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Graphite-Supported Gold Nanoparticles as Efficient Catalyst for Aerobic Oxidation of Benzylic Amines to Imines and *N*-Substituted 1,2,3,4-Tetrahydroisoquinolines to Amides: Synthetic Applications and Mechanistic Study

Man-Ho So, Yungen Liu, Chi-Ming Ho, and Chi-Ming Che*[a]

Abstract: Selective oxidation of amines using oxygen as terminal oxidant is an important area in green chemistry. In this work, we describe the use of graphite-supported gold nanoparticles (AuNPs/C) to catalyze aerobic oxidation of cyclic and acyclic benzylic amines to the corresponding imines with moderate-to-excellent substrate conversions (43–100%) and product yields (66–99%) (19 examples). Oxidation of *N*-substituted 1,2,3,4-tetrahydroisoquinolines in the presence of aqueous $NaHCO_3$ solution gave the corresponding amides in good yields (83–93%) with high selectivity (up to amide/enamide = 93:4) (6 examples). The same protocol can be applied to the synthesis of benzimidazoles from the reaction of *o*-phenylenediamines with benzaldehydes under aerobic conditions (8 examples). By simple centrifugation, AuNPs/C can be recovered and reused for ten consecutive runs for the oxidation of dibenzylamine to *N*-benzylidene(phenyl)methanamine without significant loss of catalytic activity and selectivity. This protocol "AuNPs/C+O_2" can be scaled to the gram scale, and 8.9 g (84% isolated yield) of 3,4-dihydroisoquinoline can be obtained from the oxidation of 10 g 1,2,3,4-tetrahydroisoquinoline in a one-pot reaction. Based on the results of kinetic studies, radical traps experiment, and Hammett plot, a mechanism involving the hydrogen-transfer reaction from amine to metal and oxidation of M-H is proposed.

Keywords: amines · gold · heterogeneous catalysis · nanoparticles · oxidation

Introduction

Among the transition metal-catalyzed organic transformation reactions, there has been a surge of interest in gold catalysis.[1,2] Of particular interest to us is the use of gold nanoparticles (AuNPs) as catalyst. Metal nanoparticles have a high density of active sites on the surface and usually exhibit unique catalytic properties superior to their bulk counterparts,[3] and thus, are potential catalysts for organic transformation reactions with practical interest. Monometallic gold nanoparticles have been reported to catalyze aerobic oxidation of alcohols,[4] glucose,[5] alkenes,[6] primary amines to amides,[7] anilines to azo compounds,[8] alcohols with amines to imines or oximes,[9] and oxidation of CO.[10] Hydrogenation of organic nitro-compounds[11] and activation of CO_2 for the synthesis of disubstituted ureas and cyclic carbonate[12] can also be catalyzed using solid-supported AuNPs as catalysts. Gold-containing bimetallic nanoparticles, such as Au–Pd nanoparticles[13] and Au–Pt nanoparticles,[14] can also catalyze the aerobic oxidation of alcohols.

Selective oxidation of amines is an important area in organic chemistry,[15] as the oxidation products, such as imines, are versatile building blocks for organic synthesis (e.g., Mannich addition and 1,3-dipolar [2+3] cycloaddition). Stoichiometric methods such as the use of hypervalent iodine(V) reagents have been successfully employed for amine oxidations of practical interest.[16] Nevertheless, a catalytic system utilizing oxygen as a terminal oxidant is desirable in the context of green chemistry.[15,17,18] Mizuno,[17a,c] Murahashi,[17b,g] Bäckvall,[17d] and Wang,[17i] have reported important works on ruthenium-catalyzed aerobic oxidation of amines.

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In 2007, Angelici and co-workers reported the use of bulk gold powder (~10^3 nm particle size) as catalyst for aerobic oxidative dehydrogenation of secondary amines to imines (6 examples).[17e] Realizing that this catalytic oxidation likely occurs on the active surface of the heterogeneous gold powder, we conceive that AuNPs with high density of active sites and large surface area-to-volume ratio should be a better catalyst for the aerobic oxidation of amines. Herein is described the use of graphite-supported 14.5 nm gold nanoparticles (AuNPs/C) as an efficient heterogeneous catalyst for selective aerobic oxidative dehydrogenation of a diversity of benzylic amines to imines. We also report here, for the first time, the AuNPs/C-catalyzed aerobic oxidation of *N*-substituted 1,2,3,4-tetrahydroisoquinolines to amides in good yields with high selectivity. When *N*-phenyl 1,2,3,4-tetrahydroisoquinoline is oxidized in the presence of nucleophiles, C–C bond formation products are obtained. On the basis of the results of the kinetic isotopic effect, radical traps experiment, and the effect of *para*-substituent on *N*-phenylbenzylamines (Hammett plot), a mechanism involving hydrogen transfer for the oxidation of benzylic amines is proposed. After completion of this work and during the preparation of this manuscript, reports by Angelici,[17j] Corma,[17k] Garcia,[17k] Baiker,[17l–n] and co-workers on the aerobic oxidation of amines to imines catalyzed by AuNPs supported on alumina,[17j] titania,[17k] and active carbon,[17k] or by AuNPs in situ formed from reduction of Au-$(OAc)_3$,[17l–n] were published.

Results and Discussion

Preparation and Characterization

We prepared two kinds of supported AuNPs catalyst by deposition of the AuNPs onto graphite and hydroxyapatite (HAP). Typically, citrate reduction of $KAuCl_4$ salt gave a wine-red suspension of AuNPs (12–13 nm) in water according to Turkevish's method.[19] The as-prepared AuNPs were deposited onto graphite through vigorous stirring of the solution mixture for 24 h. After centrifugation, washing with water, and drying in an oven, the graphite-supported AuNPs catalyst (AuNPs/C) was obtained as a black solid. The gold loading on graphite was 0.1 mmol g^{-1} as analyzed by inductively coupled plasma-mass spectrometry (ICP-MS).[20] Examination of the AuNPs/C catalyst by powder X-ray diffraction (XRD) confirmed the presence of metallic gold on graphite (Figure 1 a). Diffraction peaks appearing at $2\theta =$ 38.23°, 44.49°, 64.63°, 77.54°, and 81.82° correspond to the

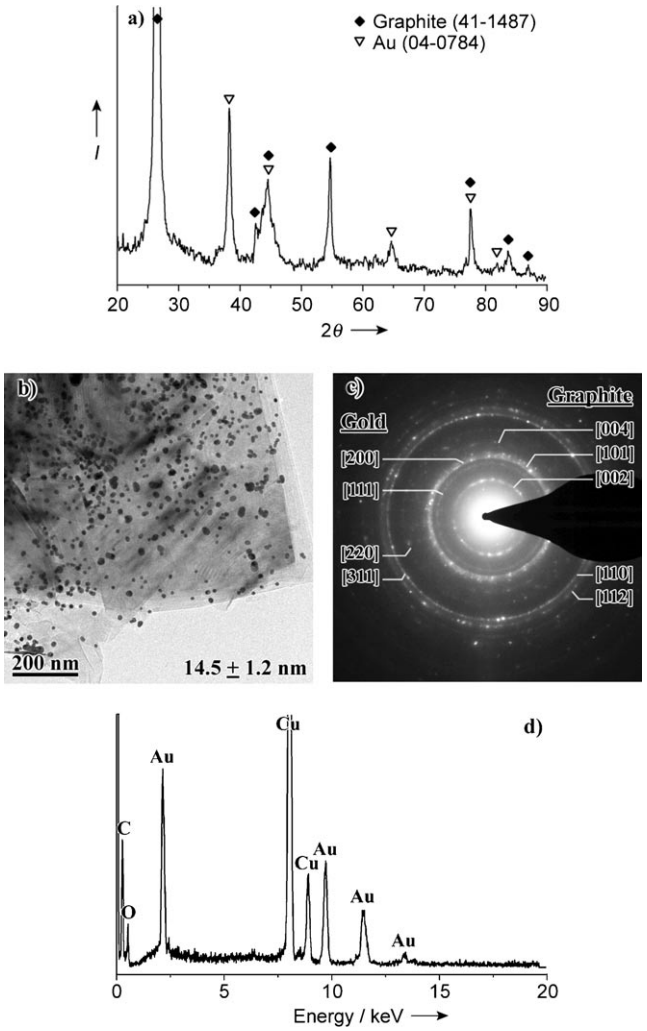


Figure 1. a) Powder XRD pattern, b) TEM image, c) SAED pattern, and d) EDX spectrum of the AuNPs/C catalyst.

