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Hydromagnesite as an Efficient Recyclable Heterogeneous Solid Base Catalyst for the Synthesis of Flavanones, Flavonols and 1,4-Dihydropyridines in Water

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Abstract: A form of hydromagnesite (HM) with flower-like thin-sheet morphology was synthesized by an environmentally benign approach using simple conventional heating at moderate temperature without using any template in water as medium. The versatility of this HM catalyst was studied in the synthesis of flavanones, flavonols and the multicomponent synthesis of 1,4-dihydropyridines in water. The recyclability of catalyst was studied for six times and there was no appreciable loss in its catalytic activity.

Keywords: 1,4-dihydropyridines; flavonols; flavanones; heterogeneous solid base catalyst; hydromagnesite

Introduction

Although many organic reactions can be promoted by homogeneous or heterogeneous catalysis, the later method offers many advantages such as easy work-up, recyclability and less waste production.[1] The global concern about the climate change, energy production and conservation has prompted scientists to develop novel heterogeneous catalysts for industrial processes. The development of solid base catalysts for an environmentally friendly synthesis of fine chemical or organic intermediates is an important research topic for the green and sustainable society. The ultimate goal of heterogeneous catalysis must be 100% product selectivity, which eliminates the unwanted side products and allows the process to be greener. Among the heterogeneous catalysts, nano-structured inorganic materials have received considerable attention and it has been well established that, depending on the shape and size of the pores, these materials can exhibit different activities in organic reactions.[2] Magnesium oxide is one such inorganic material, which has been employed as a heterogeneous catalyst in various organic reactions.[3] Magnesium oxide is prepared from hydromagnesite at very high temperature (>450 °C) and it releases carbon dioxide which makes this process environmentally unfriendly.[4–6] In addition, MgO-catalyzed reactions generally require longer reaction times and toxic organic solvents which limits their efficacy towards greener methodologies.

This prompted us to study the catalytic potential of hydromagnesite, which has found applications in rubber, plastic and fire retardant industries,[7] but the catalytic potential was seldom examined. Hydromagnesite, the precursor of MgO, is a hydrated basic magnesium carbonate mineral with the formula $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$, it has a three-dimensional framework of MgO_6 octahedra and triangles of carbonate ions (Figure 1).[8] It is the only species which is stable under atmospheric conditions among the six known magnesium carbonates found in nature, the other five being magnesite ($MgCO_3$), nesquehonite

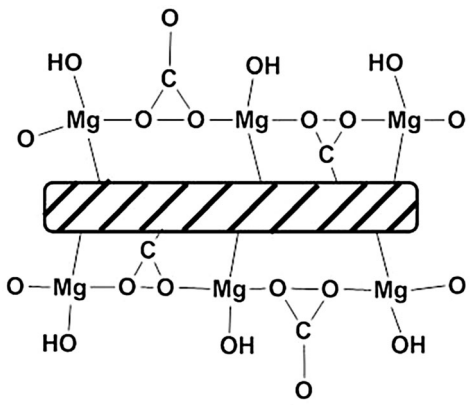


Figure 1. General representation of the surface of hydromagnesite (striped part represents the MgO_6 octahedra in a three-dimensional arrangement[8]).

($MgCO_3 \cdot 3H_2O$), lansfordite ($MgCO_3 \cdot 5H_2O$), artinite [$MgCO_3 \cdot Mg(OH)_2 \cdot 3H_2O$], and dypingite [$4MgCO_3 \cdot Mg(OH)_2 \cdot 5H_2O$).[8]

Several groups have reported the synthesis of different morphological forms of hydromagnesite during the preparation of MgO.[4,5] There are only two reports on the catalytic activity of hydromagnesite: Dai et al. reported hydromagnesite as an effective catalyst in the Baeyer–Villiger oxidation of cyclohexanone and, more recently, Ebitani et al. reported that the coexistent hydromagnesite increased the catalytic activity of hydrotalcite catalyst for transesterifications of glycols into cyclic carbonates.[9,10] Taking account of these observations, and in continuation of our work on developing novel recyclable heterogeneous catalysts for the synthesis of bioactive molecules,[11] we anticipated that hydromagnesite could be used as better single site catalyst over MgO in water medium due to the presence of basic and hydrophilic OH^-, HCO_3^- groups on its surface.[9] We report herein the synthesis of hydromagnesite (HM) with a flower-like sheet morphology by a modified literature method[4] and its catalytic potential in the synthesis of medicinally important flavanones, flavonols and 1,4-dihydropyridines in aqueous media. Flavanones and flavonols belong to a class of flavonoid natural products which exhibit various biological properties including anticancer, antibacterial, antifungal, antileishmanial, antitrypanosomal, antioxidant and α-glucosidase inhibitory activities.[12]

