

Nanoparticle-supported and magnetically recoverable palladium (Pd) catalyst: a selective and sustainable oxidation protocol with high turnover number†

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A magnetic nanoparticle-supported Pd catalyst was readily prepared from inexpensive starting materials and shown to catalyze various oxidation reactions with high turnover number (TON) and excellent selectivity. The ease of recovery using an external magnetic field, high activity, and the intrinsic stability of the catalyst make this protocol economic and sustainable.

The oxidation of alcohols and olefins to carbonyl compounds is of paramount importance in synthetic organic chemistry because of their use in a wide range of products, such as drugs, agro-chemicals, and fragrances.¹ They have conventionally been oxidized in non-catalytic ways with stoichiometric oxidants such as chromium and manganese compounds in the presence of strong mineral acids, which generate enormous amounts of poisonous metal salts as waste.² Due to the increasing environmental concerns, many efforts have been made to develop the environmentally benign oxidation systems.² Various heterogeneously catalyzed protocols were developed, including the use of silver nanoparticles supported on hydrotalcites,³ gold nanoparticles supported on metal oxides,⁴ metallic iron nanoparticles on MCM-41,⁵ and palladium nanoparticles on hydroxyapatite,⁶ mesoporous carbon,⁷ silica-alumina,⁸ and titania.⁹ Among the various protocols, ruthenium hydroxide supported on Fe₃O₄¹⁰ and palladium (Pd) nanoparticles supported on SBA-15¹¹ show promising results. However, most systems can be applicable for the oxidations of only activated substrates or large quantities of additives such as bases and electron transfer mediators were used. Recently, Beller and co-workers reported the use of nano- γ -Fe₂O₃ for oxidation of alcohols with high selectivity.¹² Although this work led the way to advance oxidation catalysis, the TON of the reaction is very low, ranging from 6 to 36. As clearly stated by Beller *et al.* “for general applications in organic synthesis, the activity of catalyst system should be further improved”.¹² There is an urgent need to develop less expensive and sustainable oxidation catalyst systems with high TON.

Recently, functionalized magnetic nanoparticles have emerged as viable alternatives to conventional materials, as robust, readily available, high-surface-area heterogeneous catalyst supports.¹³ They offer an added advantage of being magnetically separable, thereby eliminating the requirement of catalyst filtration after completion of the reaction. Engaged in the development of greener and sustainable pathways for organic transformations,¹⁴

nanomaterials,¹⁵ and nano-catalysis,¹⁶ herein, we report a simple and efficient synthesis of a nano-ferrite-supported, magnetically recyclable, and inexpensive Pd catalyst and its application in oxidation reactions. At the outset of this study, no example of magnetic nanoparticle-supported Pd catalysts had been reported for oxidation reactions, despite the potential inherent stability and activity of such materials.

The first step in the accomplishment of this goal was the synthesis and functionalization of magnetic nanoparticles (Scheme 1). The catalyst was prepared by sonicating nano-ferrites with dopamine (which acts as a robust anchor and avoids Pd-leaching) in water for 2 h, followed by addition of sodium palladium (Pd) chloride at a basic pH. Material with Pd nanoparticles on the amine-functionalized nano-ferrites was obtained in excellent yield.

Catalyst characterization by X-ray diffraction (XRD) (Fig. 1b and d) and transmission electron microscopy (TEM) (Fig. 1a and c) confirm formation of single-phase Fe₃O₄ nanoparticles, with spherical morphology and a size range of 10–16 nm, which is comparable with the crystallite size calculated from the X-ray spectrum, by using the Scherer formula (10.23 nm). FT-IR evidently confirms the anchoring of dopamine on ferrite surfaces (S4, ESI†). The signals of palladium metal were not detected in XRD, showing that the Pd species is highly dispersed on ferrites. The weight percentage of palladium was found to be 10.23% by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) analysis.