[111], [200], [220], [311], and [222] Miller planes of the cubic gold, respectively (JCPDS no. 04-0784). Broadening of these diffraction peaks is attributed to the small crystal size of the gold nanoparticles. The structure of graphite was retained after grafting of the AuNPs on its surface. As revealed by transmission electron microscopy (TEM), uniform AuNPs were deposited on the graphite surface with an average diameter and monodispersity of 14.5 ± 1.2 nm and 8.3 %, respectively (Figure 1 b). The selected-area electron diffraction (SAED) pattern revealed diffraction rings which could

Abstract in Chinese:

以氧氣爲起始氧化劑選擇性氧化胺類化合物是綠色化學研究的一個重要領域。本工作利用石墨負載的納米金顆粒（AuNPs/C）催化需氧氧化環型和非環型苄基胺類化合物，以中等至很高的轉化率（43-100%）和產率（66-99%）獲得對應的亞胺化合物（共 19 例）。在飽和碳酸氫鈉水溶液存在的條件下，氧化氮取代的 1，2，3，4-四氫異喹啉類化合物，以高產率（83-93%）和很高的選擇性（醯胺與醯烯胺之比最高可達 93：4）得到對應的醯胺類化合物（共 6 例）。本方法可用於以苯甲醛和鄰苯二胺爲原料合成苯並咪唑類化合物（共 8 例）。通過簡單的離心分離，AuNPs/C 可以方便地回收和重複用於催化氧化二苄基胺成苯亞甲基苄基胺 10 次而無明顯喪失其催化活性及選擇性。本方法可以放大至克級反應，以 10 克 1，2，3，4-四氫異喹啉爲原料，一次得到 8.9 克（84%產率）3，4-二氫異喹啉。基於動力學研究，自由基捕獲實驗和 Hammett 圖，提出一個涉及胺向金屬的氫轉移和 M-H 氧化的反應機制。

be attributed to the ring pattern of metallic gold and of graphite (Figure 1c). Energy-dispersive X-ray (EDX) microanalysis revealed the presence of Au and C peaks, further supporting the presence of gold on graphite (Figure 1d).

We have also prepared AuNPs of smaller size (6.0±0.5 nm) by borohydride reduction,[21] and these AuNPs were then deposited on graphite. However, the average particle size (8.9±2.2 nm) and size distribution (monodispersity: 25.2%) of the AuNPs increased dramatically by 48.3% after adsorption onto the graphite surface. We have also attempted to prepare AuNPs by a polyvinylpyrrolidone-protected method,[22] which allows better control of particle size distribution, but the as prepared AuNPs failed to be deposited onto the graphite surface. We have attempted to prepare other solid-supported AuNPs catalysts using HAP, ZnO, Al_2O_3, and SiO_2 as solid supports. However, attempts to immobilize 14.5 nm AuNPs on ZnO, Al_2O_3, and SiO_2 were not successful, as the Au contents were lower than 2.0 wt%. Therefore, catalytic activities of these solid-supported AuNPs catalysts were not evaluated in this work. As depicted from the TEM image of the HAP-supported AuNPs (AuNPs/HAP), uniform AuNPs were deposited on the HAP surface (Figure 2). The average diameter and monodispersity of the AuNPs were 14.5±1.2 nm and 8.3%, respectively. We have also attempted to increase the loading to 0.2 mmol g^{-1}, but the result was less reproducible. As a result, the AuNPs/C catalyst with 14.5 nm gold nanoparticles was used in this work unless otherwise specified.

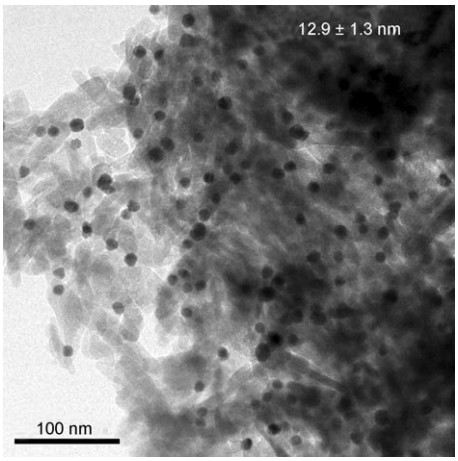


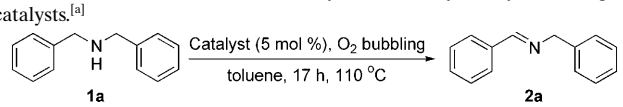
Figure 2. TEM image of the AuNPs/HAP catalyst.

Catalytic Aerobic Oxidation of Amines

Catalyst Screening and Optimization

The catalytic activities of various gold catalysts (5 mol%) towards the oxidation of dibenzylamine (**1a**) using oxygen (1 atm, bubbling) as oxidant at 110°C were examined (Table 1). Complete substrate conversion and excellent product yield (95%) were obtained with AuNPs/C catalyst (Table 1; entry 1). When air was used instead of oxygen, only 69% conversion was attained for the same reaction time (entry 11). And a longer reaction time was needed to achieve complete substrate conversion (55 h; entry 12). Comparable catalytic activity and product yield were obtained when AuNPs/HAP was used as the catalyst (entry 13). Notably, the same amount of commercially available gold powder (2–5 μm; Strem Chemicals, Inc.) was found to be catalytically inactive under the same conditions (entry 14). AuCl and $KAuCl_4$ were active catalysts but both resulted in lower substrate conversions (~50%) and product yields (86–89%; entries 15, 16), and Au^0 metal was deposited on the glass vial. $[Au^{III}(Salen)]PF_6$, $Au(PPh_3)Cl$, and $[Au^{III}(TPP)]Cl$ (Figure 3) were inactive (<5% conv.; entries 17–19). No substrate conversion was found with graphite alone or without a catalyst (entries 20–21).

Table 1. Aerobic oxidation of dibenzylamine catalyzed by various gold catalysts.[a]



1a 2a

Entry	Catalyst	Run	Conv. [%][b]	Yield [%][b,c]
1	AuNPs/C	1	100[d]	95[d]
2		2	100[d]	95[d]
3		3	98[d]	97[d]
4		4	98[d]	95[d]
5		5	97[d]	98[d]
6		6	96[d]	98[d]
7		7	93[d]	94[d]
8		8	86[d]	98[d]
9		9	84[d]	98[d]
10		10	80[d]	98[d]
11	AuNPs/C	–	69[e]	95
12	AuNPs/C	–	100[e,f]	95
13	AuNPs/HAP	–	100	95
14	Au powder	–	4[g]	90
15	AuCl	–	55	86
16	$KAuCl_4$	–	47	89
17	$[Au^{III}(Salen)]PF_6$	–	4	66
18	$Au(PPh_3)Cl$	–	3	93
19	$[Au^{III}(TPP)]Cl$	–	2	85
20	Graphite	–	Nil[h]	–
21	–	–	Nil	–

[a] Reaction conditions: **1a** (0.4 mmol), gold catalyst (Au: 5 mol%), toluene (8 mL), O_2 bubbling, 110°C, 17 h; unless otherwise stated. [b] Conversion and yield were determined by ^1H NMR using $Ph_2C{=}CH_2$ as the internal standard. [c] Yield was calculated based on substrate conversion. [d] Conversion and yield were determined by GC-MS using naphthalene as the internal standard. [e] Air bubbling was used instead of O_2 bubbling. [f] Reaction time: 55 h. [g] Au powder (4.0 mg) was used. [h] Graphite (200 mg) was used.