In general, flavanones have been synthesized under homogeneous conditions using $Ca(OH)_2$, KOH, NaOH, piperidine, K_2CO_3, proline, H_2SO_4, H_3PO_4 etc., and heterogeneous catalysts such as hydrotalcites, zeolites, silica hydroxyapatite, MgO, KF/natural phosphate, alumina supported $CeCl_3 \cdot 7H_2O$, NaI etc.[13] There have been limited reports found on the synthesis of 2,3-dihydroflavonol.[14] However, the conversion of chalcone into flavanone and 2,3-dihydroflavonol has limitations such as low conversion, high temperature, toxic organic solvents, non-recyclable catalysts and usage of additives etc. In contrast, hydromagnesite as catalyst has become increasingly appealing because of its affordability, low toxicity, greener, sustainable and environmentally benign nature and which, in addition, explores the superior catalytic activity as a novel solid base catalyst.

To the best of our knowledge this is the first report on the synthesis of a flower-like thin-sheet morphology of hydromagnesite and its catalytic application in the synthesis of flavanones, flavonols and 1,4-dihydropyridines in aqueous medium. This opens up a new direction for the exploration of the catalytic potential of the hydromagnesite, a precursor of magnesium oxide, a well-known catalyst for many organic transformations.

Results and Discussion

Preparation and Characterization of the Catalyst

Hydromagnesite was prepared as described in the Experimental Section and characterized by the powder X-ray diffraction technique. The pattern could be indexed in monoclinic symmetry (space group p2/c) with refined lattice parameters of $a = 10.0451(2)$, $b = 8.9046(6)$, $c = 8.3542(3)$ Å and $\beta = 114$ °C. The average crystallite size is 20 nm as estimated by the Scherrer analysis. All the reflections matched well with the reported ones (JCPDS File No: 25-513) (Figure 2a).[4] The lattice parameters were obtained from the Le-bail fitting of the X-ray diffraction pattern using the program Full Prof suite (Figure 2b).[15]

The surface morphology of HM was revealed as a flower-like arrangement of sheets (Figure 3), which was further supported by the transmission electron microscopy (TEM) images as shown in Figure 2c. The

