Macroporous metal oxides as an efficient heterogeneous catalyst for various organic transformations—A comparative study

Harjyoti Thakuria, Ballav Moni Borah, Gopal Das[*]

Department of Chemistry, Indian Institute of Technology Guwahati, Guwahati 781 039, Assam, India

Abstract

Porous materials have attracted the attention of chemists due to their various applications such as heterogeneous catalysis, chemical separations via adsorption. Macroporous transition metal oxides *viz.* CuO, NiO, CoO, Mn_2O_3, Cr_2O_3 and ZnO were synthesized and used as an efficient, heterogeneous, reusable and eco-friendly catalyst for four different organic transformations *viz.* *N*-formylation, *N*-acylation, *O*-acylation and Friedel Craft acylation under solvent-free conditions in good yields. These results were compared with the literature.
© 2007 Elsevier B.V. All rights reserved.

Keywords: Metal oxide; Solvent-free; Heterogeneous catalyst

1. Introduction

Synthetic chemists continue to explore new methods to carry organic transformations. One of the new methods is to perform reactions on the surface of a solid as a heterogeneous catalyst. Inexpensive and commercially available transition metal oxides and zinc oxide are most studied metal oxides as a heterogeneous catalyst for various organic transformations [1]. Metal oxides are important class of heterogeneous catalyst because of their high level of chemo-selectivity, environmental compatibility, simplicity of operation and availability at low cost.

N-Formylation is an important reaction in the formation of formamides. Formamides are again important intermediates in the synthesis of pharmaceutically important compounds [2]. A numerous methods have been reported for the formation of for-mamides [3]. However, there are several factors such as low yield, difficulties in workup procedure and use of expensive reagents limiting their applications. Very recently ZnO as a heterogeneous solid state catalyst have been reported for *N*-formylation reactions [4].

An acyclic *N*-acylamide core constitutes various natural products such as immunosuppressant microcolin [5] anticancer agent dolastatin 15 [6]. To construct these *N*-acylamide structures, acti-vation of amides and/or acyl donors is generally required. Since the nitrogen atom of amides is less basic than that of the corresponding amines due to amide resonance. Reported methods for the *N*-acylation by a combination of amides and acyl donors are as follows: lithiated amide–acyl chloride [7], trimethylsilylated amide–acyl chloride [8], lithiated amide–pentafluorophenyl esters [9], amide–LiCl–acid anhydride [10]. Recently, ZnO under solvent-free conditions is reported as an efficient catalyst for *N*-acylation [11].

The protection of hydroxyl groups by esterification constitutes the major backbone of many preparations of natural and synthetic products such as perfumes, flavors, food additives, cosmetics, pharmaceuticals, plasticizers and polymers. Generally, esterification is carried out by acylation of alcohols and phenols with carboxylic acids and more conveniently anhydrides or acyl chlorides in the presence of basic catalysts, Bronsted or Lewis acids and metal salts [12]. Amongst the catalysts used for activation of anhydrides and acyl chlorides, pyridine [13] and KF–Al₂O₃ [14] are the most significant, whereas H_2SO_4 [15], and NH_2SO_3H [16] are commonly used acidic catalysts. Recently, other reagents such as distannoxane [17], metal triflates [18], $AlPW_{12}O_{40}$ [19], $ZrCl_4$ [20], $ZrOCl_2·8H_2O$ [21], $BiOClO_4·xH_2O$ [22], metal triflates in ionic liquids [23] and lipase enzymes have been applied for acylation of alcohols and phenols. However, there is always the need for better methodology for these types of widely used reactions. Recently, ZnO under solvent-free conditions have proved to be useful to

---

[*] Corresponding author. Tel.: +91 361 2582 fax: +91 361 2582349.
E-mail address: gdas@iitg.ernet.in (G. Das).

chemists in the laboratory and industry due to the good activation of adsorbed compounds, reaction rate enhancement, selectivity, easier work-up and recyclability of the supports. These metal oxides are eco-friendly and green in nature [11,23].

The Friedel Craft reaction is an important reaction for C–C bond formation. After over a century of development, it still attracts much research interest in both academia and industry. Brønsted acid or Lewis acid-catalyzed imine or iminium Friedel Craft reactions (aza-Friedel Craft reactions) are important methods to construct a variety of nitrogen containing compounds [24]. The industrial production of various pharmaceuticals and fine chemicals involves the synthesis and further transformation of aromatic ketones. The common routes for preparation of these ketones proceed via the Friedel Craft acylation of the concerned aromatic hydrocarbon with derivates of carboxylic acids. These reactions are traditionally catalyzed by either Lewis acids such as $AlCl_3$, $FeCl_3$ and BF_3 or Brønsted acids such as HF or H_3PO_4 [25]. Recently zinc powder promotes the acylation of activated as well as inactivated aromatics under microwave irradiation [26]. Cheap and commercially available ZnO is also reported recently as a catalyst in solvent-free condition for the reactions described above [27].

Although numerous methods are known for all these type of organic transformations, newer methods still continue to attract attention for their experimental simplicity and effectiveness. Porous materials have attracted the attention of chemists and materials scientists due to commercial interest in their application in ion exchange, adsorption (for chemical separations) and heterogeneous catalysis. These porous materials have the ability to interact with atoms, ions and molecules not only at their surfaces, but also throughout the bulk of the material, which is responsible for its functional diversities [28].

As the part of our ongoing research, we are trying to synthesize some porous materials having catalytic activities, which are economical for large-scale preparation. We have already synthesized ZnO nano-particles via thermal decomposition [29]. Here we have described the use of five macroporous transition metal oxide (*viz*. CuO, NiO, CoO, Mn_2O_3, Cr_2O_3) and non-transition zinc oxide as a simple and efficient heterogeneous eco-friendly catalyst for different types of organic reactions (*viz*. N-formylation, N-acylation, O-acylation and Friedel Craft acylation). These results were compared with that of already reported commercially available ZnO. To the best of our knowledge, these reactions are never been reported by any group using the porous transition metal oxides.

