E-mail: liaojianhua715@163.com

† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d3ra05736d

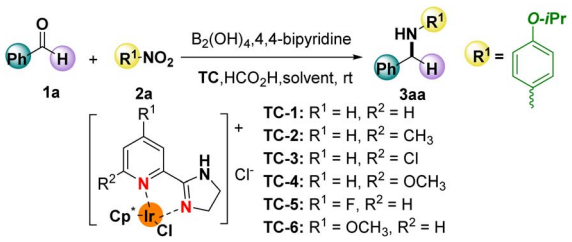
$NaBH_4$,[25] $B_{10}H_{14}$,[26] $B_2(OH)_4$,[27] and Zn,[28] for the reductive amination with nitro compounds have been established (Scheme 1a). However, great efforts to circumvent the harsh reaction conditions, narrow the substrate scope, long reaction times, complicated catalyst preparation processes, high catalyst loading, and well as side-reactions have been made in the past years.

As such, transfer hydrogenation, which uses polyatomic molecules, including formic acid, alcohol, hydrazine hydrate, and silane as hydrogen donors, to migrate hydrogen to the unsaturated functional group directly with the assistance of catalysts. In this context, formic acid obtained from biomass, bearing the merits of high energy density, low cost, non-poisonousness, and stability, has been widely applied as a hydrogen source in transfer hydrogenation reactions. Recently, we have been working on the transfer hydrogenation of C=O, C=C, C=N bonds using Cp*Ir complexes as catalysts and formic acid as the hydrogen donor.[29] In these methods, we have demonstrated that these Cp*Ir complexes could enable indirect and direct reductive amination for the construction of amine compounds.[29a,d] However, reductive amination for the construction of C–N bond *via* transfer hydrogenation with nitro compounds as the source of amine remains relatively limited. Herein, we present an iridium-catalyzed one-pot reductive amination of carbonyl compounds with nitro compounds (Scheme 1b). In this protocol, the reduction of nitro compounds occurs *in situ* first, followed by reductive amination to form the amine products, providing a new one-pot procedure for amine synthesis.

To explore the possibility of the reaction, the reductive amination was started by using 1-isopropoxy-4-nitrobenzene (**2a**) and benzaldehyde (**1a**) as templates, and **TC** as the catalyst. As shown in Table 1, 98% conversion of the desired product **3aa** was observed using **TC-1** as a catalyst, 15.0 equiv. HCO_2H as the hydrogen donor, as well as DMF and H_2O as the mixed solvent (v/v = 1 : 1) after 4 h (Table 1, entry 1). Catalyst screening demonstrated the corresponding product **3aa** could be formed as well, though a lower conversion of the product was obtained (Table 1, entries 2–6). For instance, only moderate yields of the desired product were afforded when catalysts bearing methyl or chlorine substituents were employed (Table 1, entries 2 and 3). In contrast, good to excellent yields of the corresponding product were observed using fluorine or methoxyl-substituted catalysts (Table 1, entries 4–6). Of note, the increase in the reaction time had no influence on the yield of the product (Table 1, entry 7). However, a sharp decrease in the yield was observed when the catalyst loading of **TC-1** was decreased to 0.5 mol% (Table 1, entry 8). A similar negative influence on the yield of the product was also observed when different reaction media were loaded (Table 1, entries 9–12).

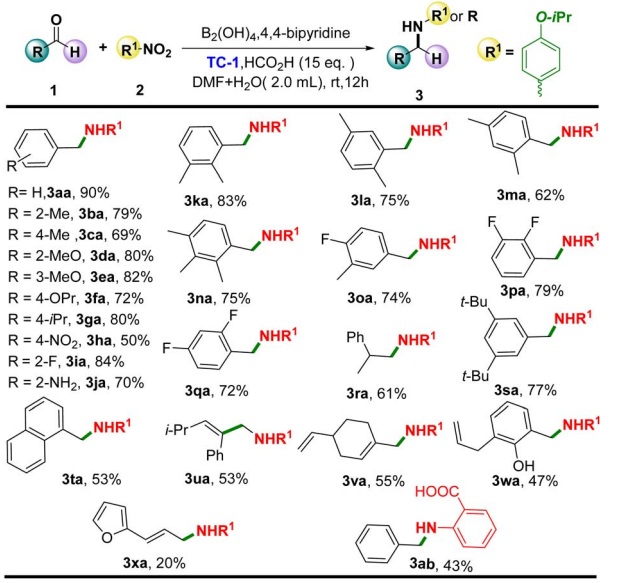
With the optimized conditions in hand, the substrate scope was investigated to explore its versatility (Scheme 2). Firstly, the 1-isopropoxy-4-nitrobenzene (**2a**) was loaded as an amination agent to react with various aldehydes. Gratifyingly, the desired reductive amination products of **3ba–3ga**, **3ia**, **3ja**, as well as **3sa** were afforded good yields with mono-substituted benzaldehydes as substrates. Of note, only a moderate yield of the corresponding product was achieved when 4-nitrobenzaldehyde

