Chemoselective transfer hydrogenation of nitroarenes, aldehydes and ketones with propan-2-ol catalysed by Ni-stabilized zirconia

T. T. Upadhya, S. P. Katdare, D. P. Sabde, Veda Ramaswamy and A. Sudalai*

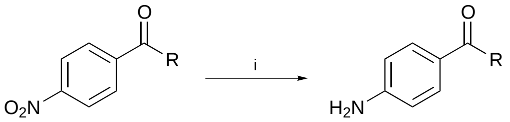
National Chemical Laboratory, Pune-411 008, India

Nickel-stabilized zirconia ($Zr_{0.8}Ni_{0.2}O_2$), a reusable, solid catalyst, efficiently catalyses the chemoselective reduction of nitroarenes, aldehydes and ketones using propan-2-ol and KOH, in the liquid phase, exhibiting the reactivity order $NO_2 \gg C{=}O > C{-}X \gg C{=}C$.

The chemoselective reduction of organic compounds is synthetically important, both in the laboratory and in industry. In comparison with catalytic reduction using molecular hydrogen,[1] transfer reduction using hydrogen donors, *viz.* propan-2-ol, has real and potential advantages because neither hydrogen containment nor a pressure vessel is required. Moreover, the transfer hydrogenation method could offer enhanced selectivity in the reduction process. A wide variety of homogeneous and heterogeneous catalytic systems in combination with different hydrogen donors have been employed to selectively reduce most major functional groups attached to aliphatic and aromatic structures.[2] Chemoselective reduction of the functional groups can be achieved by classical Meerwein–Ponndorf–Verley reductions. However, the use of aluminium isopropoxide in stoichiometric amounts and under drastic reaction conditions often leads to undesired side reactions.[3] Recently, transfer hydrogenation of ketones using homogeneous complexes of Cu, Fe, Rh, Ru, Ir, Pd and Ni with propan-2-ol has been reported.[4] However, it has been observed that controlling the reduction rates is difficult with these active catalysts.[5] On the other hand, the use of heterogeneous catalysts offers several advantages over the homogeneous systems such as ease of recovery, recycling and enhanced stability. Raney Ni catalyst has also been extensively used in combination with hydrazine hydrate or propan-2-ol as a hydrogen source for reductions. However, Raney Ni is pyrophoric and does not show any selectivity towards functional groups such as C–X, C=O and NO_2, reducing all of them simultaneously. Further it has been observed that the use of Raney Ni for the reduction of aromatic ketones leads to hydrogenolysis of alcohols quite easily at the benzylic position.[6]

Considerable efforts have been devoted in use of zirconium oxide, which is known to be a bifunctional catalyst, either as a single oxide or in a mixed metal oxide, for application in organic synthesis as is evident from the literature.[7] Here, we report the potential application of nickel-stabilized zirconia as an active, heterogeneous catalyst for chemoselective reduction of nitro and carbonyl functions under transfer hydrogenation conditions in the liquid phase using propan-2-ol (Scheme 1).

Zirconia samples stabilized by Cr, Mn, Fe, Co or Ni were prepared by the procedure reported from our laboratory.[8] In particular, $Zr_{0.8}Ni_{0.2}O_2$ was prepared by treating an aqueous solution of zirconyl nitrate and nickel nitrate (molar ratio 80 : 20) with tetramethylammonium hydroxide (25% aqueous solution) as a precipitating agent under vigorous stirring until a pH of 8.0 was achieved. The resultant hydroxide precipitate was washed with deionised water, acetone and dried at 110 °C for 24 h and was subsequently heated to 500 °C under a programmed heating rate of 2 °C min^{-1} and then calcined for 8 h. It was then characterized by powder X-ray diffraction, FTIR, surface area determination by the BET method, X-ray fluorescence (XRF), temperature programmed reduction (TPR) and cyclic voltammetry (CV) techniques.