2. Results and discussion

2.1. Metal oxide-catalyzed formylation of amine

For all the organic transformations, we first prepared the various transition metal hydroxides in presence of agar agar gel as template. Later all these hydroxides were heated to ~600 °C to transform them to corresponding metal oxides. In case of N-formylation (Scheme 1) by macroporous ZnO, we got marginal improvement compared to the reported value [4] as indicated in Table 1.
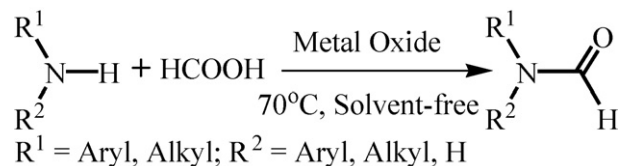
Scheme 1. *N*-Formylation of amine under solvent-free condition.

Table 1

Comparison of *N*-formylation of aniline (1 mmol) with formic acid (2.5 mmol) by using ZnO as catalyst

Entry	Catalyst	Catalyst (mmol)	Time (min)	Yield (%)[a]	Reference
1	Commercial ZnO	0.50	10	99	[4]
2	ZnO (macroporous)	0.50	08	99	This
3		0.25	120	55	work

[a] Isolated yields.

The reaction conditions were standardized after conducting the *N*-formylation of aniline in different amounts of metal oxides catalyst (Table 2) and reaction time. For *N*-formylation of aniline, 70 °C is proven to be the optimum temperature. This corresponds well with the reported value [4]. Thus under optimum conditions, 1 mmol of aniline was formylated in solvent-free conditions with 2.5 mmol of formic acid using 0.25 mmol CuO, 0.20 mmol NiO, 0.20 mmol CoO, 0.05 mmol Mn_2O_3, and 0.05 mmol Cr_2O_3 as a heterogeneous catalyst. Under similar
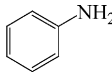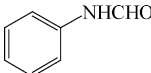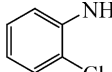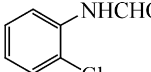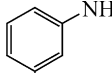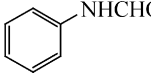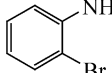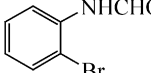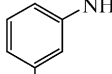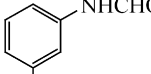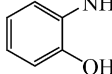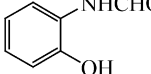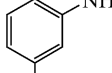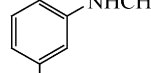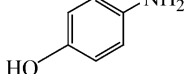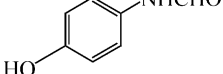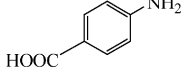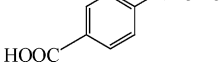
Table 2

N-Formylation of aniline (1 mmol) with formic acid (2.5 mmol) at 70 °C

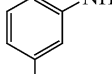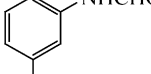| Entry	Catalyst	Catalyst (mmol)	Time (min)	Yield (%)[a]
1	CuO	0.50	25	90
2		0.25	25	95
3		0.25	40	80[b]
4		0.10	40	50
5		0.05	120	–
6	NiO	0.50	60	60
7		0.20	10	99
8		0.20	25	84[b]
9		0.10	20	95
10		0.05	25	80
11	CoO	0.50	45	80
12		0.20	30	99
13		0.20	60	85[b]
14		0.10	40	95
15		0.05	70	85
16	Mn_2O_3	0.50	120	–
17		0.20	60	50
18		0.10	45	74
19		0.05	15	92
20		0.05	35	80[b]
21	Cr_2O_3	0.50	30	80
22		0.20	35	90
23		0.10	25	95
24		0.05	25	90
25		0.05	55	80[b]

[a] Yields are of the isolated compounds.
[b] Reaction performed at 60 °C.

Table 3
N-Formylation amine in presence of metal oxides as heterogeneous catalyst at 70 °C

Entry	Substrates	Product	Metal oxides (mmol)	Time (min)	Yield (%)[a]
1			CuO (0.25)	15	96
2			NiO (0.20)	10	99
3			CoO (0.20)	25	99
4			Mn_2O_3 (0.05)	15	95
5			Cr_2O_3 (0.05)	25	98
6			CuO (0.25)	60	90
7			NiO (0.20)	55	90
8			CoO (0.20)	60	92
9			Mn_2O_3 (0.05)	75	85
10			Cr_2O_3 (0.05)	70	85
11			CuO (0.25)	20	92
12			NiO (0.20)	20	90
13			CoO (0.20)	25	88
14			Mn_2O_3 (0.05)	30	88
15			Cr_2O_3 (0.05)	30	85
16			CuO (0.25)	60	94
17			NiO (0.20)	60	90
18			CoO (0.20)	60	92
19			Mn_2O_3 (0.05)	70	85
20			Cr_2O_3 (0.05)	70	85
21			CuO (0.25)	25	92
22			NiO (0.20)	25	95
23			CoO (0.20)	25	88
24			Mn_2O_3 (0.05)	35	85
25			Cr_2O_3 (0.05)	35	85
26			CuO (0.25)	40	98
27			NiO (0.20)	40	95
28			CoO (0.20)	60	85
29			Mn_2O_3 (0.05)	75	85
30			Cr_2O_3 (0.05)	50	85
31			CuO (0.25)	50	94
32			NiO (0.20)	55	92
33			CoO (0.20)	60	92
34			Mn_2O_3 (0.05)	80	88
35			Cr_2O_3 (0.05)	75	90
36			CuO (0.25)	45	98
37			NiO (0.20)	50	95
38			CoO (0.20)	60	85
39			Mn_2O_3 (0.05)	75	85
40			Cr_2O_3 (0.05)	60	85
41			CuO (0.25)	60	88
42			NiO (0.20)	40	92
43			CoO (0.20)	80	85
44			Mn_2O_3 (0.05)	90	88
45			Cr_2O_3 (0.05)	90	92
46			CuO (0.25)	65	92
47			NiO (0.20)	60	91
48			CoO (0.20)	70	92
49			Mn_2O_3 (0.05)	90	82
50			Cr_2O_3 (0.05)	90	80
51			CuO (0.25)	40	90
52			NiO (0.20)	45	88
53	$CH_3CH_2CH_2NH_2$	$CH_3CH_2CH_2CH_2NHCHO$	CoO (0.20)	50	90
54			Mn_2O_3 (0.05)	60	90
55			Cr_2O_3 (0.05)	60	85

[a] Yields are of the isolated compounds.