Table 1 Optimization of the conditions for Ir-catalysed reductive amination of aldehydes with nitro compounds[a]



Entry	Catalyst	Solvent	HCO_2H (eq.)	Time (h)	Yield[b] (%)
1	**TC-1**	DMF + H_2O	15	4	98
2	**TC-2**	DMF + H_2O	15	4	66
3	**TC-3**	DMF + H_2O	15	4	48
4	**TC-4**	DMF + H_2O	15	4	92
5	**TC-5**	DMF + H_2O	15	4	89
6	**TC-6**	DMF + H_2O	15	4	76
7	**TC-1**	DMF + H_2O	15	12	99
8[c]	**TC-1**	DMF + H_2O	15	12	54
9	**TC-1**	DMSO + H_2O	15	12	10
10	**TC-1**	H_2O	15	12	<5
11	**TC-1**	DMSO	15	12	<5
12	**TC-1**	DMF	15	12	<5

[a] Reaction conditions: **1a** (0.5 mmol), **2a** (1.0 mmol), solvent (2.0 mL), catalyst (0.005 mmol), HCO_2H (15.0 equiv.), $B_2(OH)_4$ (6.0 equiv.), 4,4-bipyridine (0.05 mmol) at room temperature under air for 12 h. [b] Determined using GC-MS. [c] With 0.0025 mmol of the catalyst.



Scheme 2 Substrate scope of the aldehydes and nitro compounds. Reaction conditions: **1** (0.5 mmol), **2** (1.0 mmol), solvent (2.0 mL), catalyst (0.005 mmol), HCO_2H (10.0 equiv.), $B_2(OH)_4$ (6.0 equiv.), 4,4-bipyridine (0.05 mmol) at room temperature in air for 12 h. Yield of the isolated product.

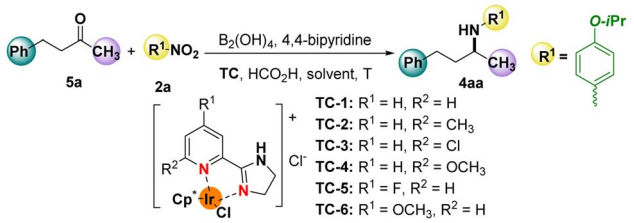
was loaded as the substrate (**3ha**). Interestingly, the employment of multi-substituted benzaldehydes, including electron-donating or electron-withdrawing substituents on the phenyl group, could also enable the delivery of the corresponding products (**3ka–3pa**) in similar excellent yields. Obviously, the substrate **2w** bearing the potential oxidized hydroxyl group reacted smoothly as well under this system. Satisfactorily, employing aliphatic aldehydes, naphthaldehyde, as well as unsaturated aldehyde as substrates also furnished the corresponding products **3ra**, **3ta–3xa** in moderate to good yields. It is worth noting that the amino acid product of **3ab** was produced when 2-nitrobenzoic acid was loaded as the substrate.

Encouraged by the results of the Ir-catalysed reductive amination of aldehydes with nitro compounds, the feasibility of using ketones as substrates was also investigated (Table 2). Firstly, 4-phenyl-2-butanone (**5a**) and 1-isopropoxy-4-nitrobenzene (**2a**) were chosen for the model reaction to optimize the reaction parameters. Catalyst screening (Table 2, entries 1–6) demonstrated that, unlike aldehydes, **TC-4** was found to be the optimal catalyst for the reductive amination of ketones, delivering 90% conversion of the desired product **4aa** at room temperature (Table 2, entry 4). Gratifyingly, the yield of the product was slightly increased when the reaction temperature was increased to 80 °C (Table 2, entry 7). Similar to aldehydes, solvents have a significant influence on the reaction, producing completely different yields of the product in different reaction media (Table 2, entries 8–11). Of note, a similar high yield of the product was obtained even when the loading of the catalyst was decreased to 0.1 mol%, or the reaction time was shortened to 2 h (Table 2, entries 12–15). Control experiments evidenced that, indeed, a 30% yield of the corresponding reductive amination product of **4aa** could be afforded in the absence of B_2OH_4 under standard conditions (Table 2, entry 16). However, the iridium catalyst was essential for the formation of the desired product (Table 2, entry 17) (see ESI† for further details, **F**).