Solid-supported catalyst facilitates product separation and can be easily recycled. For the aerobic oxidation of **1a** catalyzed by in situ formed AuNPs/CeO_2, the conversion decreased from 80% to 67% upon using the catalyst for two consecutive runs.[17n] In the case of aerobic oxidation of benzylamine, using catalyst Au/Al_2O_3 for two consecutive runs decreased the yield from 92% to 71%,[17j] and using in situ formed catalyst AuNPs/CeO_2/FeO_x for four consecutive runs reduced the conversion from ~50% to ~34%.[17m]

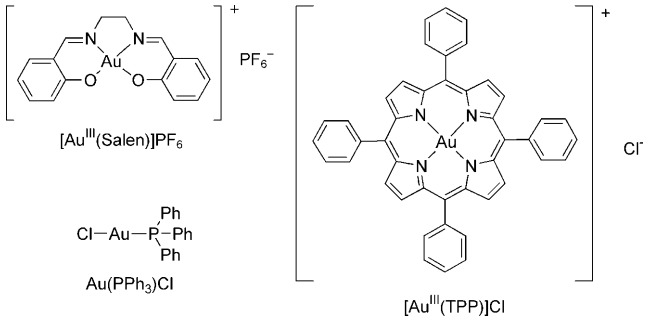


Figure 3. Chemical structures of $[Au^{III}(Salen)]PF_6$, $Au(PPh_3)Cl$, and $[Au^{III}(TPP)]Cl$ complexes.

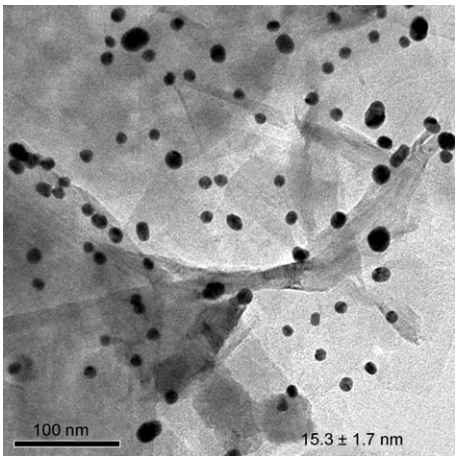
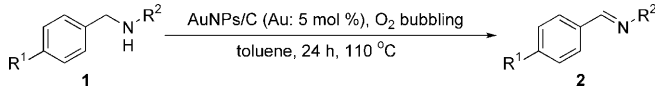


Figure 4. TEM image of the recycled AuNPs/C catalyst.

As depicted in Table 1, AuNPs/C catalyst (which can be recovered by centrifugation) was used for ten consecutive runs without deterioration of product yield (>94% yield; entries 1–10). A total product turnover number of 180 was obtained. Only a slight decrease in conversion from 100% to 93% was found after seven consecutive runs. We have determined the Au content in the reaction mixture by ICP-MS. No detectable amount of Au was found after each run, indicating that leaching of the Au metal was insignificant. The stability of AuNPs under the reaction conditions is an important factor contributing to its catalytic activities. TEM analysis of AuNPs/C catalyst after ten recycling runs showed that the average size and monodispersity of AuNPs were slightly increased from its original values to 15.3 ± 1.7 nm and 11.3%, respectively (Figure 4), which might account for the decrease in substrate conversion upon recycling of the catalyst.

Table 2. Aerobic oxidation of secondary amines using the "AuNPs/C+O_2" protocol.[a]



1 2

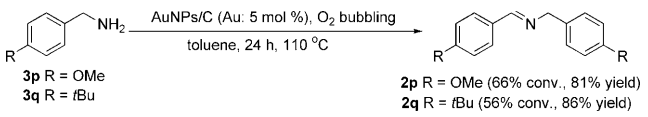
Entry	Substrate	R^1	R^2	Product	Conv. [%][b]	Yield [%][b,c]
1	**1b**	OMe	Ph	**2b**	100	95
2	**1b**	OMe	Ph	**2b**	100[d]	97
3	**1b**	OMe	Ph	**2b**	81[e]	95
4	**1c**	Me	Ph	**2c**	100	97
5	**1d**	*t*Bu	Ph	**2d**	100	98
6	**1e**	H	Ph	**2e**	100	96
7	**1f**	Cl	Ph	**2f**	94	99
8	**1g**	Br	Ph	**2g**	88	99
9	**1h**	NMe_2	Ph	**2h**	100	95
10	**1i**	OMe	4-$MeOC_6H_4$	**2i**	100	95
11	**1j**	H	$(CH_2)_5CH_3$	**2j+2a**	100	93 (79:14)
12	**1k**	H	$(CH_2)_2Ph$	**2k+2a**	100	88 (78:10)
13	**1L**	H	$(CH_2)_2CN$	**2l**	100	88
14	**1m**	H	Cy	**2m+2a**	100	81 (58:23)
15	**1n**	NO_2	Cy	**2n+2a**	71	93 (48:45)
16	**1o**	OMe	Cy	**2o**	100	86

[a] Reaction conditions: amines (0.4 mmol), AuNPs/C (Au: 5 mol%), toluene (8 mL), O_2 bubbling, 110°C, 24 h; unless otherwise stated. [b] Conversion and yield were determined by ^1H NMR using $Ph_2C{=}CH_2$ as the internal standard. [c] Yield was calculated based on substrate conversion. The ratio of products is shown in parentheses. [d] AuNPs/C (Au: 1 mol%), 17 h. [e] AuNPs/C (Au: 0.5 mol%), 17 h.

Oxidation of Benzylic Amines

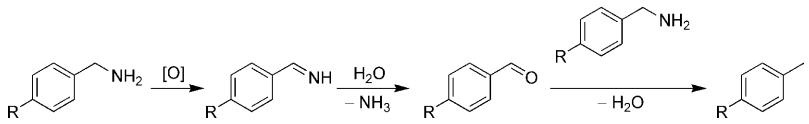
Using the "AuNPs/C+O_2" protocol, we investigated the substrate scope and limitations of the catalyst (Table 2). *N*-phenylbenzylamines **1b–i** were efficiently oxidized to their corresponding imines **2b–i** in up to 100% substrate conversion and ≥95% yields (entries 1–10). The protocol was less effective towards **1f** and **1g**, both bearing an electron-withdrawing substituent (Cl or Br) at the *para*-position (entries 7–8). For *N*-alkyl-*N*-aryl amines **1j–o**, their effective oxidation by the "AuNPs/C+O_2" protocol resulted in the selective formation of corresponding imines at the benzylic position (entries 11–16).