Scheme 1 *Reagents and conditions:* i, $Zr_{0.8}Ni_{0.2}O_2$ (cat.), Pr^iOH, KOH, reflux, 3 h

The XRD profiles of nickel-stabilized zirconia shows the formation of a cubic (fluorite) phase The FTIR spectrum in the framework region shows a broad band at *ca.* 480 cm^{-1} characteristic of the cubic phase of ZrO_2.[9] Scanning electron microscopy indicates the presence of uniform particles with sizes ranging between 0.5 and 1.0 μm. The surface area of the sample as determined by the BET method† was 96 $m^2\ g^{-1}$. The chemical composition determined by XRF[10] was 79.97 mol% Zr and 20.03 mol% Ni. TPR[11] shows a single peak at *ca.* 417 °C which can be attributed to a single step reduction of Ni^{2+} to Ni^0. The cyclic voltammogram of nickel-stabilized zirconia shows a reversible system (E_{pa} + 0.32 V, E_{pc} = 0.40 V *vs.* SCE with $E_{1/2}$ = 0.04 V). This electrochemical behaviour is attributed to the Ni^{2+}–Ni^0 redox cycle indicating that Ni in the solid matrix of zirconia undergoes a facile two-electron transfer process.[12]

The selective and rapid reduction of nitro compounds is an interesting area of research, particularly when other potentially reducible moieties are present in the molecule.[13] The results of the reduction of nitrobenzene to aniline over various catalysts are presented in Table 1 which shows that nickel-stabilized zirconia exhibits significantly higher activity and selectivity than pure ZrO_2, $Ni(O_2CMe)_2$ or Raney Ni. In the absence of either catalyst or KOH, no reaction took place. In a typical reaction procedure, a mixture of nitrobenzene (1 g, 0.0081 mol), KOH pellets (0.045 g, 0.0008 mol) and $Zr_{0.8}Ni_{0.2}O_2$ (10% *m/m*)

Table 1 Transfer hydrogenation of nitrobenzene to aniline with propan-2-ol over different catalysts[a]

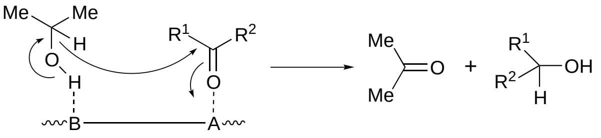
			Yield[b]	
Entry	Catalyst	Surface area/ $m^2\ g^{-1}$	Aniline (mass%)	Unreacted nitrobenzene (mass%)
1	No catalyst/No KOH	—	0	100
2	ZrO_2	56	14.5	85.5
3	$Ni(O_2CMe)_2$	—	10.0	90.0
4	Raney Ni	—	21.2	78.8
5	$Zr_{0.8}Cr_{0.2}O_2$	118	28.1	71.9
6	$Zr_{0.8}Mn_{0.2}O_2$	105	39.0	61.0
7	$Zr_{0.8}Fe_{0.2}O_2$	102	38.4	61.6
8	$Zr_{0.8}Co_{0.2}O_2$	98	50.0	50.0
9	$Zr_{0.8}Cu_{0.2}O_2$	94	70.8	29.2
10	$Zr_{0.8}Ni_{0.2}O_2$	96	96.0	4.0

[a] *Reaction conditions*: nitrobenzene (8 mmol), KOH pellets (8 mmol) and catalyst (10% *m/m*) in propan-2-ol (15 ml), refluxing for 3 h. [b] Determined by capillary gas chromatography.