Based on the above optimizations, the substrate scope of ketones and nitro compounds was investigated (Scheme 3).

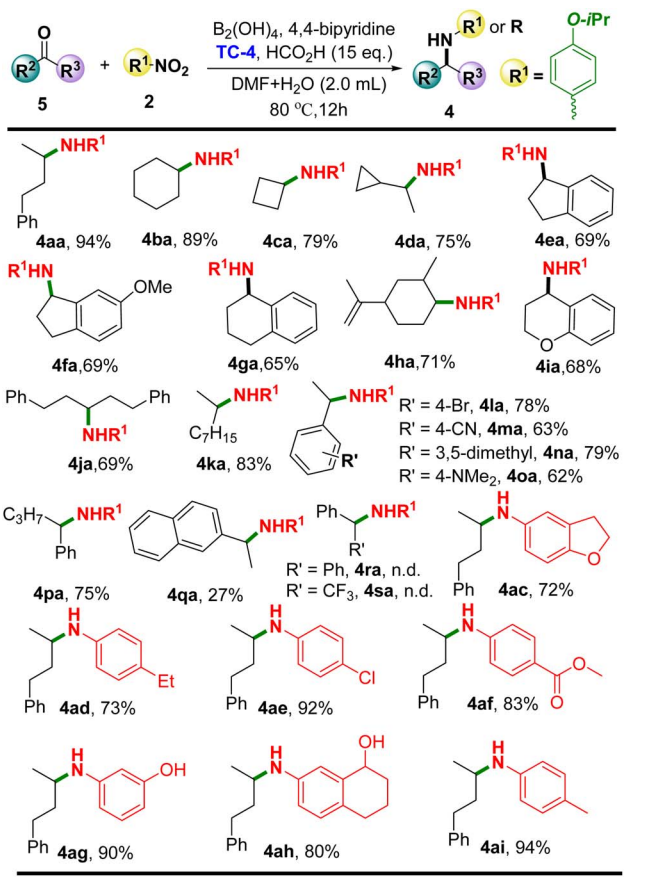
Firstly, the use of 4-phenylbutan-2-one (**5a**) as the substrate to react with 4-isopropylnitrobenzene or heterocyclic nitrobenzene was explored to examine the versatility of this reductive amination. Gratifyingly, various cyclic aliphatic ketones loaded as substrates enabled the delivery of the target products (**4ba–4ga**) in moderate to good yields. Similar results were also

Table 2 Optimization of conditions for the Ir-catalysed reductive amination of ketone with nitro compounds[a]



Entry	Cat.	T (°C)	Solvent	HCO_2H (eq.)	Time (h)	Yield[b] (%)
1	**TC-1**	rt	DMF + H_2O	15	12	59
2	**TC-2**	rt	DMF + H_2O	15	12	66
3	**TC-3**	rt	DMF + H_2O	15	12	38
4	**TC-4**	rt	DMF + H_2O	15	12	90
5	**TC-5**	rt	DMF + H_2O	15	12	34
6	**TC-6**	rt	DMF + H_2O	15	12	34
7	**TC-4**	80	DMF + H_2O	15	12	97
8	**TC-4**	80	DMF	15	12	34
9	**TC-4**	80	DMSO	15	12	<5
10	**TC-4**	80	H_2O	15	12	n.d.
11	**TC-4**	80	DMSO + H_2O	15	12	n.d.
12	**TC-4**	80	DMF + H_2O	10	12	95
13	**TC-4**	80	DMF + H_2O	12	12	97
14	**TC-4**	80	DMF + H_2O	15	2	97
15[c]	**TC-4**	80	DMF + H_2O	15	12	94
16[d]	**TC-4**	80	DMF + H_2O	15	12	30
17	—	80	DMF + H_2O	15	12	n.d.