Oxidation of the primary benzylamines **3p** and **3q** gave the imines **2p** and **2q**, respectively (Scheme 1). The formation of **2p** and **2q** probably occurred by means of the first oxidation of primary amines to imine intermediates, which were subsequently hydrolyzed to give aldehydes and ammonia. Condensation of aldehydes and starting amines gave the



Scheme 1. Aerobic oxidation of primary amines using the "AuNPs/C+O_2" protocol.

imines (Scheme 2). No benzonitrile was detected, which is the major product for ruthenium-catalyzed oxidation of primary amines.[17a,c,g,i]



Scheme 2. Proposed mechanism for the formation of coupled imines from primary amines.

Oxidation of Heterocyclic Amines

Heterocyclic secondary amines were selectively oxidized using the "AuNPs/C+O_2" protocol (Table 3). 1,2,3,4-Tetrahydroisoquinoline (**4**) was converted into 3,4-dihydroisoquinoline (**5**) in complete substrate conversion and good product yield (86% yield, entry 1). In the case of 1,2,3,4-tetrahydroquinolines (**7a**,**b**) and indoline (**7c**), quinolines (**8a**,**b**) and indole (**8c**) were obtained, respectively, in moderate to excellent yields (entries 3, 4, 6). Using AuNPs/HAP as the catalyst, the substrate conversion and product yield for the oxidation of **7b** to **8b** could be improved to 60% and 84%, respectively (entry 5).

Table 3. Aerobic oxidation of heterocyclic secondary amines using the "AuNPs/C+O_2" protocol.[a]

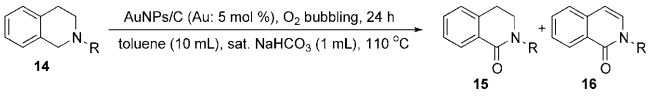
Entry	Substrate	Product	Conv. [%][b]	Yield [%][b,c]
1		**5**	100	95 (86:9)
2	**4**	**6**	100[d]	92 (84:8)
3	**7a**	**8a**	92	95
4	**7b**	**8b**	43	78
5			60[e]	84
6	**7c**	**8c**	68	66

[a] Reaction conditions: amines (0.4 mmol), AuNPs/C (Au: 5 mol%), toluene (8 mL), O_2 bubbling, 110°C, 24 h; unless otherwise stated. [b] Conversion and yield were determined by ^{1}H NMR using $Ph_2C{=}CH_2$ as the internal standard. [c] Yield was calculated based on substrate conversion. The ratio of products is shown in parentheses. [d] **4** (80 mmol), AuNPs/C (Au: 3 mol%), toluene (1.6 L). [e] AuNPs/HAP (Au: 5 mol%) was used as the catalyst.

In a recent report by Angelici and co-workers,[17j] a 1.0 gram-scale aerobic oxidation of **4** catalyzed by Au/Al_2O_3 at 100°C for 80 h was described. Without modification of the conditions noted in Table 3, our "AuNPs/C+O_2" protocol could be performed on a 10 gram-scale. Oxidation of 10.7 g of **4** (80 mmol) furnished 8.9 g of **5** (84% yield) using the "AuNPs/C+O_2" protocol in a one-pot reaction at 110°C for 24 h (entry 2, Table 3). After removal of the catalyst (by filtration) and evaporation of the solvent, the crude product **5** could be directly used as a precursor for C–C bond formation reactions including the following 1,3-dipolar [2+3] cycloaddition and Mannich reaction of **5** (Scheme 3). Structurally intriguing 3,4-dihydroisoquinoline derivatives **10** and **11** with high product yields (83% yield) and complete substrate conversions were obtained from [Ru(*p*-cymene)Cl_2]$_2$-catalyzed 1,3-dipolar [2+3] cycloaddition of the crude imine **5** with ethyl diazoacetate (**9**). Crude product **5** could also undergo Mannich type C–C bond formation with ketones **12a–c** to give **13a–c** in 56-81% yields.

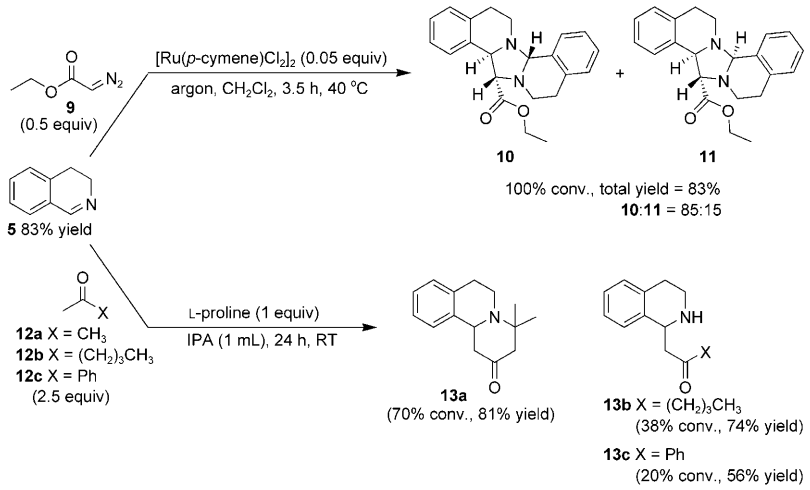
We have examined the oxidation of heterocyclic tertiary amines using the "AuNPs/C+O_2" protocol. Oxidation of *N*-alkyl 1,2,3,4-tetrahydroisoquinoline **14a** by the "AuNPs/C+O_2" protocol produced a mixture of amide **15a** and enamide **16a** in a ratio of 32:61 (entry 1, Table 4). This product ratio was subsequently tuned by the following reaction conditions. Under vigorously dried conditions, only enamide **16a** was obtained, albeit in low yield (entry 2). Amide **15** could be selectively obtained in good yield in the presence of H_2O (9% v/v) (entries 3 and 4). When saturated $NaHCO_3$ solution, instead of H_2O, was added to the reaction mixture, the ratios of **15a**/**16a** and **15b**/**16b** increased from 90:5 to 92:4 and 79:12 to 93:6, respectively (compare entries 3 and 4 with entries 5 and 6). Prior to this work, no

Table 4. Aerobic oxidation of tertiary amines **14** using the "AuNPs/C+O_2" protocol.[a]



Entry	Substrate	R	Products	Conv. [%][b]	Yield [%][b,c]
1	**14a**	Me	**15a+16a**	100	93(32:61)[d]
2	**14a**	Me	**16a**	27	90[e]
3	**14a**	Me	**15a+16a**	100	95 (90:5)[f]
4	**14b**	Et	**15b+16b**	100	91 (79:12)[f]
5	**14a**	Me	**15a+16a**	100	96 (92:4)
6	**14b**	Et	**15b+16b**	100	99 (93:6)
7	**14c**	*n*Pr	**15c+16c**	100	90 (85:5)
8	**14d**	*n*Bu	**15d+16d**	100	90 (83:7)
9	**14e**	Octyl	**15e+16e**	100	94 (88:6)
10	**14f**	Bn	**15f+16f**	100	97 (93:4)

[a] Reaction conditions: amine (0.4 mmol), AuNPs/C (Au: 5 mol%), toluene (10 mL), saturated $NaHCO_3$ aqueous solution (1 mL), O_2 bubbling, 110°C, 24 h; unless otherwise stated. [b] Conversion and yield were determined by ^{1}H NMR using $Ph_2C{=}CH_2$ as the internal standard. [c] Yield was calculated based on substrate conversion. The ratio of products is shown in parentheses. [d] Without addition of saturated $NaHCO_3$ aqueous solution. [e] Only anhydrous toluene (10 mL) was used as solvent without addition of saturated $NaHCO_3$ aqueous solution. [f] H_2O (1 mL) was used instead of saturated $NaHCO_3$ aqueous solution.