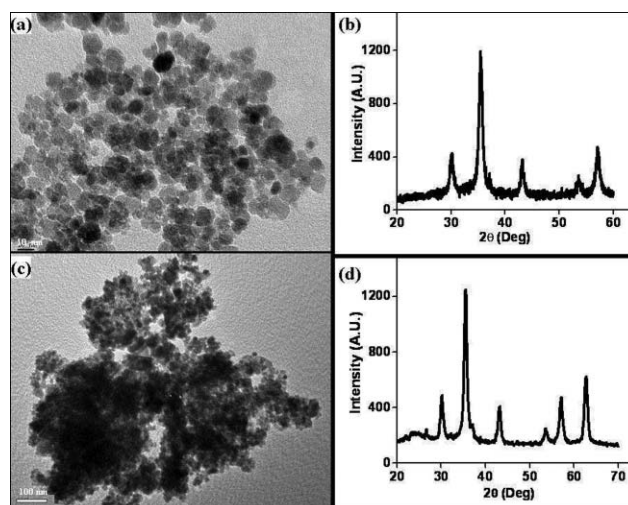
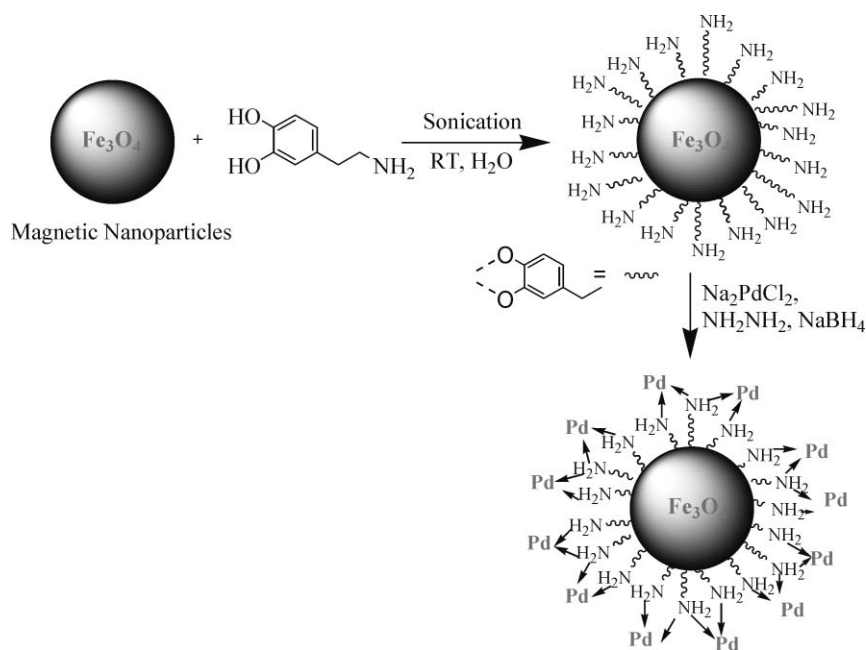


Fig. 1 (a) TEM of Fe₃O₄, (b) XRD of Fe₃O₄, (c) TEM of Fe₃O₄-Pd, (d) XRD of Fe₃O₄-Pd.

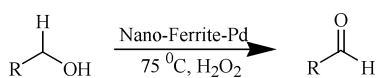
This Pd-coated nanomaterial was then explored as a heterogeneous catalyst for the oxidation of alcohols (Scheme 2).

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† Electronic supplementary information (ESI) available: Experimental procedures; recyclability and Pd-leaching of catalyst, TEM, XRD of nano-ferrites; NMR and MS data of compounds. See DOI: 10.1039/b817669h



Scheme 1 Synthesis of functionalized nano-ferrite-Pd.



Where,
R- alkyl, aryl

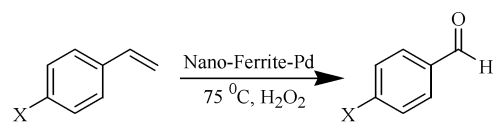
Scheme 2 Nano-ferrite-Pd catalyzed alcohol oxidation.

Initially, experiments were performed to optimize reaction conditions for oxidation of benzyl alcohol as a substrate, using one equivalent of hydrogen peroxide, to get a high TON of product (Table 1). First the reaction was conducted using nano- α - Fe_2O_3 with particle sizes from 2–3 μm (see ESI S7 for TEM images and XRD data[†]) and conversion with low TON (160) was observed. Then, we tested nano- Fe_3O_4 with particle sizes from 10–15 nm (Fig. 1a and b) as catalyst, and the TON reached 240 with high selectivity. However, we wanted to develop a high TON protocol and thus prepared Pd-coated nano- Fe_3O_4 (as discussed in Scheme 1) with particle sizes from 10–16 nm (Fig. 1c) and tested for this oxidation protocol. We observed conversion with very high TON (720), with >99% selectivity.

Using the above optimized condition, this catalyst was then explored for oxidation of a variety of alcohols (Table 2). Excellent

turnover numbers were observed for various aromatic alcohols (entries 1 to 7) as well as aliphatic alcohols (entries 8, 9) within 6 h. However, in the case of hexanol, conversion with low TON is due to volatility of the ensuing aldehyde (entry 9). Heterocyclic alcohols (entries 10, 11), extensively used building-blocks in drug discovery, also underwent oxidation reaction with high TON, proving the suitability of this protocol for assembly of biomolecules. In all the reactions, we observed more than 95% selectivity because of the very low catalyst amount (0.025 mole%). This will be very useful in total synthesis of drug molecules, where it is required that an alcoholic group be selectively oxidized to its aldehyde without any over-oxidation. The catalytic activity of our system is superior to that of Beller's,⁸ *i.e.*, TON of benzyl alcohol oxidation is 720 in 6 h, as compared to TON of 32 in 12 h, with comparable selectivity.