[a] Reaction conditions: **5a** (0.5 mmol), **2a** (0.75 mmol), solvent (2.0 mL), catalyst (1.0% mol), HCO_2H (15.0 equiv.), $B_2(OH)_4$(2.25 mmol), 4,4-bipyridine (0.0375 mmol) at 80 °C in air for 12 h. [b] Determined using GC-MS. [c] The reaction was carried out using 0.0005 mmol of the catalyst. [d] Without $B_2(OH)_4$.

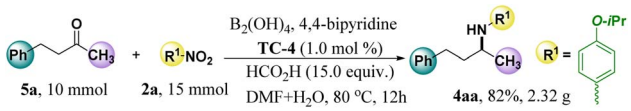


Scheme 3 Substrate scope of ketones and nitro compounds for reductive amination. Reaction conditions: **5** (0.5 mmol), **2** (0.75 mmol), solvent (2.0 mL), catalyst (1.0 mol%), HCO_2H (15.0 equiv.), $B_2(OH)_4$ (2.25 mmol), 4,4-bipyridine (0.0375 mmol) at room temperature under air for 12 h. Yield of the isolated product.

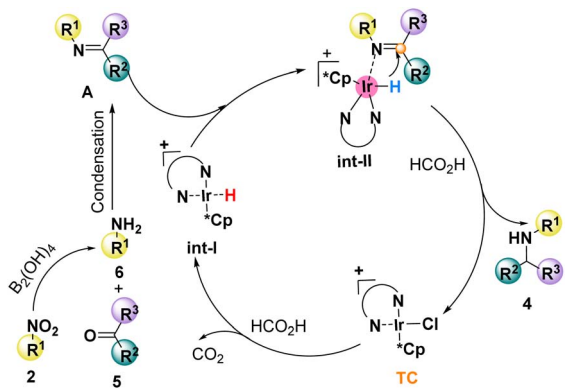
observed (**4ha** and **4ia**) when unsaturated ketones or heterocyclic ketones were employed in this catalytic system. Obviously, the use of aliphatic ketones with long carbon chains **5j** and **5k** as the substrates did not have an influence on the yields of the desired products (**4ja** and **4ka**). It should be noted that aromatic ketones were also well tolerated in this system to produce the corresponding products (**4la–4pa**). Nevertheless, only 27% of the target product (**4qa**) was provided using a more steric hindrance of 1-(naphthalen-2-yl)ethan-1-one (**5q**) as the substrate. Disappointingly, benzophenone (**5r**) or 2,2,2-trifluoro-1-phenylethan-1-one (**5s**) substrates could not be tolerated in this catalytic system. On the other hand, different substituted nitro compounds were also investigated in this system. Satisfyingly, heterocyclic substrates such as 5-nitro-2,3-dihydrobenzofuran (**2c**) were well tolerated to afford the desired product **4ac** in good yield. Interestingly, di-functional conversion products of **4ad** and **4ah** were observed when 1-ethynyl-4-nitrobenzene (**2d**) and 7-nitro-3,4-dihydronaphthalen-1(2*H*)-one (**2h**) were loaded, in which, both the alkyne and carbonyl groups were reduced simultaneously. It is notable that the chlorine (**2e**), methyl (**2i**), ester (**2f**), and even the readily oxidized phenol hydroxyl (**2g**) substituted nitro compounds were compatible with this system, delivering the corresponding products in excellent yields.

The model reaction was scaled up to investigate the practicability of this protocol (Scheme 4). Gratifyingly, 2.32 g target product of **4aa** was produced in 82% yield after 12 h by loading 10.0 mmol of **5a** as substrate under standard conditions, indicating that this protocol could be followed for scalable performance. Of note, this model reaction was also investigated with chiral **TC-7** as the catalyst, and only the racemic product **4aa** was afforded (see ESI† **E**).

According to the experiment and previous work,[29d] a possible mechanism was proposed, as shown in Scheme 5. This catalytic



Scheme 4 Scheme for the gram-scale experiment.



Scheme 5 Proposed mechanism.

cycle involved two processes, in which amine **6** was produced *in situ* with $B_2(OH)_4$ as the catalyst, followed by condensation with carbonyl compounds to form the imine intermediate **A**. With the intermediate in hand, the second process occurred successively, in which the **Int-I** was formed firstly, then followed by transfer hydrogenation to afford the desired product **4** and the catalytic cycle.