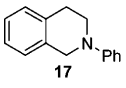
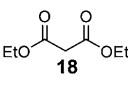
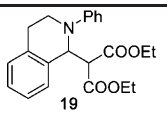
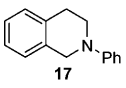
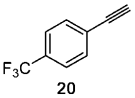
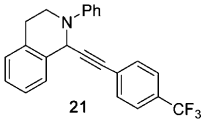
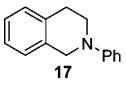
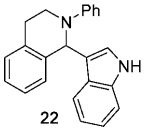
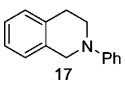
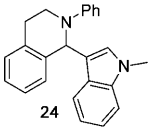


Scheme 3. Utilization of the 3,4-dihydroisoquinoline (**5**) obtained from AuNPs/C-catalyzed aerobic oxidation of **4**. When **12a** was used, trifluoroacetic acid (1.5 equiv) was added after the reaction.

AuNPs catalyst had been reported to be an efficient catalyst for the conversion of amines **14** to amides **15**.

Imines and iminium cations are versatile building blocks for C–C bond formation reactions. In recent years, Li and co-workers have extensively studied the cross-dehydrogenative coupling (CDC) reaction of tertiary amines using copper catalysts.[17f,23] In this work, we found that when *N*-phenyl tetrahydroisoquinoline (**17**) was oxidized by the "AuNPs/C+O_2" protocol, a cationic iminium intermediate was generated, which could react with nucleophiles (**8c**, **18**, **20**, and **23**) to give the desired products in 70–80% yields (Table 5). Complete substrate conversion was obtained with malonate **18** or phenylacetylene **20** as nucleophile.

Table 5. Addition of nucleophiles to cationic iminium intermediates generated using the "AuNPs/C+O_2" protocol.[a]

Entry	Substrate	Nucleophile	Product	*t* [d]	Conv. [%][b]	Yield [%][b,c]
1	 **17**	 **18**	 **19**	1.5	100	78[d]
2	 **17**	 **20**	 **21**	2	100	80[d]
3	 **17**	 **8c**	 **22**	1	27	70
4	 **17**	 **23**	 **24**	1	35	70

[a] Reaction conditions: **17** (0.4 mmol), nucleophile (0.8 mmol), AuNPs/C (Au: 5 mol%), toluene (8 mL), O_2 bubbling, 110°C; unless otherwise stated. [b] Conversion and yield were determined by ^{1}H NMR using $Ph_2C{=}CH_2$ as the internal standard. [c] Yield was calculated based on substrate conversion. [d] In the presence of K_2CO_3 (1 mmol).

Synthesis of Benzimidazoles

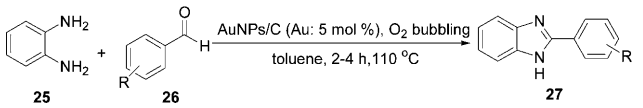
Benzimidazole compounds are known to exhibit a wide range of therapeutic activities,[24] and they are commonly synthesized by the coupling of *o*-phenylenediamines with carboxylic acids, or oxidative cyclo-dehydrogenation of the aniline Schiff base.[25] In a recent work by Sharghi and co-workers, porphyrinatoiron(III) was used as a catalyst for the synthesis of benzimidazoles using oxygen as oxidant.[25b] In this work, the "AuNPs/C+O_2" protocol could be applied to the synthesis of benzimidazole derivatives **27a**–**h**, by means of a one-pot oxidative coupling reaction of *o*-phenylenediamine (**25**) with benzaldehydes (**26**) with complete substrate conversion and high product yields (90–99% yield; Table 6). Using the reaction of **25** with **26b** as an example, lowering the catalyst loading to 1 mol% gave **27b** in a satisfactory 86% yield (entry 3).

Mechanism

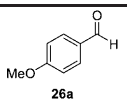
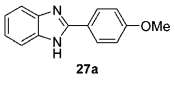
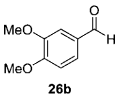
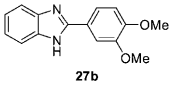
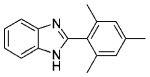
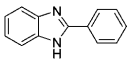
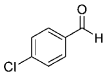
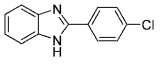
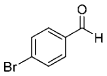
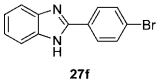
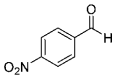
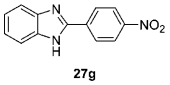
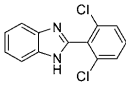
To obtain information on the reaction mechanism, we first examined the kinetic isotopic effect for the oxidation of *N*-phenyl-α-deutero-4-methylbenzylamine (**28**) by the "AuNPs/C+O_2" protocol at 110°C (Scheme 4). The yield and ratio of deuterated **29** and non-deuterated **2c** products were determined by ^{1}H NMR using $Ph_2C{=}CH_2$ as the internal standard. A moderate primary kinetic isotopic effect (KIE) ($k_H/k_D = 4.9$ at 110°C) was found, indicative of C–H bond cleavage at the benzylic position as the rate-determining step.

To investigate the influence of electron-withdrawing or electron-donating substituents on the rate of the oxidation reaction, a series of *para*-substituted *N*-phenylbenzylamines were tested. Competitive oxidation of p-$YC_6H_4CH_2NHPh$ (Y = OMe, Me, H, Cl and CF_3) using the "AuNPs/C+O_2" protocol revealed a good linear free energy relationship ($R^2 = 0.99$) with a negative reaction constant ($\rho = -2.05$) (Figure 5

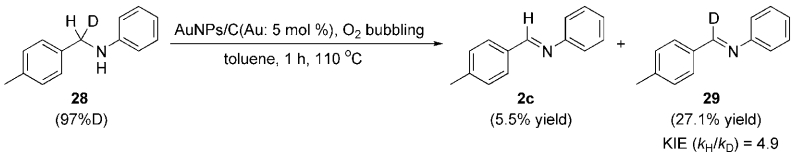
Table 6. One-pot synthesis of benzimidazole **27** using the "AuNPs/C+O_2" protocol.[a]



25 26 27

Entry	Benzaldehyde **26**	Benzimidazole **27**	t [h][b]	Yield [%][c]
1	 **26a**	 **27a**	2	96
2	 **26b**	 **27b**	2	99
3			15	86[d]
4	 **26c**	 **27c**	3.5	95
5	 **26d**	 **27d**	2	93
6	 **26e**	 **27e**	3	97
7	 **26f**	 **27f**	3	94
8	 **26g**	 **27g**	3.5	90
9	 **26h**	 **27h**	4	94

[a] Reaction conditions: **25** (0.4 mmol), **26** (0.4 mmol), AuNPs/C (Au: 5 mol %), toluene (10 mL), O_2 bubbling, 110 °C; unless otherwise stated. [b] Completeness of the reaction was checked by ^{1}H NMR. [c] Isolated yield. [d] AuNPs/C (Au: 1 mol %), t = 15 h.