Table 4
Reuse of various metal oxides for *N*-formylation amine

| Catalyst (mmol)	Number of cycle	Yield (%)	Recovery of catalyst (%)
CuO (0.25)	1, 2, 3	96, 90, 88	96, 92, 92
NiO (0.20)	1, 2, 3	99, 94, 90	96, 91, 91
CoO (0.20)	1, 2, 3	99, 95, 90	95, 90, 90
Mn_2O_3 (0.05)	1, 2, 3	95, 89, 84	95, 90, 90
Cr_2O_3 (0.05)	1, 2, 3	98, 92, 84	94, 90, 90

reaction conditions more amount (0.50 mmol) of ZnO is required [4]. Thus we can conclude, macroporous transition metal oxides (*viz*. CuO, NiO, CoO, Mn_2O_3, and Cr_2O_3) are more efficient heterogeneous catalyst. This is because macroporous metal oxides have large internal surface area and pore volume. This in turn allows control over the diffusion of both reagents and products into and out of the porous medium as well as control over the possible reaction intermediates that might form within the pore system [28]. But when we used lesser amount of CuO (Table 2, entries 4 and 5), CoO (Table 2, entries 14 and 15) and Cr_2O_3 (Table 2, entries 23 and 24) we got comparatively poor yield.

The results of *N*-formylation (Scheme 1) in optimized reaction conditions of different substrates were summarized in the Table 3. Both aromatic amine possessing electron donating and electron withdrawing groups (Table 3, entries 1–50) as well as aliphatic amine (Table 3, entries 51–55) proceed smoothly to give *N*-formylated products in excellent yield. To the best of our knowledge, these reactions were never been reported by using these macroporous transition metal oxides. The catalytic activity of the recovered catalyst was examined as shown in the Table 4. In each case, after two and three reuses of these catalyst, almost >90% of the catalyst was easily recovered from the reaction mixture by simple filtration after washing with dichloromethane. Catalytic activity remains even after third cycle.

2.2. Metal oxide-catalyzed acylation of amines

In case of *N*-acylation (Scheme 2) by macroporous ZnO, we got excellent result using half of the amount (0.25 mmol) of catalyst compared to that reported value (0.50 mmol) [11]. The results with ZnO are summarized in Table 5.

Catalytic activity of the transition metal oxides as a heterogeneous catalyst for *N*-acylation of amine are summarized in the Table 6. Here we can notice that, we got better result using less amount (0.25–0.05 mmol) of catalyst with respect to the
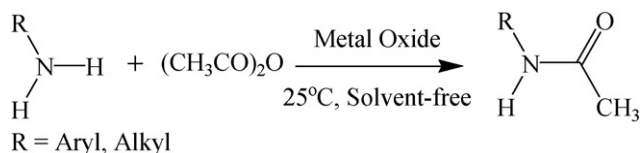
Scheme 2. *N*-Acylation of amine under solvent-free condition.

Table 5
Comparison of *N*-acylation of aniline (1 mmol) with acetic anhydride (1 mmol) by using commercial ZnO and macroporous ZnO

Entry	Catalyst	Amount of catalyst (mmol)	Time (min.)	Yield (%)[a]	Reference
1	Commercial ZnO	0.5	10	96	[11]
2		0.50	08	98	
3	ZnO (macroporous)	0.25	12	92	This
4		0.10	35	75	work
5		0.05	65	50	

[a] Yields are of the isolated compounds.

commercial powder ZnO. As shown in Table 6, the reaction of aniline (1 mmol) as a standard with acetic anhydride (1 mmol) was examined under various solvent-free reaction conditions. The best results were obtained using 0.05 mmol CuO, NiO, CoO, Mn_2O_3 and Cr_2O_3, whereas 0.50 mmol ZnO was required to carry out the same conversion as reported in literature [11].
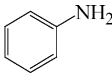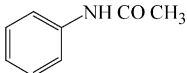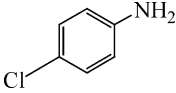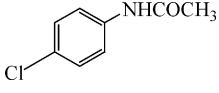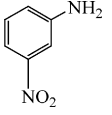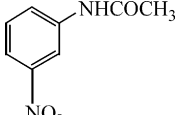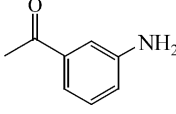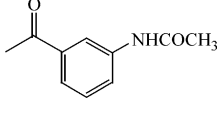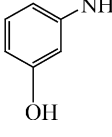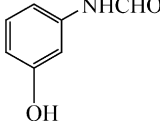
The experimental result of the acylation of different classes of amines are summarized in the Table 7. In these reactions, acetic anhydride was preferred over acid chlorides because amines reacted very rapidly to acid chlorides at room temperature, which makes it difficult to monitor the reactions. Acylation of aromatic amines containing both electron donating as well as electron withdrawing group (Table 7, entries 1–35) and aliphatic amines (Table 7, entries 36–40) were efficient as well as fast. Macroporous transition metal oxide catalyzed efficient *N*-acylation of amines are rare to the best of our knowledge. Recovery and catalytic activity of the catalyst were tested for three cycles and found that more that 90% catalyst was easily recovered. The catalytic activities of the recovered catalyst were examined as shown in the Table 8.