Conclusions

In summary, we established a new strategy for the synthesis of secondary amines *via* the iridium-catalysed reductive amination of carbonyl compounds with nitro compounds. A wide range of carbonyl compounds, including aliphatic or aromatic aldehydes and ketones, were well tolerated in this catalytic system, delivering the desired products in moderated to excellent yields under mild conditions. In this transformation, first, the reduction of nitro compounds was realized *in situ* with $B_2(OH)_4$ as the reductant, followed by reductive amination of carbonyl compounds to afford amine products, providing a new one-pot procedure for amine synthesis.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (21961002, 22161004), the Fundamental Research Funds for Gannan Medical University (QD202019, QD202106, and TD2021YX05) and Shaoguan University (408/9900064703) for financial support.

Notes and references

1 (*a*) C. A. Buehler and D. E. Pearson, *Survey of Organic Synthesis*, Wiley Interscience, New York, 1970, vol. 1, p. 413; (*b*) O. Mitsunobu, B. M. Trost and I. Fleming, *Comprehensive Organic Synthesis*, Oxford, 1991, vol. 6, p. 65; (*c*) R. S. Vardanyan and V. J. Hruby, *Synthesis of Best-Seller Drugs*, Academic Press, Amsterdam, 2016; (*d*) S. A. Lawrence, *Amines. Synthesis, Properties and Applications*, Cambridge University Press, Cambridge, UK, NY, 2004.

2 (*a*) R. N. Salvatore, C. H. Yoon and K. W. Jung, Synthesis of secondary amines, *Tetrahedron*, 2001, **57**, 7785; (*b*) J.-C. Castillo, J. Orrego-Hernández and J. Portilla, Cs_2CO_3-Promoted Direct *N*-Alkylation: Highly Chemoselective Synthesis of *N*-Alkylated Benzylamines and Anilines, *Eur. J. Org Chem.*, 2016, **2016**, 3824.

3 (*a*) S. Elangovan, J. Neumann, J. B. Sortais, K. Junge, C. Darcel and M. Beller, Efficient and selective *N*-alkylation of amines with alcohols catalysed by manganese pincer complexes, *Nat. Commun.*, 2016, **7**, 12641; (*b*) S. Rösler, M. Ertl, T. Irrgang and R. Kempe, Cobalt-Catalyzed Alkylation of Aromatic Amines by Alcohols, *Angew. Chem.*,

Int. Ed., 2015, **54**, 15046; (*c*) M. Mastalir, B. Stöger, E. Pittenauer, M. Puchberger, G. Allmaier and K. Kirchner, Air Stable Iron (II) PNP Pincer Complexes as Efficient Catalysts for the Selective Alkylation of Amines with Alcohols, *Adv. Synth. Catal.*, 2016, **358**, 3824.

4 (*a*) D. S. Surry and S. L. Buchwald, Biaryl phosphane ligands in palladium-catalyzed amination, *Angew. Chem., Int. Ed.*, 2008, **47**, 6338; (*b*) J. F. Hartwig, Evolution of a fourth-generation catalyst for the amination and thioetherification of aryl halides, *Acc. Chem. Res.*, 2008, **41**, 1534.

5 (*a*) S. V. Ley and A. W. Thomas, Modern synthetic methods for copper-mediated C(aryl)[bond]O, C(aryl)[bond]N, and C(aryl)[bond]S bond formation, *Angew. Chem., Int. Ed.*, 2003, **42**, 5400; (*b*) S. D. Surry and S. L. Buchwald, Diamine Ligands in Copper-Catalyzed Reactions, *Chem. Sci.*, 2010, **1**, 13.

6 E. W. Baxter and A. B. Reitz, *Reductive Aminations of Carbonyl Compounds with Borohydride and Borane Reducing Agents. Organic Reactions*, John Wiley & Sons, Inc, 2002.

7 R. E. Malz and H. Greenfield, Tertiary Amine Preparation by Reductive Alkylation of Aliphatic Secondary Amines with Ketones, *Stud. Surf. Sci. Catal.*, 1991, **59**, 351.

8 (*a*) S. Das, S. Zhou, D. Addis, S. Enthaler, K. Junge and M. Beller, Selective Catalytic Reductions of Amides and Nitriles to Amines, *Top. Catal.*, 2010, **53**, 979; (*b*) M. Stein and B. Breit, Catalytic hydrogenation of amides to amines under mild conditions, *Angew. Chem., Int. Ed.*, 2013, **52**, 2231.