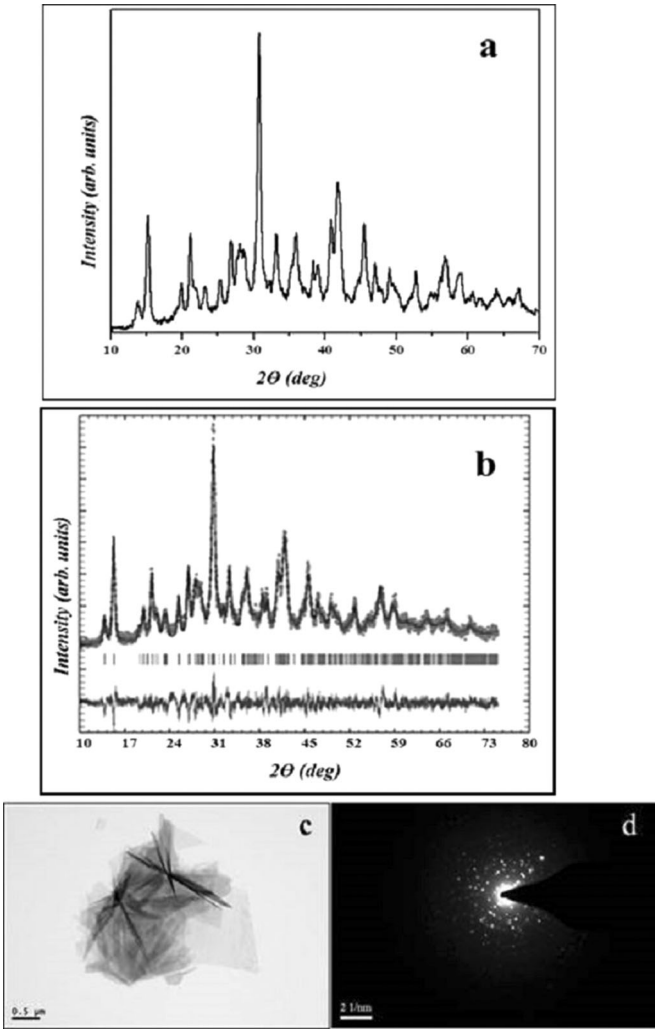


Figure 2. (a) PXRD and (b) Le Bail fitting of PXRD; (c) TEM and (d) SAED images of hydromagnesite.

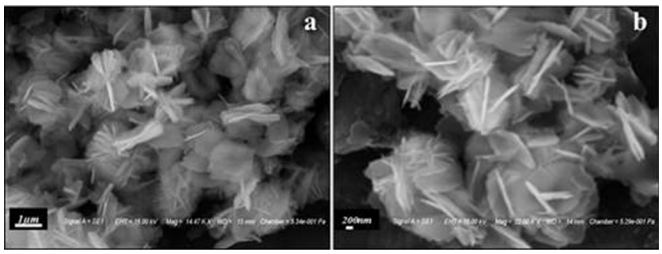


Figure 3. (a) and (b) SEM images of hydromagnesite.

higher intense peaks in the powder XRD pattern indicate the high crystallinity of the prepared hydromagnesite material (Figure 2). Morever, it was further supported by the selected area electron diffraction (SAED) image (Figure 2d and see the Supporting Information for the EDX pattern of HM).

The BET surface area and pore volume of HM were calculated, and found to be 45.5 $m^2 g^{-1}$ and 0.15 $cm^3 g^{-1}$, respectively. The concentration of basic sites of HM was calculated using titration method, and found to be 21.7 mmol g^{-1}.

The room temperature FT-IR spectrum (Figure 4) shows the asymmetric stretching vibration of carbonate ion split into two bands at 1485 and 1420 cm^{-1} (ν_3 mode). In addition the characteristic crystalline water is observed as strong bands at 3524 and 3453 cm^{-1}. Moreover, an almost free O–H symmetric stretching vibration band is seen at 3650 cm^{-1} and all the other bands are in good agreement with the reported data.[4]

The thermal decomposition study of HM was studied by using TGA analysis under an N_2 atmosphere as shown in Figure 5.

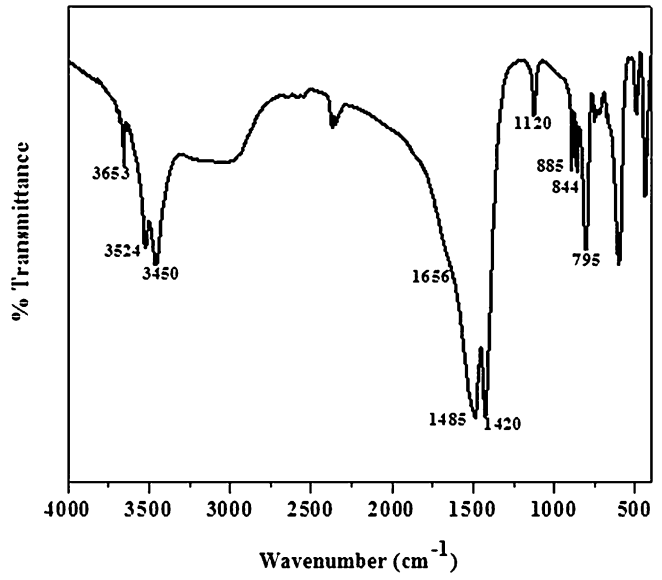


Figure 4. FT-IR of hydromagnesite.