Scheme 4. KIE on the oxidation of **28** by the "AuNPs/C+O_2" protocol.

and Table S1 in the Supporting Information). The negative ρ value indicated the generation of positively-charged intermediates during the reaction. The involvement of radical species is unlikely, because addition of the radical scavenger 2,6-di-*tert*-butyl-4-methylphenol (3 equiv to substrate) to the reaction mixture did not perturb the substrate conversion and product yield, revealing that the AuNPs/C-catalyzed oxidation is unlikely to proceed through a radical chain pathway.[26]

We have studied the effect of oxygen pressure on the initial reaction rate for the oxidation of amine **1a** by the

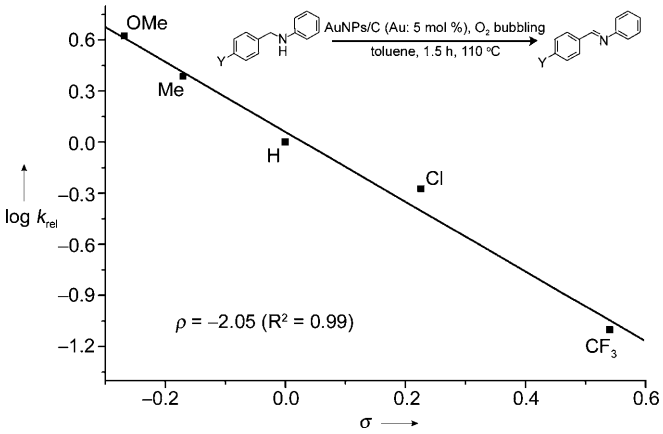


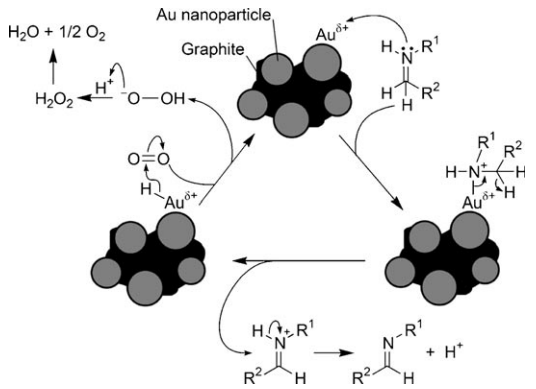
Figure 5. Hammett plot (log k_{rel} vs σ) for the oxidation of *p*-$YC_6H_4CH_2NHPh$ (Y = OMe, Me, H, Cl, and CF_3) using the "AuNPs/C+O_2" protocol.

"AuNPs/C+O_2" protocol. No significant effect on the initial reaction rate was noted when the oxygen partial pressure was >0.1 atm (Figure S1 in the Supporting Information). It should be noted that no conversion of the substrate was found in the absence of oxygen (under argon atmosphere).

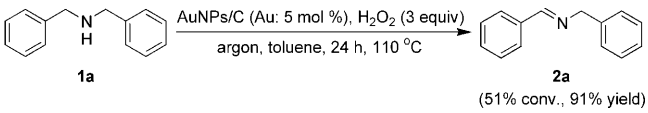
On the basis of the above results, we proposed a mechanism for the AuNPs/C-catalyzed aerobic oxidation of amines, which is depicted in Scheme 5. First, amine coordinates to the surface $Au^{\delta+}$ site. This is followed by C–H bond cleavage at the benzylic position as the rate-determining step. A recent report also showed that AuNPs catalyzed aerobic alcohol oxidation involves a β-hydride shift from carbon to gold,[4e] lending support to our hypothesis of β-hydrogen elimination. Lastly, oxygen acts as a hydrogen atom acceptor, and would possibly be reduced to H_2O_2. The $Au^{\delta+}$ site is regenerated, and starts another catalytic cycle.

We have not been able to detect any H_2O_2 in the reaction mixture, presumably owing to its instability at high temperature.[27] Note that amine **1a** could also be oxidized into imine **2a** using a "AuNPs/C+H_2O_2" protocol under an argon atmosphere, although the substrate conversion was lower (51 % conv.; Scheme 6).

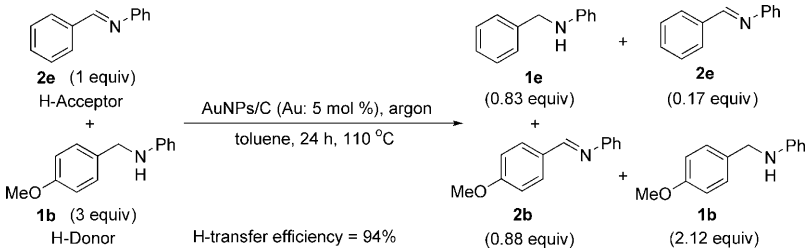
To further support that hydrogen on the gold surface is "transferred" to an H-acceptor (oxygen), oxygen was replaced with another H-acceptor (imine). The H-transferability of the AuNPs/C catalyst was demonstrated by the transfer of H from amine **1b** (H-donor) to imine **2e** (H-acceptor) under anaerobic conditions (Scheme 7). In this work, the product yield ratio of amine **1e** to imine **2b** was 1:1.06, revealing excellent H-transfer efficiency (94 %). In the absence of the AuNPs/C catalyst, neither amine **1e** nor imine **2b** was detected. 1,4-Cyclohexadiene (H-donor) was also found to reduce imine **2e** to amine **1e** (20 % conv.; 99 % yield), and benzene was detect-



Scheme 5. Proposed mechanism of AuNPs/C-catalyzed aerobic oxidation of amines.

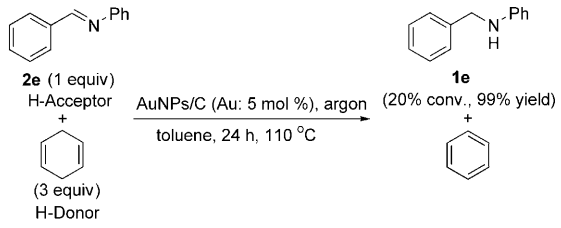


Scheme 6. Oxidation of **1a** using the "AuNPs/C+H_2O_2" protocol.



Scheme 7. H-transfer from donor **1b** to acceptor **2e** catalyzed by AuNPs/C under an argon atmosphere.

ed in the reaction mixture by gas chromatography-mass spectrometry (GC-MS) (Scheme 8). Again, the involvement



Scheme 8. Hydrogen transfer from donor 1,4-cyclohexadiene to acceptor **2e** catalyzed by AuNPs/C under an argon atmosphere.

of radical species and the radical chain pathway is unlikely, because the addition of the radical scavenger 2,6-di-*tert*-butyl-4-methylphenol (3 equiv to substrate) to the reaction mixture did not perturb the substrate conversion, product yield, and H-transfer efficiency of the above reactions.[26]

Conclusions

Heterogeneous gold nanoparticles catalysts have shown interesting oxidation of various organic compounds using oxygen as oxidant.[4–10] Despite the extensive studies on the catalytic activities of AuNPs, only a few types of the catalysts have found study and application in the oxidation of amines. Examples are the oxidation of amines to amides,[7] and anilines to aromatic azo compounds by Au/TiO_2.[8]

In this study, we prepared a graphite-supported AuNPs catalyst and examined its catalytic activities. Graphite is a stable allotrope of carbon at standard temperature and pressure. It is inexpensive and readily available worldwide by natural mining. The good electrical conductivity ($10^6\ S{\cdot}m^{-1}$ at ambient temperature) of graphite also enables its common use as an electrode. Owing to the stability and availability, graphite has been used as a solid support in heterogeneous catalysis for a long time.[28]

The small particle size exhibited by metal nanoparticles is important to their catalytic activity. Small particle size has a large surface area-to-volume ratio and high density of active sites on the particle surface. Several reviews and books have described the utilization of transition metal nanoparticles in organic transformations.[3,29] We have recently demonstrated the superior catalytic activities of hydroxyapatite-supported and non cross-linked soluble polystyrene supported ruthenium nanoparticles towards *cis*-dihydroxylation and oxidative cleavage of alkenes,[30] and carbenoid transfer reactions,[31] respectively. To illustrate the superiority of gold nanoparticles, the commercially available bulk gold powder (2–5 μm) was found to show low catalytic activity on the aerobic oxidation of dibenzylamine **1a** (4% conv.; entry 14, Table 1), while AuNPs/C showed complete substrate conversion under similar reaction conditions (entry 1, Table 1). This result is consistent with the large surface area provided by the AuNPs. Realizing the benefit from small sized metal nanoparticles, we have attempted to prepare graphite-supported catalysts with smaller AuNPs by the borohydride-reduction method (6.0 nm). However, these smaller gold nanoparticles aggregated upon grafting onto the graphite surface.