9 (*a*) T. Irrgang and R. Kempe, Transition-Metal-Catalyzed Reductive Amination Employing Hydrogen, *Chem. Rev.*, 2020, **120**, 9583; (*b*) R. I. Storer, D. E. Carrera, Y. Ni and D. W. MacMillan, Enantioselective organocatalytic reductive amination, *J. Am. Chem. Soc.*, 2006, **128**, 84; (*c*) S. Liang, P. Monsen, G. B. Hammond and B. Xu, Au/TiO_2 catalyzed reductive amination of aldehydes and ketones using formic acid as reductant, *Org. Chem. Front.*, 2016, **3**, 505.

10 (*a*) N. Ono, *The nitro group in organic synthesis*, John Wiley & Sons, 2003; (*b*) D. Green and T. Johnson, Nitroalkane chemistry, *Innovations Pharm. Technol.*, 2000, **1**, 79.

11 R. T. Major, Catalytic reduction of mixtures of para-nitro- and nitrosophenols with aldehydes and ketones, *J. Am. Chem. Soc.*, 1931, **53**, 1901.

12 (*a*) L. Hu, X. Cao, D. Ge, H. Hong, Z. Guo, L. Chen, X. Sun, J. Tang, J. Zheng, J. Lu and H. Gu, Ultrathin platinum nanowire catalysts for direct C-N coupling of carbonyls with aromatic nitro compounds under 1 bar of hydrogen, *Chemistry*, 2011, **17**, 14283; (*b*) F. G. Cirujano, A. Leyva-Pérez, A. Corma, F. Llabrés and F. X. Xamena, MOFs as Multifunctional Catalysts: Synthesis of Secondary Arylamines, Quinolines, Pyrroles, and Arylpyrrolidines over Bifunctional MIL-101, *ChemCatChem*, 2013, **5**, 538.

13 (*a*) M. O. Sydnes, M. Kuse and M. Isobe, Reductive monoalkylation of nitro aryls in one-pot, *Tetrahedron*, 2008, **64**, 6406; (*b*) B. Sreedhar, P. S. Reddy and D. K. Devi, Direct one-pot reductive amination of aldehydes with nitroarenes in a domino fashion: catalysis by gum-acacia-stabilized palladium nanoparticles, *J. Org. Chem.*, 2009, **74**, 8806; (*c*) M. M. Dell'anna, P. Mastrorilli, A. Rizzuti and C. Leonelli, Onepot synthesis of aniline derivatives from nitroarenes under mild conditions promoted by a recyclable polymer-supported palladium catalyst, *Appl. Catal., A*, 2011, **401**, 134; (*d*) S. Wei, Z. Dong, Z. Ma, J. Sun and J. Ma, Palladium supported on magnetic nanoparticles as recoverable catalyst for one-pot reductive amination of aldehydes with nitroarenes under ambient conditions, *Catal. Commun.*, 2013, **30**, 40; (*e*) X. Zhou, X. Li, L. Jiao, H. Huo and R. Li, Programmed Synthesis Palladium supported on Fe_3O_4@C: an efficient and heterogeneous recyclable catalyst for one-pot reductive amination of aldehydes with nitroarenes in aqueous reaction medium, *Catal. Lett.*, 2015, **145**, 1591; (*f*) H. Sharma, M. Bhardwaj, M. Kour and S. Paul, Highly efficient magnetic Pd (0) nanoparticles stabilized by amine functionalized starch for organic transformations under mild conditions, *Mol. Catal.*, 2017, **435**, 58.

14 L. Huang, Z. Wang, L. Geng, R. Chen, W. Xing, Y. Wang and J. Huang, Selective and recyclable rhodium nanocatalysts for the reductive *N*-alkylation of nitrobenzenes and amines with aldehydes, *RSC Adv.*, 2015, **5**, 56936.

15 (*a*) M. Pintado-Sierra, A. M. Rasero-Almansa, A. Corma, M. Iglesias and F. Sánchez, Bifunctional iridium-(2-aminoterephthalate)-Zr-MOF chemoselective catalyst for the synthesis of secondary amines by one-pot three step cascade reaction, *J. Catal.*, 2013, **299**, 137; (*b*) D. Sui, F. Mao, H. Fan, Z. Qi and J. Huang, General reductive amination of aldehydes and ketones with amines and nitroaromatics under H_2 by recyclable iridium catalysts, *Chin. J. Chem.*, 2017, **35**, 1371.