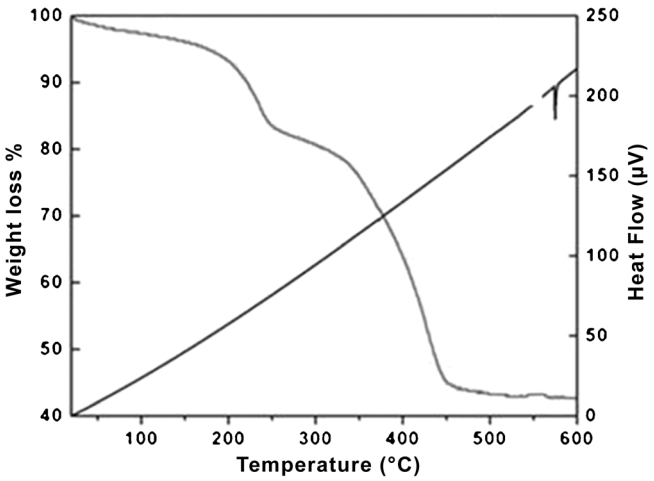
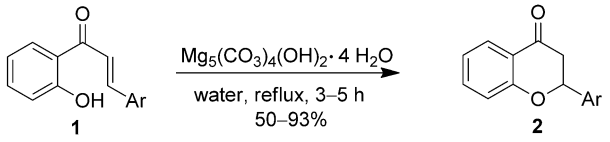


Figure 5. TGA of hydromagnesite.

The first weight loss (17.8%) was attributed to the dehydration of crystalline water and dehydroxylation process at 100–280 °C, and the second weight loss (37.9%) was due to the evolution of CO_2 at 280–480 °C. The total weight loss in both the steps is summed up to 55.7%, which is close to a predicted theoretical weight loss of 56.7% for the stoichiometric conversion of hydromagnesite to MgO.[16]

Initially, the catalytic potential of as synthesized HM material was studied as a heterogeneous solid base catalyst in the synthesis of flavanones through intramolecular oxa-Michael addition involving cyclization of 2′-hydroxychalcones (Scheme 1). The reaction worked best when HM was taken as catalyst and water as solvent.

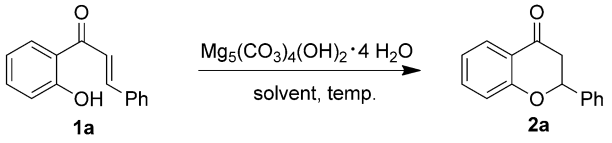


Scheme 1.

For the preliminary study and optimization of the reaction conditions involving flavanones (**2**), we studied the intramolecular oxa-Michael cyclization of 2′-hydroxychalcone (**1a**) in the presence of hydromagnesite as a catalyst. At first, the reaction was carried out in the presence of various dry organic solvents under conventional heating, generally at their reflux temperatures. This afforded the flavanone **2a** in poor to moderate yields as shown in Table 1.

Interestingly, excellent results were obtained when the cyclization was performed in water as a solvent at reflux temperature, which afforded the product in 85% isolated yield and it was observed that yield of the product **2a** drops significantly at lower tempera-

Table 1. Optimization of the reaction conditions for the synthesis of flavanone **2a** under conventional heating.[a]



Entry	Solvent	Temp. [°C]	Time [h]	Yield[b] [%]
1	tetrahydrofuran	75	5	10
2	toluene	110	5	30
3	acetonitrile	90	5	32
4	1,4-dioxane	110	5	36
5	acetone	65	4	45
6	PEG-400	120	2	70
7	PEG-600	120	2	73
8	ethylene glycol	120	2	65
9	ethanol	85	3	45
10	water	100	3	85
11	water	70	3	35
12	water	50	3	20
13	water	25	3	–

[a] *Reaction conditions:* 2-hydroxychalcone (1 mmol), HM catalyst (50 mol%) in 3 mL of solvent, reflux conditions.
[b] Isolated yield.

ture and no product formation was observed at room temperature (Table 1, entries 10–13). The optimization and standardization of reaction conditions revealed that HM (50 mol%) as a catalyst, in water as solvent at 100 °C are the optimum conditions for the preparation of these biologically active molecules (see the Supporting Information for a catalyst loading study).