Table 6
N-Acylation of aniline (1 mmol) with acetic anhydride (1 mmol) at 25 °C
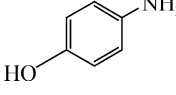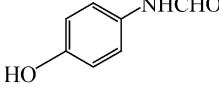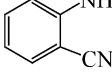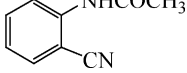
Entry	Catalyst	Catalyst (mmol)	Time (min)	Yield (%)[a]
1	CuO	0.05	10	95
2		0.10	15	90
3		0.20	15	80
4		0.50	25	70
5	NiO	0.05	15	98
6		0.10	20	95
7		0.20	30	93
8		0.50	30	90
9	CoO	0.05	15	98
10		0.10	30	95
11		0.20	40	90
12		0.50	40	80
13	Cr_2O_3	0.05	10	90
14		0.10	15	85
15		0.20	25	80
16		0.50	25	70
17	Mn_2O_3	0.05	15	90
18		0.10	25	80
19		0.20	40	80
20		0.50	40	70

[a] Yields are of the isolated compounds.

Table 7
N-Acylation of amine in presence of various metal oxides as heterogeneous catalyst

Entry	Substrates[a]	Product	Metal oxides (mmol)	Time (min)	Yield (%)[b]
1			CuO (0.05)	10	95
2			NiO (0.05)	10	98
3			CoO (0.05)	10	98
4			Mn$_2$O$_3$ (0.05)	10	90
5			Cr$_2$O$_3$ (0.05)	10	90
6			CuO (0.05)	15	95
7			NiO (0.05)	15	95
8			CoO (0.05)	20	95
9			Mn$_2$O$_3$ (0.05)	20	90
10			Cr$_2$O$_3$ (0.05)	25	88
11			CuO (0.05)	30	92
12			NiO (0.05)	40	90
13			CoO (0.05)	60	85
14			Mn$_2$O$_3$ (0.05)	65	85
15			Cr$_2$O$_3$ (0.05)	75	95
16			CuO (0.05)	15	96
17			NiO (0.05)	12	92
18			CoO (0.05)	20	96
19			Mn$_2$O$_3$ (0.05)	25	88
20			Cr$_2$O$_3$ (0.05)	25	85
21			CuO (0.05)	12	86
22			NiO (0.05)	15	90
23			CoO (0.05)	15	85
24			Mn$_2$O$_3$ (0.05)	30	90
25			Cr$_2$O$_3$ (0.05)	35	92
26			CuO (0.05)	15	96
27			NiO (0.05)	20	95
28			CoO (0.05)	20	95
29			Mn$_2$O$_3$ (0.05)	40	90
30			Cr$_2$O$_3$ (0.05)	35	88
31			CuO (0.05)	25	80
32			NiO (0.05)	30	80
33			CoO (0.05)	30	82
34			Mn$_2$O$_3$ (0.05)	45	75
35			Cr$_2$O$_3$ (0.05)	45	78
36			CuO (0.05)	10	92
37			NiO (0.05)	10	95
38	CH$_3$CH$_2$CH$_2$CH$_2$NH$_2$	CH$_3$CH$_2$CH$_2$CH$_2$NHCOCH$_3$	CoO (0.05)	12	92
39			Mn$_2$O$_3$ (0.05)	20	90
40			Cr$_2$O$_3$ (0.05)	15	90

[a] Yields are of the isolated compounds.

Table 8
Reuse of various metal oxides for *N*-acylation of amine
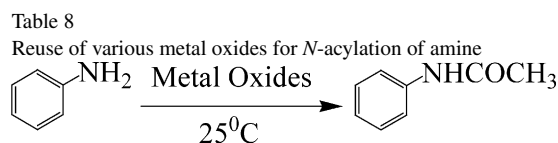
Catalyst (mmol)	Number of cycle	Yield (%)	Recovery of catalyst (%)
CuO (0.25)	1, 2, 3	95, 90, 87	96, 92, 92
NiO (0.20)	1, 2, 3	98, 94, 90	96, 93, 93
CoO (0.20)	1, 2, 3	98, 95, 92	95, 91, 91
Mn$_2$O$_3$ (0.05)	1, 2, 3	90, 84, 80	95, 91, 91
Cr$_2$O$_3$ (0.05)	1, 2, 3	90, 83, 80	95, 90, 90

2.3. Metal oxide-catalyzed acylation of phenols

In case of *O*-acylation phenols (Scheme 3) by macroporous ZnO, we again got better result using half of the amount (0.25 mmol) compared to the reported one (0.50 mmol) [11]. The results are summarized in Table 9. When we used other transition metal oxides as a heterogeneous catalyst as shown in Table 10, in each case we got better result with respect to the porous ZnO.

As shown in Table 10, the reaction of phenol (1 mmol) as a standard with acetyl chloride (1 mmol) was examined under various catalyst concentrations. The best results were obtained in solvent-free conditions using 0.20 mmol CuO (entry 2), 0.20 mmol CoO (entry 5), 0.20 mmol NiO (entry 8), 0.05 mmol

Table 9
Comparison of *O*-acylation of phenol (1 mmol) with acetyl chloride (1 mmol) by using commercially available ZnO and macroporous ZnO at 25 °C

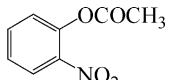| Entry	Catalyst	Catalyst (mmol)	Time (min.)	Yield (%)[a]	Reference
1	Commercial ZnO	0.50	15	94	[15]
2		0.50	08	96	
3		0.25	10	90	This
4	ZnO (macroporous)	0.10	15	78	work
5		0.05	45	57	

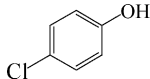[a] Yields are of the isolated compounds.