16 C. Del Pozo, A. Corma, M. Iglesias and F. Sánchez, Multisite solid (NHC)NN-Ru-catalysts for cascade reactions: synthesis of secondary amines from nitro compounds, *J. Catal.*, 2012, **291**, 110.

17 E. A. Artiukha, A. L. Nuzhdin, G. A. Bukhtiyarova and V. I. Bukhtiyarov, Flow synthesis of secondary amines over Ag/Al_2O_3 catalyst by one-pot reductive amination of aldehydes with nitroarenes, *RSC Adv.*, 2017, **7**, 45856.

18 (*a*) Y. Yamane, X. Liu, A. Hamasaki, T. Ishida, M. Haruta, T. Yokoyama and M. Tokunaga, One-pot synthesis of indoles and aniline derivatives from nitroarenes under hydrogenation condition with supported gold nanoparticles, *Org. Lett.*, 2009, **11**, 5162; (*b*) E. A. Artiukha, A. L. Nuzhdin, G. A. Bukhtiyarova, S. Y. Zaytsev, P. E. Plyusnin and Y. V. Shubin, One-pot reductive amination of aldehydes with nitroarenes over an Au/Al_2O_3 catalyst in a continuous flow reactor, *Catal. Sci. Technol.*, 2015, **5**, 4741.

19 (*a*) A. M. Fiore, G. Romanazzi, M. M. Dell'anna, M. Latronico, C. Leonelli and M. Mali, Mild and efficient synthesis of secondary aromatic amines by one-pot stepwise reductive amination of arylaldehydes with nitroarenes promoted by reusable nickel nanoparticles, *Mol. Catal.*, 2019, **476**, 110507; (*b*) J. Li, B. Wang, Y. Qin, Q. Tao and L. Chen,

MOF-derived Ni@NC catalyst: synthesis, characterization, and application in one-pot hydrogenation and reductive amination, *Catal. Sci. Technol.*, 2019, **9**, 3726.

20 (*a*) T. Stemmler, F. A. Westerhaus, A.-E. Surkus, M.-M. Pohl, K. Junge and M. Beller, General and selective reductive amination of carbonyl compounds using a core-shell structured Co_3O_4/NGr@C catalyst, *Green Chem.*, 2014, **16**, 4535; (*b*) R. V. Jagadeesh, K. Murugesan, A. S. Alshammari, H. Neumann, M.-M. Pohl and J. Radnik, J. MOF-derived cobalt nanoparticles catalyze a general synthesis of amines, *Science*, 2017, **358**, 326; (*c*) T. Senthamarai, K. Murugesan, K. Natte, N. V. Kalevaru, H. Neumann and P. C. J. Kamer, Expedient synthesis of *N*-methyl- and *N*-alkylamines by reductive amination using reusable cobalt oxide nanoparticles, *ChemCatChem*, 2018, **10**, 1235.

21 A. L. Nuzhdin, E. A. Artiukha, G. A. Bukhtiyarova, E. A. Derevyannikova and V. I. Bukhtiyarov, Synthesis of secondary amines by reductive amination of aldehydes with nitroarenes over supported copper catalysts in a flow reactor, *Catal. Commun.*, 2017, **102**, 108.

22 K. Natte, H. Neumann, R. V. Jagadeesh and M. Beller, Convenient iron catalyzed reductive aminations without hydrogen for selective synthesis of *N*-methylamines, *Nat. Commun.*, 2017, **8**, 1344.

23 (*a*) P. Zhou, C. Yu, L. Jiang, K. Lv and Z. Zhang, One-pot reductive amination of carbonyl compounds with nitro compounds with CO/H_2O as the hydrogen donor over non-noble cobalt catalyst, *J. Catal.*, 2017, **352**, 264; (*b*) J. W. Park and Y. K. Chung, Hydrogen-free cobalt-rhodium heterobimetallic nanoparticle-catalyzed reductive amination of aldehydes and ketones with amines and nitroarenes in the presence of carbon monoxide and water, *ACS Catal.*, 2015, **5**, 4846.