The oxidation of olefinic compounds to the corresponding aldehydes (Scheme 3) is a synthetically important transformation and notably, this catalytic system also oxidized aromatic olefins with high TON and the results are summarized in Table 3.



Where,
X - H, Cl, F, Br

Scheme 3 Nano-ferrite-Pd catalyzed olefin oxidation.

The scope of the catalyst was established for a range of aromatic olefins and the reactions were completed within 6 h. In all the reactions, TON ranging from 600 to 680 were observed, which is superior as compared to the TON of known protocols, which range from 19 to 36.⁸

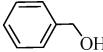
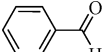
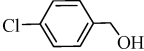
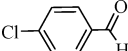
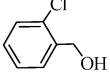

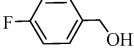
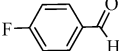
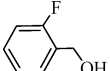

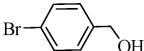

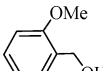
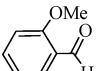
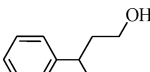
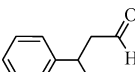
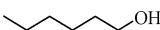

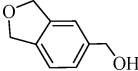
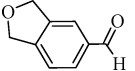


Separation and recovery of the catalyst is also an important aspect for the synthesis of fine chemicals; which is generally performed by filtration with reduced efficiency. In our catalytic

Table 1 Optimization of reaction conditions^a

Entry	Catalyst	Reaction time/h	TON ^b	Selectivity (%) ^c
1	nano- α - Fe_2O_3	6	160	>99
2	nano- α - Fe_2O_3	12	200	>99
3	nano- Fe_3O_4	6	240	>99
4	nano- Fe_3O_4	12	280	>99
5	nano- Fe_3O_4 -Pd	6	720	>99
6	nano- Fe_3O_4 -Pd	12	760	>99

^a Reactions were carried out with 10 mmol of benzyl alcohol, 0.025 mole% of catalyst, and 1 equiv of H_2O_2 , at 75–80 °C. ^b Number of moles of aldehyde formed per mole of catalyst. ^c Selectivity based on alcohol conversion.

Table 2 Oxidation of alcohols using nano-ferrite-Pd catalyst^a

Entry	Substrate	Product	TON
1			720
2			760
3			680
4			760
5			640
6			760
7			800
8			600
9			520
10			760
11			800

^a Reactions were carried out with 10 mmol of alcohol, 0.025 mole% of catalyst, and 1 equiv of H₂O₂, at 75–80 °C for 6 h.

system, because of the super-paramagnetic nature of the nano-Fe₃O₄-Pd catalyst, it can be recovered by simply using external magnets, with high efficiency and up to 99% recovery of catalyst (Fig. 2). After completion of the reaction, within 30–45 sec, the reaction mixture turned clear and catalyst was deposited on the

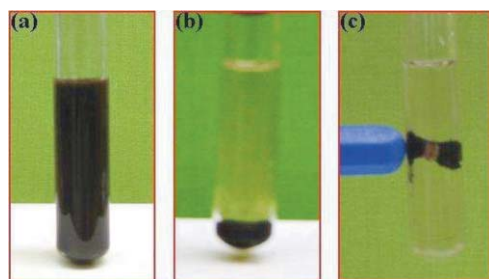

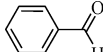


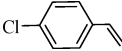
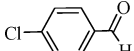
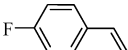

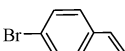
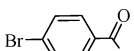


Fig. 2 Oxidation of alcohols using nano-ferrite-Pd catalyst, (a) during reaction under stirring, (b) after completion of reaction without stirring, (c) catalyst removal by external magnet.

Table 3 Oxidation of olefins using nano-ferrite-Pd catalyst^a

Entry	Substrate	Product	TON
1			640
2			680
3			600
4			620
5			600

^a Reactions were carried out with 10 mmol of olefin, 0.025 mole% of catalyst, and 2 equiv of H₂O₂, at 75–80 °C for 6 h.

magnetic bar (Fig. 2b), which was easily removed from reaction mixture using an external magnet (Fig. 2c).

For practical applications of heterogeneous systems, the lifetime of the catalyst and its level of reusability are very important factors. To clarify this issue, we established a set of experiments for the oxidation of benzyl alcohol using the recycled nano-Fe₃O₄-Pd catalyst. After the completion of the first reaction to afford the corresponding aldehyde, the catalyst was recovered magnetically, washed with methanol, and finally dried at 60 °C for 10 min. A new reaction was then performed with fresh reactants and H₂O₂, under the same conditions. The nano-ferrite-supported Pd catalyst could be used at least 5 times without any change in activity.