Table 10
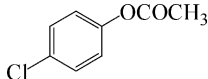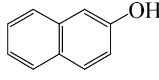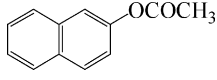*O*-Acylation of phenol (1 mmol) with acetyl chloride (1 mmol) at 25 °C
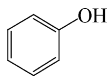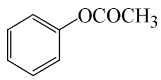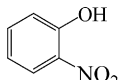
Entry	Catalyst	Catalyst (mmol)	Time (min)	Yield (%)[a]
1	CuO	0.10	15	80
2		0.20	10	95
3		0.30	25	95
4	CoO	0.10	20	60
5		0.20	10	95
6		0.30	25	90
7	NiO	0.10	15	80
8		0.20	10	92
9		0.30	20	88
10	Mn_2O_3	0.05	10	90
11		0.10	15	80
12		0.30	25	80
13	Cr_2O_3	0.05	10	85
14		0.10	15	80
15		0.30	25	70

[a] Yields are of the isolated compounds.

Scheme 3. *O*-Acylation of phenols under solvent-free condition.

Table 12
Reuse of various metal oxides for *O*-acylation of phenol
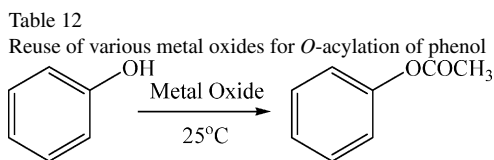
Catalyst (mmol)	Number of cycle	Yield (%)	Recovery of catalyst (%)
CuO (0.20)	1, 2, 3	95, 90, 86	95, 92, 92
NiO (0.20)	1, 2, 3	95, 90, 86	95, 92, 92
CoO (0.20)	1, 2, 3	90, 84, 80	95, 91, 91
Mn_2O_3 (0.05)	1, 2, 3	90, 86, 81	95, 91, 91
Cr_2O_3 (0.05)	1, 2, 3	85, 82, 78	95, 91, 91

Mn_2O_3 (entry 10) and 0.05 mmol Cr_2O_3 (entry 13); whereas, 0.50 mmol ZnO was reported in literature [11].

The results of *O*-acylation of different phenols are summarized in Table 11. For these set of reactions, acid chloride was preferred over corresponding acetic anhydride because reaction with acetic anhydride was too sluggish to have any practical applications. Phenolic compounds containing both electron-withdrawing and donating groups reacted almost equally efficiently under these reaction conditions. This is the first demonstration of the macroporous transition metal oxides based *O*-acylation reactions. The catalytic activity of the recovered catalyst were examined as shown in the Table 12, In
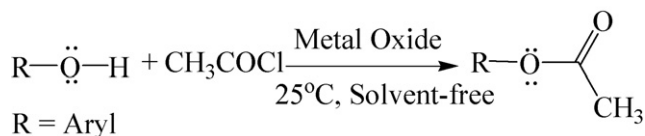
Table 11
O-Acylation of phenols in presence of metal oxides as heterogeneous catalyst at 25 °C

Entry	Substrates	Product	Metal oxides (mmol)	Time (min)	Yield (%)[a]
1	OH	OCOCH3	CuO (0.20)	10	95
2			NiO (0.20)	10	92
3			CoO (0.20)	10	95
4			Mn_2O_3 (0.05)	10	90
5			Cr_2O_3 (0.05)	10	85
6	OH, NO2	OCOCH3, NO2	CuO (0.20)	25	92
7			NiO (0.20)	25	90
8			CoO (0.20)	30	92
9			Mn_2O_3 (0.05)	40	88
10			Cr_2O_3 (0.05)	40	90
11	OH, Cl	OCOCH3, Cl	CuO (0.20)	12	90
12			NiO (0.20)	10	86
13			CoO (0.20)	15	90
14			Mn_2O_3 (0.05)	20	90
15			Cr_2O_3 (0.05)	20	90
16	OH	OCOCH3	CuO (0.20)	25	92
17			NiO (0.20)	30	95
18			CoO (0.20)	25	86
19			Mn_2O_3 (0.05)	45	85
20			Cr_2O_3 (0.05)	50	82

[a] Yields are of the isolated compounds.

Table 13

Comparison of O-acylation of ethanol (1 mmol) with acetyl chloride (1 mmol) by using commercially available ZnO and macroporous ZnO at 25 °C

Entry	Catalyst	Amount of catalyst (mmol)	Time (min)	Yield (%)[a]	Reference
1	Commercial ZnO	0.50	10	95	[11]
2		0.50	10	98	
3	ZnO (macroporous)	0.20	12	95	This
4		0.10	20	82	work
5		0.05	50	60	

[a] Yields are of the isolated compounds.

R—O—H + CH$_3$COCl $\xrightarrow[\text{25°C, Solvent-free}]{\text{Metal Oxide}}$ R—O—C(=O)—CH$_3$

R = Alkyl
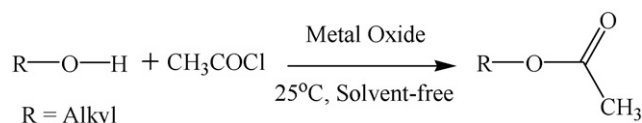
Scheme 4. O-Acylation of alcohols under solvent-free condition.

each case, after two and three reuses of these catalyst, almost >90% was easily recovered from the reaction mixture by simple washing with dichloromethane, which retain their catalytic activity.

2.4. Metal oxide-catalyzed acylation of alcohols

In case of acylation of alcohols (Scheme 4) by macroporous ZnO, we also got better result with lesser amount (0.20 mmol)

Table 14

O-Acylation of ethanol (1 mmol) with acetyl chloride (1 mmol) at 25 °C

Entry	Catalyst	Catalyst (mmol)	Time (min)	Yield (%)[a]
1	CuO	0.10	10	78
2		0.20	10	95
3		0.30	15	90
4	CoO	0.10	15	74
5		0.20	10	94
6		0.30	10	90
7	NiO	0.10	15	80
8		0.20	10	94
9		0.30	15	88
10	Mn$_2$O$_3$	0.05	15	92
11		0.10	25	80
12		0.30	25	80
13	Cr$_2$O$_3$	0.05	15	94
14		0.10	35	86
15		0.30	40	70

[a] Yields are of the isolated compounds.

of catalyst compared to the literature (0.50 mmol) as shown in Table 13 [11]. When we used other transition metal oxides as a heterogeneous catalyst as shown in Table 14, in each case we got better result by using less amount (0.25–0.05 mmol) of catalyst with respect to ZnO.