These optimized conditions were further used to explore the generality of the reaction and a series of flavanones bearing electron-donating and electron-withdrawing substituents on the phenyl ring were synthesized (Table 2, **2a**–**2n**). The study revealed that the electron-withdrawing substituents enhanced the rate of reaction and gave good isolated yield (**2b**–**2d**). Moreover, the presence of halogens (chloro, bromo and fluoro) at the *para* position of the benzene ring gave moderate yields of 50–68% (**2j**, **2k** and **2m**). On the other hand, chloro substitution at the *meta* position improved the yield to 75% (**2l**). As soon as they were replaced with electron-donating groups like Me, *i*-Pr, *t*-Bu (Table 2, **2e**–**2g**) yields dropped significantly from 65 to 55%. Also, the presence of a strong electron-donating group like methoxy at the *para* position gave a moderate yield, whereas such substitution at the *meta* position improved the yield (Table 2, **2h** and **2i**).

Next, we studied the comparative catalytic activity of HM with other commercially available base catalysts under our optimized conditions and found that HM was the most suitable catalyst that can be employed for this reaction The reactions with other base catalyst gave poor yields (Table 3, entries 2 to 7) and in the presence of Lewis acid catalysts either trace amounts or no product formation was observed. Without catalyst, the reaction did not proceed even after a prolonged time under the optimized conditions. This gives an insight that addition of catalyst is crucial for driving the course of the reaction.

In order to further explore the catalytic activity of hydromagnesite, we studied this catalyst for the syn-

Table 2. Hydromagnesite-catalyzed intramolecular oxa-Michael addition of 2-hydroxychalcones (**1a**–**n**) to afford flavanones (**2a**–**n**) at 100 °C in water as solvent.[a]

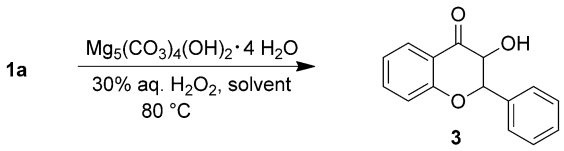
Compound	Ar	Time [h]	Conversion[b] [%]	Yield[c] [%]	Observed mp [°C]	Lit. mp [°C]
2a	C_6H_5	3	94	85	78–79	77–78[17]
2b[d]	3-C_5H_4N	3	96	88	liquid	unknown
2c	2-$NO_2C_6H_4$	3	90	84	123–125	121–122[22]
2d	4-$NO_2C_6H_4$	3	97	93	155–157	156–157[22]
2e	4-MeC_6H_4	4	73	65	69–70	68–70[17]
2f	4-*i*-PrC_6H_4	4	70	60	75–76	76–77[18]
2g	4-*t*-BuC_6H_4	4	63	55	105–107	104[19]
2h	4-$MeOC_6H_4$	4	72	65	95–96	95–97[17]
2i	3-$MeOC_6H_4$	3	88	83	78–79	79–80[17]
2j	4-FC_6H_4	5	62	53	79–80	78–79[20]
2k	4-ClC_6H_4	5	76	68	83–85	84–85[17]
2l	3-ClC_6H_4	4	84	75	96–98	97–99[21]
2m	4-BrC_6H_4	5	60	50	118–119	117[17]
2n	piperonyl	4	72	60	124–126	125–126[17]

[a] *Reaction conditions:* 2-hydroxychalcone (1 mmol), HM catalyst (50 mol%) in 3 mL of solvent, reflux conditions.
[b] Conversion was determined by ^{1}H NMR spectroscopy of the crude reaction mixture.
[c] Yield refer to isolated pure products.
[d] Compound **2b** is a liquid.

Table 3. Role of the catalyst in the synthesis of flavanone **2a** in water.[a]

Entry	Catalyst[b]	Yield[c] [%]
1	HM	85
2	$(MgCO_3)_4{\cdot}Mg(OH)_2{\cdot}5H_2O$	40
3	$Mg(OH)_2$	38
4	MgO	45
5	CaO	30
6	K_2CO_3	45
7	Al_2O_3	20
8	I_2	trace
9	$FeCl_3$	trace
10	$BF_3{\cdot}OEt_2$	no reaction
11	no catalyst	no reaction

[a] *Reaction conditions:* 2-hydroxychalcone (1 mmol), HM catalyst (50 mol%) in 3 mL of water, reflux conditions.
[b] All are commercially available bulk materials except for HM (hydromagnesite with flower-like sheet morphology).
[c] Isolated yield of pure products.