24 (*a*) X. Xu, J. Luo, L. Li, D. Zhang, Y. Wang and G. Li, Unprecedented catalytic performance in amine syntheses *via* Pd/g-C_3N_4 catalyst assisted transfer hydrogenation, *Green Chem.*, 2018, **20**, 2038; (*b*) P. Zhou and Z. Zhang, One-pot reductive amination of carbonyl compounds with nitro compounds by transfer hydrogenation over Co-Nx as catalyst, *ChemSusChem*, 2017, **10**, 1892; (*c*) H. Guo, B. Wang, P. Qiu, R. Gao, M. Sun and L. N. Chen, S codoped carbon shells embedded with ultrafine co NPs for reductive amination with formic acid, *ACS Sustain. Chem. Eng.*, 2019, **7**, 8876.

25 (*a*) R. J. Kalbasi and O. Mazaheri, Synthesis and characterization of hierarchical ZSM-5 zeolite containing Ni nanoparticles for one-pot reductive amination of aldehydes with nitroarenes, *Catal. Commun.*, 2015, **69**, 86; (*b*) R. J. Kalbasi and O. Mazaheri, Facile one-pot tandem reductive amination of aldehydes from nitroarenes over a hierarchical ZSM-5 zeolite containing palladium nanoparticles, *New J. Chem.*, 2016, **40**, 9627.

26 J. W. Bae, Y. J. Cho, S. H. Lee, C.-O. M. Yoon and C. M. Yoon, A one-pot synthesis of -alkylaminobenzenes from nitroaromatics: reduction followed by reductive amination using BH, *Chem. Commun.*, 2000, **19**, 1857.

27 (*a*) H. Zhou, S. Liu, D. Pi and G. Shen, Water as a hydrogen source in palladium-catalyzed reduction and reductive amination of nitroarenes mediated by diboronic acid, *Tetrahedron*, 2017, **73**, 3898; (*b*) M. Jang, T. Lim, B. Y. Park and M. S. Han, Metal-Free, Rapid, and Highly Chemoselective Reduction of Aromatic Nitro Compounds at Room Temperature, *J. Org. Chem.*, 2022, **87**, 910; (*c*) D. Chen, Y. Zhou, H. Zhou, S. Liu, Q. Liu, K. Zhang and Y. Uozumi, Metal-free Reduction of Nitro Aromatics to Amines with $B_2(OH)_4/H_2O$, *Synlett*, 2018, **29**, 1765; (*d*) H.-C. Du, N. Simmons, J. C. Faver, Z. Yu, M. Palaniappan, K. Riehle and M. M. Matzuk, A Mild, DNA-Compatible Nitro Reduction Using $B_2(OH)_4$, *Org. Lett.*, 2019, **21**, 2194.

28 (*a*) C.-H. Lin, B.-C. Hong and G.-H. Lee, Asymmetric synthesis of functionalized pyrrolizidines by an organocatalytic and pot-economy strategy, *RSC Adv.*, 2016, **6**, 8243; (*b*) A. E. Wahba and M. T. Hamann, Reductive *N*-alkylation of nitroarenes: a green approach for the *N*-alkylation of natural products, *J. Org. Chem.*, 2012, **77**, 4578.

29 (*a*) L. Ouyang, R. Miao, Z. Yang and R. Luo, Iridium-catalyzed reductive amination of carboxylic acids, *J. Catal.*, 2023, **418**, 283–289; (*b*) L. Ouyang, Y. Xia, R. Miao, J. Liao and R. Luo, Iridium-catalyzed reductive etherification of α,β-unsaturated ketones and aldehydes with alcohols, *Org. Biomol. Chem.*, 2022, **20**, 2621; (*c*) Y. Xia, S. Wang, R. Miao, J. Liao, L. Ouyang and R. Luo, Synthesis of *N*-alkoxy amines and hydroxylamines *via* the iridium-catalyzed transfer hydrogenation of oximes, *Org. Biomol. Chem.*, 2022, **20**, 6394; (*d*) L. Ouyang, Y. Xia, J. Liao and R. Luo, One-Pot Transfer Hydrogenation Reductive Amination of Aldehydes and Ketones by Iridium Complexes "on Water", *Eur. J. Org Chem.*, 2020, **2020**, 6387; (*e*) N. Luo, J. Liao, L. Ouyang, H. Wen, J. Liu, W. Tang and R. Luo, Highly pH-Dependent Chemoselective Transfer Hydrogenation of α,β-Unsaturated Aldehydes in Water, *ACS Omega*, 2019, **38**, 3025.