Metal leaching was studied by ICP-AES analysis of the catalyst before and after the five reaction cycles. The Pd concentration was found to be 7.91% before reaction and 7.86% after the reaction, and also no Pd metal was detected in the final oxidation product (see ESI S5 for details[†]), which confirmed negligible Pd leaching. The negligible Pd leaching is due to a well defined amine-binding site located on the surface of the nano-ferrite (Scheme 1), which acts as a pseudo-ligand by non-covalent binding with Pd through a metal–ligand interaction. This non-covalent anchoring minimizes deterioration and metal leaching and allows efficient catalyst recycling. Also, the most important criteria in choosing a catalyst is metal recovery. It would be preferable to use a more accessible, economic Pd catalyst, provided that the process works at high TON and that the catalyst leaves no remnants of metal in the end product, since metal contamination is highly regulated by the pharmaceutical industry. All above conditions were well satisfied by our recyclable nano-ferrite-supported Pd catalyst.

In summary, we have developed a convenient synthesis of a nano-ferrite-supported Pd catalyst which was readily prepared from inexpensive starting materials in water. This catalyst then catalyzed the oxidation of alcohols and olefins with high TON and excellent selectivity. Also, being magnetically separable eliminated the requirement of catalyst filtration after completion of the reaction, which is an additional sustainable attribute of this oxidation protocol.

Experimental section

Synthesis of magnetic nano-ferrites

FeSO₄·7H₂O (13.9 g) and Fe₂(SO₄)₃ (20 g) were dissolved in 500 mL water in a 1000 mL beaker. Ammonium hydroxide (25%) was added slowly to adjust the pH of the solution to 10. The reaction mixture was then continually stirred for 1 h at 60 °C. The precipitated nanoparticles were separated magnetically, washed with water until the pH reached 7, and then dried under a vacuum at 60 °C for 2 h. Ferrite was characterized by X-ray diffraction (XRD) (Fig. 1b) and transmission electron microscopy (TEM) (Fig. 1a). This magnetic nano-ferrite (Fe₃O₄) was then used for further chemical modification.

Surface modification of nano-ferrites

Nano-Fe₃O₄ (2 gm) was dispersed in 25 mL water by sonication for 30 min. Dopamine hydrochloride (2 gm) dissolved in 5 mL of water was added to this solution and again sonicated for 2 h. The amine-functionalized nanomaterial was then precipitated using acetone, isolated by centrifugation, and dried under vacuum at 60 °C for 2 h.

Synthesis of nano-ferrite-Pd catalyst

Amine-functionalized nano-Fe₃O₄ (1 gm) was dispersed in water and sodium palladium chloride solution in water was added to the mixture to get 10 wt% of Pd. Hydrazine monohydrate solution in water was added dropwise to bring the pH of this mixture to 9, followed by addition of 0.1 gm of NaBH₄. The reaction mixture was then stirred for 24 h at room temperature. The product was allowed to settle, washed several times with water and acetone, and dried under vacuum at 60 °C for 2 h. Catalyst characterization by X-ray diffraction (XRD) (Fig. 1d) and transmission electron microscopy (TEM) (Fig. 1c) confirm the anchoring of Pd nanoparticles on ferrite surfaces. The weight percentage of Pd in the catalyst was found to be 7.91% by ICP-AES analysis.

Oxidation of alcohols using nano-ferrite-Pd catalyst

10 mmol of alcohol and 0.025 mole% of nano-ferrite-Pd catalyst were placed in a 10 mL glass tube with a magnetic stirrer bar. H₂O₂ (1 equiv) was then added dropwise to the reaction mixture under stirring at room temperature. The reaction was continuously stirred at 75–80 °C for 6 h. Conversion and selectivity were periodically determined by GC analysis. After completion of the reaction, stirring was stopped. Within 30–45 s, the reaction mixture turned clear and catalyst was deposited on the magnetic bar, which was easily removed from the reaction mixture using an external magnet. The crude product obtained was further purified by column chromatography. All products are known in the literature and were identified by comparison of their ¹H and ¹³CNMR with literature data and comparing their GC-MS spectra with standard Wiley mass spectral library.

Oxidation of olefins using nano-ferrite-Pd catalyst

10 mmol of olefins and 0.025 mole% of nano-ferrite-Pd catalyst were placed in a 10 mL glass tube with a magnetic stirrer bar. H₂O₂

(2 equiv) was then added dropwise to the reaction mixture under stirring at room temperature and the same procedure described above was followed.

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