Scheme 2.

thesis of 2, 3-dihydroflavonol (**3**) starting from compound **1a** (Scheme 2).

It was found that a 30% aqueous solution of H_2O_2 and hydromagnesite (50 mol%) as a catalyst at a temperature of 80 °C in water as solvent were the optimum conditions (see the Supporting Information for a catalyst loading study) and led to the desired product selectively with good yields (Scheme 2). In order to get an insight into the mechanism, the samples were collected from the reaction mixture at different time intervals and analyzed by ^1H NMR spectroscopy, no peaks were observed corresponding to an epoxide intermediate. This gives a clear idea about the highly reactive and unstable nature of the epoxide intermediate, and that it cyclized to yield 2,3-dihydroflavonol (**3**) (Figure 6).

Moreover, in order to study the utility of hydrogen peroxide in the reaction, the effective concentration of H_2O_2 was calculated after completion of the reaction and it was observed that approximately 87% of H_2O_2 was utilized in the reaction.[23] Table 4 depicts the role of solvent for the optimization of the reaction conditions involving the synthesis of 2,3-dihydroflavonol (**3**).

We further investigated the efficacy of HM catalyst in terms of the formation of flavanone *versus* time in comparison with other Mg-based catalysts as shown in Figure 6.

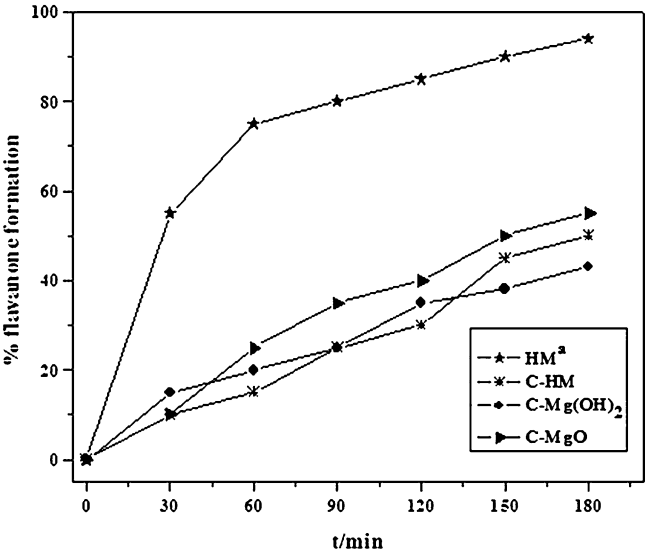


Figure 6. Comparative study of hydromagnesite flower-like sheets (HM) with other magnesium-based catalysts in the synthesis of flavanone **2a** under our optimized conditions. [a] Hydromagnesite flower-like sheet (HM, BET: 45.5 m^2g^{-1}); C-HM = $[(MgCO_3)_4{\cdot}Mg(OH)_2{\cdot}5H_2O$; BET: 10.3 m^2g^{-1}], C-$Mg(OH)_2$ (BET: 12 m^2g^{-1}) and C-MgO (BET: 14.5 m^2g^{-1}) are commercially available bulk materials.

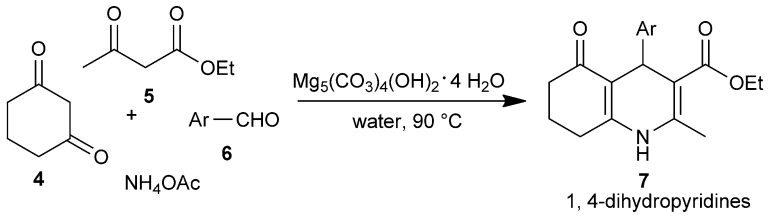
Table 4. Role of the solvent for the HM-catalyzed synthesis of 2,3-dihydroflavonol (**3**).[a]

Entry	Solvent	Temp. [°C]	Time [h]	Yield[b] [%]
1	ethanol	80	4	60
2	acetone	65	4	50
3	PEG-400	80	4	48
4	PEG-600	80	4	55
5	glycerol	80	3	62
6	**water**	**80**	**2**	**75**
7	water	25	6	–

[a] *Reaction conditions:* 2-hydroxychalcone (1 mmol), HM catalyst (30 mol%), 30% H_2O_2 (0.6 mL) in 3 mL of solvent at 80 °C.
[b] Isolated yield.