As shown in Table 14, the reaction of ethanol with acetyl chloride was examined under various reaction conditions in presence of different macroporous transition metal oxides.

Table 15

O-Acylation of alcohols in presence of metal oxides as heterogeneous catalyst at 25 °C

Entry	Substrates	Product	Metal oxides (mmol)	Time (min)	Yield %[a]
1			CuO (0.20)	10	95
2			NiO (0.20)	10	92
3	CH$_3$CH$_2$OH	CH$_3$CH$_2$OCOCH$_3$	CoO (0.20)	12	92
4			Mn$_2$O$_3$ (0.05)	15	85
5			Cr$_2$O$_3$ (0.05)	15	82
6	HO⌇OH	H$_3$COCO⌇OCOCH$_3$	CuO (0.20)	10	90
7			NiO (0.20)	12	88
8			CoO (0.20)	15	92
9			Mn$_2$O$_3$ (0.05)	25	90
10			Cr$_2$O$_3$ (0.05)	25	90
11	OH (sec-butyl)	OCOCH$_3$	CuO (0.20)	25	80
12			NiO (0.20)	25	76
13			CoO (0.20)	30	78
14			Mn$_2$O$_3$ (0.05)	35	72
15			Cr$_2$O$_3$ (0.05)	35	70
16	OH⌇OH	OCOCH$_3$⌇OCOCH$_3$	CuO (0.20)	20	90
17			NiO (0.20)	20	90
18			CoO (0.20)	25	86
19			Mn$_2$O$_3$ (0.05)	40	80
20			Cr$_2$O$_3$ (0.05)	45	78
21	OH (menthol)	OCOCH$_3$	CuO (0.20)	20	85
22			NiO (0.20)	20	80
23			CoO (0.20)	25	85
24			Mn$_2$O$_3$ (0.05)	30	78
25			Cr$_2$O$_3$ (0.05)	35	85

[a] Yields are of the isolated compounds.

Table 16
Reuse of various metal oxides for *O*-acylation of ethanol

$$CH_3CH_2OH \xrightarrow[25\,°C]{metal\ oxide} CH_3CH_2OCOCH_3$$

Catalyst (mmol)	Number of cycle	Yield (%)	Recovery of catalyst (%)
CuO (0.20)	1, 2, 3	95, 90, 86	96, 92, 92
NiO (0.20)	1, 2, 3	92, 85, 81	95, 92, 91
CoO (0.20)	1, 2, 3	92, 84, 78	95, 91, 91
Mn_2O_3 (0.05)	1, 2, 3	85, 80, 72	95, 90, 90
Cr_2O_3 (0.05)	1, 2, 3	82, 75, 70	95, 90, 90

The best results were obtained when 1 mmol of ethanol and 1 mmol of acetyl chloride were used in solvent-free conditions using 0.20 mmol CuO (entry 2), 0.20 mmol CoO (entry 5), 0.20 mmol NiO (entry 8), 0.05 mmol Mn_2O_3 (entry 10) and 0.05 mmol Cr_2O_3 (entry 13) as catalyst. However, 0.50 mmol ZnO was reported in literature for the same reaction [11].

Acylation of diverse range of alcohols *viz* primary alcohol (Table 15, entries 1–5), diol (Table 15, entries 6–10), secondary alcohol (Table 15, entries 11–15), bearing both primary as well as secondary alcohol group (Table 15, entries 16–20) and optically active alcohol (Table 15, entries 21–25) results in excellent yield without any side product. To the best of our knowledge, these reactions were never been reported by using these types of macroporous transition metal oxides as a heterogeneous catalyst. The catalytic activity of the recovered catalyst were examined as shown in the Table 16, In each case, after two and three recycles of these catalyst, almost >90% was easily recovered from the reaction mixture by simple washing with dichloromethane.

2.5. Metal oxide-catalyzed Friedel Craft acylation

Finally, we tried Friedel Craft acylation reaction also under solvent-free conditions using the various metal oxides as a heterogeneous catalyst.

For Friedel Craft acylation (Scheme 5) also we got better result using half the amount of macroporous ZnO (0.25 mmol) compared to the reported value [27]. The results with ZnO are summarized in Table 17. When we used other transition metal oxides as a heterogeneous catalyst as shown in the Tables 18 and 19 in each case we got better result by using less amount (0.25–0.05 mmol) of catalyst.

From the Table 18, it is clear that only Cr_2O_3 and CoO were catalyzing the Friedel Craft reaction while the other oxides *viz*. CuO, NiO and Mn_2O_3 were unable to catalyze this reaction. This is because in the course of the reaction, only Cr_2O_3 and CoO is generating *in situ* Lewis acids $CrCl_2$

$$RH + PhCOCl \xrightarrow[25\,°C,\ Solvent\text{-}free]{Metal\ Oxide} RCOPh$$

$$R = Aryl$$

Scheme 5. Friedel Craft acylation under solvent-free condition.

Table 17
Comparison of Friedel Craft acylation of toluene (1 mmol) with benzoyl chloride (1 mmol) by using commercially available ZnO and macroporous ZnO at 25 °C

Entry	Catalyst	Catalyst (mmol)	Time (min)	Yield (%)[a]	Reference
1	Commercial ZnO	0.50	10	86	[27]
2		0.50	05	95	
3	ZnO (macroporous)	0.25	08	88	This
4		0.10	25	78	work
5		0.05	30	56	

[a] Yields are of the isolated compounds.