In summary, a heterogeneous catalyst composed of 14.5 nm AuNPs supported on graphite has been prepared and found to efficiently catalyze the oxidation of benzylic amines. A variety of benzylic secondary amines (18 examples; Tables 2 and 3) could be successfully oxidized with good-to-excellent substrate conversions and product yields. This AuNPs/C catalyst can be recovered easily by centrifugation. The "AuNPs/C+O_2" protocol is applicable to the 10-gram scale reaction, in which 8.9 g (84% yield) of 3,4-dihydroisoquinoline can be obtained by a one pot reaction. Re-

moval of the catalyst by filtration gave the crude imine products, which can be directly used as building blocks in organic synthesis as demonstrated by the synthesis of structurally intriguing 3,4-dihydroisoquinoline derivatives **10**, **11**, and **13** (Scheme 3). Notably, oxidation of *N*-alkyl 1,2,3,4-tetrahydroisoquinolines **14** gave amides with good yields and high selectivity (Table 4), and this catalytic oxidation has not been reported in previous catalytic systems. Considering the simple preparation and recycling ability of the AuNPs/C catalyst, the application of this catalyst to organic transformation with practical interest is being pursued.

Experimental Section

Chemicals: All the chemicals (analytical reagent grade) were purchased from Aldrich and were used as received without further purification unless otherwise noted. $KAuCl_4$ was purchased from Oxkem Limited. Gold powder (2–5 micron; catalog number 93-7915) was purchased from Strem Chemicals, Inc. Toluene (analytical reagent grade) was purchased from TEDIA. $[Au^{III}(Salen)]PF_6$,[32] $[Au^{III}(TPP)]Cl$,[33] and $[Ru(p\text{-cymene})Cl_2]_2$[34] were synthesized according to the literature methods.

Instrumentation: The AuNPs/C catalyst was characterized by powder X-ray diffraction (XRD), transmission electron microscope (TEM), selected area electron diffraction (SAED) analysis, energy-dispersive X-ray microanalysis (EDX) and inductively coupled plasma–mass spectrometry (ICP–MS). The powder XRD measurements were performed on a Bruker D8 ADVANCE X-ray diffractometer with parallel $Cu_{K\alpha}$ radiation ($\lambda = 1.5406$ Å). The scanning rate is $0.01°\,s^{-1}$ in the 2θ range from 20 to 90° and the step size is 0.05°. The XRD samples were prepared by placing the catalyst on a glass slide. TEM and SAED analysis were done on Philips Tecnai G2 20 S-TWIN with an accelerating voltage of 200 kV. The TEM images were taken by Gatan MultiScan Camera Model 794. The EDX analysis was performed on Oxford Instruments Inca with a scanning range from 0 to 20 keV. The TEM samples were prepared by dropping a drop of dispersion of the catalyst in ethanol to the formvar-coated copper grids and then dried in vacuum desiccator. The average particle size and monodispersity of the nanoparticles were measured against 300 nanoparticles using DigitalMicrograph(TM) Demo 3.6.5 software. ICP–MS was performed on an Agilent 7500a detector. The organic products were characterized by nuclear magnetic resonance (NMR) spectroscopy (^1H and ^{13}C NMR) and electron-impact mass spectrometry (EI-MS). ^1H and ^{13}C NMR spectra were recorded on Bruker DPX-300, Avance400, or Bruker DPX-500 FT-NMR spectrometers with chemical shifts (in ppm) relative to tetramethylsilane. Mass spectra were obtained on a Finnigan MAT 95 mass spectrometer. Gas chromatography-mass spectrometry (GC-MS) was performed on Agilent Technologies 6890N gas chromatograph equipped with Agilent Technologies 5973 mass selective detector and an Agilent HP-5 (Cat. No. 19091J-433) capillary column using helium as the carrier gas.

Synthesis of gold nanoparticles (AuNPs) by citrate reduction: Gold nanoparticles were prepared according to the literature with some modifications.[19] Briefly, sodium citrate (0.5 mmol) was added to a refluxing aqueous solution of $KAuCl_4$ (1 mM, 100 mL) with vigorous stirring. The mixture was heated for further 15 min resulting in a wine red solution.

Synthesis of graphite-supported gold nanoparticles (AuNPs/C) catalyst: Graphite (1 g) was added to the freshly prepared gold nanoparticles solution and the mixture was stirred vigorously for 1 day. The AuNPs/C catalyst was collected by centrifugation and washed three times with distilled water and absolute ethanol. The final product was oven-dried at 75 °C for an hour and stored in a desiccator for further characterizations by XRD (Figure 1a), TEM (Figure 1b), SAED (Figure 1c), and EDX (Figure 1d).

Synthesis of hydroxyapatite-supported gold nanoparticles (AuNPs/HAP) catalyst: HAP (1 g) was added to the freshly prepared gold nanoparticles solution and the mixture was stirred vigorously for 1 day. The AuNPs/HAP catalyst was collected by centrifugation and washed three times with distilled water and absolute ethanol. The final product was oven-dried at 75 °C for an hour and stored in a desiccator for further characterization by TEM (Figure 2). The average particle size and monodispersity of the deposited nanoparticles are 12.9 ± 1.3 nm and 9.8%, respectively. The gold loading on HAP was $0.1\ mmol\,g^{-1}$ as determined by ICP-MS.

Catalyst screening for aerobic oxidation of amine 1a: **1a** (0.4 mmol) and gold catalyst (Au: 5 mol%) were added to toluene (8 mL) in a glass tube connected with a condenser. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering the tube opening. The mixture was stirred and heated at 110 °C for 17 h. The gold catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield were determined by ^1H NMR using 1,1-diphenylethylene as the internal standard. Pure product was isolated by flash chromatography and identified by ^1H and ^{13}C NMR and EI-MS.

Recycling of AuNPs/C catalyst for aerobic oxidation of amine 1a: 1a (0.4 mmol) and AuNPs/C catalyst (Au: 5 mol%) were added to toluene (8 mL) in a glass tube connected with condenser. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering the tube opening. The mixture was stirred and heated at 110 °C for 17 h. The AuNPs/C catalyst was removed by centrifugation and the organic product was collected by decantation. The AuNPs/C catalyst was washed 4–5 times with chloroform and dried in a 80 °C oven overnight before the next recycle run. The substrate conversion and product yield were determined by GC-MS using naphthalene as the internal standard.

Aerobic oxidation of secondary and primary amines: Amine (0.4 mmol) and AuNPs/C catalyst (Au: 5 mol%) were added to toluene (8 mL) in a glass tube connected with condenser. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering the tube opening. The mixture was stirred and heated at 110 °C for 24 h. The AuNPs/C catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield were determined by ^1H NMR using 1,1-diphenylethylene as the internal standard. Pure product was isolated by flash chromatography and identified by ^1H and ^{13}C NMR and EI-MS.

Aerobic oxidation of amine 4 in large scale: **4** (80 mmol) and AuNPs/C catalyst (Au: 3 mol%) were added to toluene (1.6 L) in a two-neck round-bottom flask with one of the necks connected with a condenser. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering another neck of the round-bottom flask. The mixture was stirred and heated at 110 °C for 24 h. The AuNPs/C catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield were determined by ^1H NMR using 1,1-diphenylethylene as the internal standard.