We found that HM catalyst was far superior to other Mg-based catalysts and interestingly 75% flavanone formation was observed in 30 min to 1 h and finally reached 94% in 3 h. In contrast, in the presence of other Mg-based catalysts the reaction was sluggish with poor conversions of about 40–50% in 3 h.

To explore the versatility of HM catalyst in water medium, we studied the multicomponent one-pot synthesis of 1,4-dihydropyridines. The four-component Hantzsch reaction provides access to 1,4-dihydropyridines that are known to have a wide range of biologi-



Scheme 3.

cal properties such as antitumour, antidiabetic agents, Alzheimer, vasodilator, antiatherosclerotic, geroprotective, hepatoprotective and cardiovascular agents.[24]

The model reaction (Scheme 3) was performed by condensation of benzaldehyde, 1,3-cyclohexanedione, ethyl acetoacetate, ammonium acetate and HM catalyst (30 mol%) in water at 90 °C for 20 min and gave the 1,4-dihydropyridine (**7a**) with 93% isolated yield (see Supporting Information for a catalyst loading study).

The model reaction was also carried out in the absence of catalyst with optimized conditions, but the reaction was sluggish with 30% yield in 6 h. With these interesting results in our hands, we further studied the electronic effect of the aromatic aldehyde in the one-pot synthesis of 1,4-dihydropyridines (Table 5, **7a**–**7k**). Substrates having electron-donating groups like OMe, Me at *para*, *meta* and *ortho* positions showed more reactivity and gave excellent yields (90–98%) within the time intervals of 20–35 min (Table 5, **7f**–**7j**). In contrast, those substrates having electron-withdrawing groups like NO_2, Cl at *para*, *meta* and *ortho* positions showed relatively less reactivity with good yields (80–87%) in 40–45 min (Table 5, **7b**–**7e** and **7k**).

Table 5. HM-catalyzed multicomponent synthesis of 1,4-dihydropyridines in water.[a]

Compound	Ar	Time [min]	Yield[b] [%]	Observed/Lit mp [°C]
7a	C_6H_5	25	93	239–240/240–241[25]
7b	2-$NO_2C_6H_4$	45	80	192–194/190–191[25]
7c	3-$NO_2C_6H_4$	45	83	201–202/198–200[25]
7d	4-$NO_2C_6H_4$	45	86	205–207/204–205[25]
7e	4-ClC_6H_4	45	87	235–237
7f	4-$MeOC_6H_4$	20	95	192–194/193–195[25]
7g	3-$MeOC_6H_4$	35	91	197–199/unknown
7h	3,4-$MeO_2C_6H_3$	20	94	193–195/192–194[26]
7i	3,4,5-$MeO_3C_6H_2$	20	98	182–184/180–182[26]
7j	4-MeC_6H_4	30	92	241–243/241–242[25]
7k	2,4-$Cl_2C_6H_3$	40	85	245–247/unknown

[a] Aldehyde (1 mmol), 1,3-cyclohexanedione (1 mmol), ethyl acetoacetate (1 mmol), NH_4OAc (1.5 mmol) and HM catalyst (30 mol%) in water (2 mL) at 90 °C.
[b] Isolated yield.