Table 18
Friedel Craft acylation of toluene (1 mmol) with benzoyl chloride (1 mmol) at 25 °C

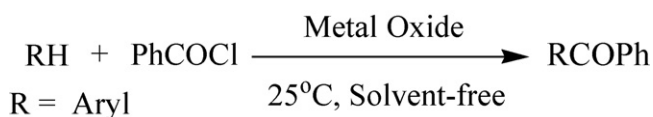| Entry	Catalyst	Catalyst (mmol)	Time (min)	Yield (%)[a]
1	Cr_2O_3	0.05	70	70
2		0.10	55	75
3		0.20	40	80
4		0.30	25	90
5		0.50	60	75
6	CoO	0.05	65	35
7		0.10	70	45
8		0.20	60	65
9		0.30	25	82
10		0.50	60	60

[a] Yields are of the isolated compounds.

and $CoCl_2$, respectively. Presence of Lewis acid is necessary for the Friedel Craft reaction. The best results were obtained when 1 mmol toluene is mixed with 1 mmol benzoyl chloride in solvent-free conditions using 0.30 mmol of Cr_2O_3 (entry 4) and CoO (entry 9).

The results of Friedel Craft acylation are summarized in the Table 19. Acylation occurs exclusively at the position para to –OMe, Me (Table 19, entries 1–4). Acylation of heterocylic compounds such as furan (Table 19, entries 7 and 8) forms 2-acylated product in excellent yield. In case of benzene and anthracene (Table 19, entries 5, 6, 9 and 10), as themselves are less reactive, hence produces very less yield. To the best of our knowledge, these reactions were also never been reported by using these macroporous transition metal oxides. Here also the catalytic activity of the recovered catalyst were examined as shown in Table 20, In each case, after two and three reuses of these catalyst, almost >90% was easily recovered from the reaction mixture by simple washing with dichloromethane.

3. Experimental section
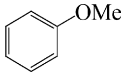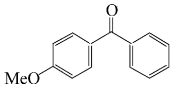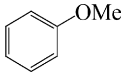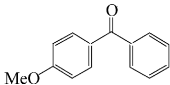
3.1. Materials and methods
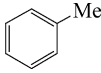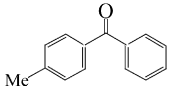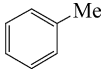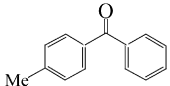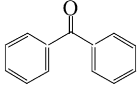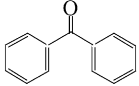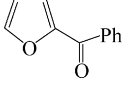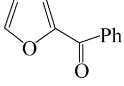
Reagents were purchased from commercial sources and, unless otherwise stated, were used as received. Agar agar, different metal salts, NaOH and substrates were purchased from Sigma–Aldrich Co. and used without further purification.

Table 19
Friedel Craft acylation in presence of metal oxides as heterogeneous catalyst at 25 °C

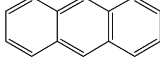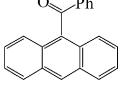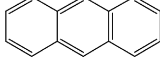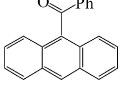| Entry	Substrates	Product	Metal oxides (mmol)	Time (min)	Yield (%)[a]
1	OMe	(structure)	Cr$_2$O$_3$ (0.30)	8	94
2			CoO (0.30)	10	90
3	Me	(structure)	Cr$_2$O$_3$ (0.30)	20	90
4			CoO (0.30)	20	82
5	(benzene)	(structure)	Cr$_2$O$_3$ (0.30)	120	55
6			CoO (0.30)	130	52
7	(furan)	Ph	Cr$_2$O$_3$ (0.30)	10	90
8			CoO (0.30)	12	90
9	(anthracene)	(structure)	Cr$_2$O$_3$ (0.30)	130	55
10			CoO (0.30)	140	54

[a] Yields are of the isolated compounds.

3.2. Preparation of macroporous metal oxides

We first prepared various transition metal and zinc hydroxides in 1.0% agar agar gel. After that metal hydroxides were kept in vacuum and finally the dried hydroxides were heated at ~600 °C for 6 h in a muffle furnace to get porous metal oxides. The oxides were characterized by scanning electron microscope, powder XRD and FT-IR.

3.3. General procedure for N-formylation

To a mixture of HCO$_2$H (2.5–3.0 mmol) and metal oxides (0.05–0.50 mmol) was added an amine (1 mmol). The reaction mixture was heated in an oil bath at 70 °C with continuous stirring. The progress of the reaction was monitored by TLC. After the completion of the reaction, CH$_2$Cl$_2$ was added to the cooled reaction mixture and then filtered to remove the metal oxides. The organic solvent was washed with H$_2$O and a saturated solution of NaHCO$_3$ and dried over anhydrous Na$_2$SO$_4$. After removal of organic solvent, the pure product was obtained. The final product was confirmed by ^{1}H NMR, FT-IR and compared with authentic samples obtained commercially or prepared by reported methods [4].

Table 20
Reuse of various metal oxides for Friedel Craft acylation

Catalyst (mmol)	Number of cycle	Yield (%)	Recovery of catalyst (%)
Cr$_2$O$_3$ (0.30)	1, 2, 3	90, 84, 80	96, 92, 91
CoO (0.30)	1, 2, 3	82, 76, 72	95, 91, 90

3.4. General procedure for acylation of amines, alcohols and phenols

To a mixture of metal oxides (0.05–0.5 mmol) and an acid chloride or anhydride (1 mmol), alcohol, phenol or amine (1 mmol) was added. In case of diols double molar equivalents of metal oxides as well as acid chloride was used. The reaction mixture was stirred with a mechanical stirrer for a certain period of time as required to complete the reaction (monitored by TLC) at room temperature. The solid mixture was then eluted with CH$_2$Cl$_2$, and the CH$_2$Cl$_2$ extract was then washed with an aqueous solution of NaHCO$_3$ and dried over anhydrous Na$_2$SO$_4$. Evaporation of solvent furnished the corresponding product. The identity of these compounds was easily established by comparison of their ^{1}H NMR spectra, FT-IR with those of authentic samples [11,30].