Aerobic oxidation of tertiary amine 14: **14** (0.4 mmol) and AuNPs/C catalyst (Au: 5 mol%) were added to toluene (10 mL) in a glass tube connected with a condenser. H_2O (1 mL) or saturated $NaHCO_3$ solution (1 mL) was added to the reaction mixture. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering the tube opening. For anhydrous condition, freshly-distilled anhydrous toluene was transferred to the reaction tube by cannula transfer technique and the O_2 gas was dried over a drying tube packed with sodium hydroxide pellets prior to use. The mixture was stirred and heated at 110 °C for 24 h. By filtration against celite, the AuNPs/C catalyst was removed and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion, product yield, and selectivity were determined by ^1H NMR using 1,1-diphenylethylene as the internal standard. Pure product was isolated by flash chromatography and identified by ^1H and ^{13}C NMR and EI-MS.

Aerobic oxidation of tertiary amine 17 with addition of nucleophiles: **17** (0.4 mmol), nucleophile (0.8 mmol) and AuNPs/C catalyst (Au: 5 mol%) were added to toluene (8 mL) in a glass tube connected with a condenser. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering the tube opening. The mixture was stirred and heated at 110°C for a given reaction time. The AuNPs/C catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield were determined by ^{1}H NMR using 1,1-diphenylethylene as the internal standard. Pure product was isolated by flash chromatography and identified by ^{1}H and ^{13}C NMR and EI-MS.

One-pot synthesis of benzimidazole 27 using the "AuNPs/C+O_2" protocol: Amine **25** (0.4 mmol), aldehyde **26** (0.4 mmol), and AuNPs/C catalyst (Au: 5 mol%) were added to toluene (10 mL) in a glass tube connected with a condenser. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering the tube opening. The mixture was stirred and heated at 110°C for a given reaction time. Completeness of the reaction was checked by ^{1}H NMR. By filtration against celite, the AuNPs/C catalyst was removed and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. Pure product was isolated by flash chromatography and identified by ^{1}H and ^{13}C NMR and EI-MS. Product yield was calculated based on the yield of isolated product.

1,3-Dipolar [2+3] cycloaddition of amine 5 and EDA 9: To a solution of crude amine **5** (0.4 mmol) and $[Ru(p\text{-cymene})Cl_2]_2$ catalyst (5 mol%) in freshly-distilled dichloromethane (3 mL) was added dropwise a solution of ethyl diazoacetate (0.2 mmol) in freshly-distilled dichloromethane (2 mL) over an hour at 40°C under argon atmosphere. After the addition, stirring and heating was continued until all the diazo compounds had been consumed (2.5 h). Solvent was evaporated away under vacuum. The product yield and selectivity were determined by ^{1}H NMR using 1,1-diphenylethylene as the internal standard. Pure product was isolated by flash chromatography and identified by ^{1}H and ^{13}C NMR and EI-MS.

Mannich-type reaction of amine 5 and ketone 12: Crude amine **5** (0.4 mmol), ketone **12** (1 mmol), and L-proline (0.4 mmol) were added to isopropyl alcohol (1 mL) in a round-bottom flask. The mixture was stirred at room temperature for 24 h. When ketone **12a** was used, trifluoroacetic acid (0.6 mmol) was added after the reaction and stirred for a further 5 min. Most of the L-proline was removed by filtration against silica gel and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield were determined by ^{1}H NMR using 1,1-diphenylethylene as the internal standard. Pure product was isolated by flash chromatography and identified by ^{1}H and ^{13}C NMR and EI-MS.

Aerobic oxidation of N-phenyl-α-deutero-4-methylbenzylamine 28: **28** (0.4 mmol) and AuNPs/C catalyst (Au: 5 mol%) were added to toluene (8 mL) in a glass tube connected with a condenser. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering the tube opening. The mixture was stirred and heated at 110°C for 1 hour. The AuNPs/C catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The product yield of **2c** and **29** were determined by ^{1}H NMR using 1,1-diphenylethylene as the internal standard.

Competitive oxidation of *para*-substituted N-phenylbenzylamines: **1e** (0.4 mmol), *para*-substituted *N*-phenylbenzylamine (0.4 mmol) and AuNPs/C catalyst (Au: 5 mol%; 20 μmol) were added to toluene (8 mL) in a glass tube connected with a condenser. O_2 gas (99.7% min., Hong Kong Oxygen and Acetylene Co., Ltd.) was bubbled into the reaction mixture through a syringe needle, which was inserted into the septum covering the tube opening. The mixture was stirred and heated at 110°C for 1.5 h. The AuNPs/C catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield were determined by ^{1}H NMR using 1,1-diphenylethylene as the internal standard. The relative reactivity (k_{rel}) is calculated as below,

$$k_{rel} = \frac{k_Y}{k_H} = \frac{\log(Y_f/Y_i)}{\log(H_f/H_i)} \quad (1)$$

where Y_f and Y_i are the final and initial quantities of the *para*-substituted *N*-phenylbenzylamine; H_f and H_i are the final and initial quantities of amine **1e**.

Oxidation of 1a by "AuNPs/C+H_2O_2" protocol: **1a** (0.4 mmol) and AuNPs/C catalyst (Au: 5 mol%) were added to a round-bottom flask connected with a condenser. The flask was filled with argon with the Schlenk line technique. Freshly-distilled toluene (8 mL) was transferred to the reaction flask by syringe under argon atmosphere. Hydrogen peroxide (30 wt.% in H_2O; 1.2 mmol) was added by syringe. The mixture was stirred and heated at 110°C for 24 h under continuous argon flow. The AuNPs/C catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield were determined by ^{1}H NMR using 1,1-diphenylethylene as the internal standard.

H-transfer from 1b to 2e by AuNPs/C: **1b** (0.3 mmol), **2e** (0.1 mmol) and AuNPs/C catalyst (Au: 5 mol% relative to substrate **1b**) were added to a round-bottom flask connected with a condenser. The flask was filled with argon using the Schlenk line technique. Freshly-distilled toluene (8 mL) was transferred to the reaction flask by syringe under argon atmosphere. The mixture was stirred and heated at 110°C for 24 h under argon atmosphere. The AuNPs/C catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield were determined by ^{1}H NMR using 1,1-diphenylethylene as the internal standard. H-transfer efficiency is calculated as below,

$$Efficiency = \frac{[1e]}{[2b]} \times 100\% \quad (2)$$

where [1e] and [2b] is the product yield of the corresponding H-acceptor product **1e** and H-donor product **2b** respectively.

H-transfer from 1,4-cyclohexadiene to 2e by AuNPs/C: **2e** (0.1 mmol) and AuNPs/C catalyst (Au: 5 mol% relative to 1,4-cyclohexadiene) were added to a round-bottom flask connected with condenser. The flask was filled with argon using the Schlenk line technique. Freshly-distilled toluene (8 mL) was transferred to the reaction flask by syringe under argon atmosphere. 1,4-Cyclohexadiene (0.4 mmol) was added to the flask under argon atmosphere. The mixture was stirred and heated at 110°C for 24 h under argon atmosphere. The crude reaction mixture was immediately analyzed by GC-MS qualitatively. The AuNPs/C catalyst was removed by filtration against celite and the organic product was collected in the filtrate. Solvent was evaporated away under vacuum. The substrate conversion and product yield of **1e** were determined by ^{1}H NMR using 1,1-diphenylethylene as the internal standard.

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