Table 2 Transfer hydrogenation of nitroarenes and carbonyl compounds with propan-2-ol catalysed by Ni-stabilized zirconia ($Zr_{0.8}Ni_{0.2}O_2$)[a]

Entry	Substrate	*t*/h	Product[b]	Yield[c] (mass%)
1	Nitrobenzene	3	Aniline	96
2	4-Chloronitrobenzene	3	4-Chloroaniline	85
3	4-Nitroacetophenone	3	4-Aminoacetophenone	88
4	2-Nitroanisole	2	*o*-Anisidine	86
5	Benzaldehyde	6	Benzyl alcohol	87
6	4-Methoxybenzaldehyde	5	4-Methoxybenzyl alcohol	86
7	4-Chlorobenzaldehyde	6	4-Chlorobenzyl alcohol	90
8	4-Hydroxybenzaldehyde	5	4-Hydroxybenzyl alcohol	88
9	Furan-2-carbaldehyde	4	2-Furfuryl alcohol	81
10	Acetophenone	4	1-Phenethyl alcohol	90
11	Benzophenone	5	Benzhydrol	91[d]
12	4-Methoxybenzophenone	5	4-Methoxybenzhydrol	70
13	4-Bromobenzophenone	5	4-Bromobenzhydrol	90
14	3,4-Dichlorobenzophenone	4	3,4-Dichlorobenzhydrol	95
15	Octan-2-one	4	Octan-2-ol	68 (25[e])
16	2-Methylcyclohexanone	6	2-Methylcyclohexanol	58
17	4-Nitrobenzophenone	3	4-Aminobenzophenone	90
18	2-Nitrobenzaldehyde	3	2-Aminobenzyl alcohol	80
19	Cinnamaldehyde	3	Cinnamyl alcohol	72

[a] *Reaction conditions:* substrate (8 mmol), KOH pellets (8 mmol) and $Zr_{0.8}Ni_{0.2}O_2$ catalyst (10% *m/m*) in propan-2-ol (15 ml); reflux for 3–6 h. [b] Products were characterized by IR, ^1H, ^{13}C NMR and MS. [c] Isolated yield after chromatographic purification, the remainder is essentially unreacted starting material. [d] Diphenylmethane is obtained with Raney Ni.[6] [e] Yield with Raney Ni.[6]



Scheme 2

in propan-2-ol (15 ml) was refluxed for 3–5 h. The progress of the reaction was monitored by TLC, the catalyst was then filtered off and the product purified by flash chromatography to afford aniline (96% yield).

As summarized in Table 2, in refluxing propan-2-ol (82 °C), the present catalytic system efficiently reduces both nitroarenes and carbonyl compounds in excellent yields. Both aromatic and aliphatic aldehydes and ketones are reduced to the corresponding alcohols. It is remarkable that both C–Br and C–Cl bonds are not reduced and are stable under the reaction conditions (Table 2: entries 2, 7, 13 and 14). Another notable feature of this catalytic system is that both 4-nitroacetophenone and 4-nitrobenzophenone undergo chemoselective reduction to 4-aminoacetophenone and 4-aminobenzophenone, respectively, in high yields without reduction of the carbonyl function. Further, cinnamaldehyde is reduced chemoselectively to cinnamyl alcohol without reducing C=C. The present catalytic system did not reduce functional groups such as CO_2H, CN, CO_2R, *etc.*, under the present experimental conditions. The catalyst was easily recovered by filtration, and could be reused three times for the reduction of nitrobenzene without affecting the activity or selectivity of the process. The XRD pattern of the used catalyst shows no structural deterioration.

Mechanically, stabilization of zirconia by nickel does not alter its bifunctional behaviour.[7] Propan-2-ol is adsorbed on the basic site (B) and the ketone on the adjacent acidic site (A); the Ni^{2+} on the surface promotes dehydrogenation of propan-2-ol by KOH, and is reduced to the active Ni^0 species as evident from CV measurements and finally the hydrogen is transferred as hydride as shown in Scheme 2. It appears that the active Ni^0 species, formed instantaneously during the reaction, is responsible for the catalytic reduction.

In conclusion, incorporation of Ni into the bulk structure of ZrO_2, not only stabilizes ZrO_2 in its cubic (fluorite) form but also moderates the reactivity of Ni in the stabilized zirconia enabling chemoselective functional group reduction.

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Footnotes

* E-mail: otech@ems.ncl.res.in

† Determination of specific surface area by BET (Brunner, Emmett, Teller), using N_2 adsorption on a Omnisorp 100CX apparatus.

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