3.5. General procedure for Friedel Craft acylation

To a mixture of metal oxides (0.05–0.5 mmol) and an acid chloride (1 mmol), aromatic compound (1 mmol) was added. The reaction mixture was stirred for a certain period of time as required to complete the reaction (monitored by TLC) at room temperature. The solid mixture was then eluted with CH$_2$Cl$_2$, and the CH$_2$Cl$_2$ extract was then washed with an aqueous solution of NaHCO$_3$ and dried over anhydrous Na$_2$SO$_4$. Evaporation of organic solvent furnished the corresponding product. The identity of these compounds was easily established by comparison of their ^{1}H NMR and FT-IR spectra with those of authentic samples [30,31].

4. Conclusions

In conclusion, we have presented here a comparative study of five macroporous transition metal oxides and zinc oxide as

an efficient eco-friendly heterogeneous catalyst for different organic reactions. This is a simple, solvent-free and efficient protocol. The significant features of this method include its ease of operation, low cost of the catalyst, mild conditions, clean reaction condition, high yields, green in nature. Due to the presence of large internal surface area and pore volume, porous metal oxides has control over the diffusion of both reagents and products into and out of the porous medium. Simultaneously they have a control over the possible reaction intermediates that might form within the pore system. Optimum amount of the catalyst depends on the type of the metal oxide as well as the type of reactions. In all four transformations *viz. N*-formylation, *N*-acylation, *O*-acylation and Friedel Craft acylation, we observed a reduction in the yield of product, with the increasing the amount of catalyst. This is because with increase the amount of catalyst beyond the optimum value, they have a tendency to form aggregated cluster. Thus there is a reduction in the effective internal surface area and pore volume of the catalyst. Hence, there is a significant reduction in their catalytic activity. In this study, we got very encouraging result in all the transformations with the porous metal oxides. However, in case of Friedel Craft acylation only macroporous CoO and Cr_2O_3 has shown significant result compared to the reported methods.

Acknowledgments

References

[1] M. Lakshmi Kantam, K.B. Shiva Kumar, C. Sridhar, Adv. Synth. Catal. 347 (2005) 1212.

[2] A. Jackson, O. Meth-Cohn, J. Chem. Soc., Chem. Commun. (1995) 1319.

[3] T.W. Green, P.G.M. Wuts, Protective Groups in Organic Synthesis, 3rd ed., Wiley–Interscience, New York, 1999.

[4] M. Hosseini Sarvari, H. Sharghai, J. Org. Chem. 71 (2006) 6652.

[5] F.E. Koehn, R.E. Longley, J.K. Reed, J. Nat. Prod. 55 (1992) 613.

[6] G.R. Pettit, Y. Kamano, C. Dufresne, R.L. Cerny, C.L. Herald, J.M. Schmidt, J. Org. Chem. 54 (1989) 6005.

[7] J.R. Gage, D.A. Evans, Org. Synth. 68 (1989) 83.

[8] R.H. Mattern, S.P. Gunasekera, O.J. McConnell, Tetrahedron Lett. 38 (1997) 2197.

[9] C. Tomasini, M. Villa, Tetrahedron Lett. 42 (2001) 5211.

[10] G.J. Ho, D.J. Mathre, J. Org. Chem. 60 (1995) 2271.

[11] M. Hosseini Sarvari, H. Sharghai, Tetrahedron 61 (2005) 10903.

[12] J. Otera, Esterification, Wiley–VCH, Weinheim, 2003.

[13] T.W. Green, P.G.M. Wutz, Protective Groups in Organic Synthesis, vol. II, Wiley, New York, 1991.

[14] V.K. Yadav, K.G. Babu, M. Mittal, Tetrahedron 57 (2001) 7047.

[15] H.H. Bear, F.H. Mateo, Can. J. Chem. 68 (1990) 2055.

[16] T.S. Jin, Y.R. Ma, Z.H. Zhang, T.S. Li, Synth. Commun. 28 (1998) 3173.

[17] A. Orita, K. Sakamoto, Y. Hamadu, A. Mitsutome, J. Otera, Tetrahedron 55 (1999) 2899.

[18] R. Dalpozzo, A. DeNino, L. Maiuolo, A. Procopio, M. Nardi, G. Bartoli, R. Romeo, Tetrahedron Lett. 44 (2003) 5621.

[19] H. Firouzabadi, N. IranPoor, K. Amani, Chem. Commun. 6 (2003) 764.

[20] A.K. Chakraborti, R. Gulhane, Synlett 4 (2004) 657.

[21] R. Ghosh, M. Swarupananda, A. Chakraborty, Tetrahedron Lett. 46 (2005) 177.

[22] A.K. Chakraborti, R.G. Shivani, Synlett 12 (2003) 1805.

[23] F. Tamaddon, Md.A. Amrollahi, L. Sharafat, Tetrahedron Lett. 46 (2005) 7841.

[24] R. Noyori, Adv. Synth. Catal. 345 (2003) 15.

[25] G.A. Olah, Friedel–Crafts Chemistry, Wiley–Interscience, New York, 1973.

[26] T.W. Bastock, J.H. Clark, P. Landon, K. Martin, J. Chem. Res., Synop. (1994) 104.

[27] M. Hosseini Sarvari, H. Sharghai, J. Org. Chem. 69 (2004) 6953.

[28] M.E. Davis, Nature 417 (2002) 813.

[29] H. Thakuria, B.M. Borah, G. Das, Eur. J. Inorg. Chem. 4 (2007) 524.

[30] CRC, Handbook of Tables for Organic Compound Identification, 53rd and 54th ed., Chemical Rubber Co., Cleveland, 1967.

[31] S. Paul, P. Nand, R. Gupta, A. Loupy, Synthesis 18 (2003) 2877.