The possible mechanism for the formation of flavanone and 2,3-dihydroflavonol is represented in Figure 7. Probably, the basic sites (OH^- or HCO_3^-) of HM catalyst abstract the proton from 2-hydroxychalcone **1a** to initiate an intramolecular oxa-Michael addition[27] and give the intermediate **I**, where the Lewis-acidic site Mg^{2+} of HM catalyst stabilizes the negative charge on the carbonyl oxygen to yield the flavanone **2a**. In a second pathway, H_2O_2 attacks a basic hydroxy or carbonate function on the surface of hydromagnesite to form an HOO^- species,[9,28] and this reacts with the olefinic bond of substrate **1a** to yield the epoxide intermediate **III**, the isolation of which from the reaction mixture, is not possible and a selective intramolecular nucleophilic addition at the β-position of the epoxide ring yields 2,3-dihydroflavonol (**3**).[29]

Thus, hydromagnesite with its flower-like sheets, its defined shape, size, high surface area and accessible basic HCO_3^-, ^-OH as well as Lewis acidic Mg^{2+} sites allows the chemisorption of substrates on its surface to evolve the single-site catalyst by the successful transfer of molecular chemistry to surface metal-organic chemistry to furnish the corresponding products selectively.

The recyclability of hydromagnesite catalyst was examined in the intramolecular oxa-Michael addition of 2-hydroxychalcone (**1a**) to flavanone (**2a**) and also in the synthesis of 3-hydroxyflavanone (**3**) under the optimized conditions. The results show that there is no loss of catalyst activity even after six cycles as shown in Figure 8 (see the Supporting Information for SEM and XRD images of the recycled catalyst). For this recycling study of hydromagnesite catalyst, after each cycle the catalyst was washed with ethanol and dried at 80 °C in an oven.

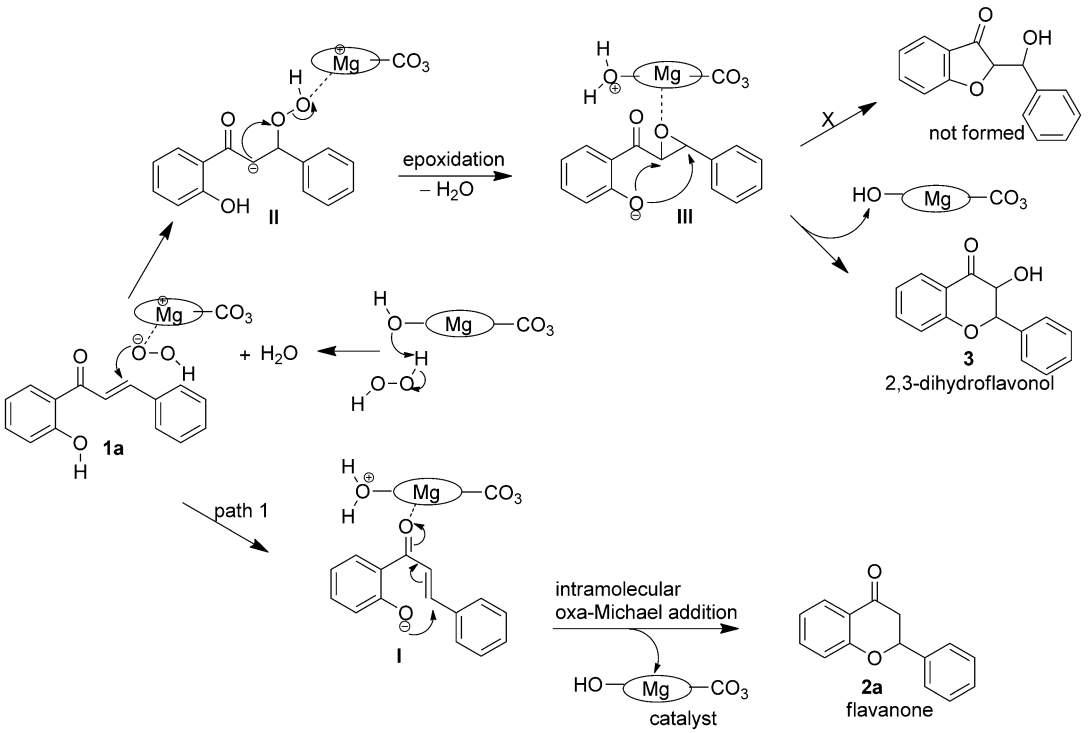


Figure 7. Plausible mechanism for the formation of flavanone **2a** and 2,3-dihydroflavonol **3**.

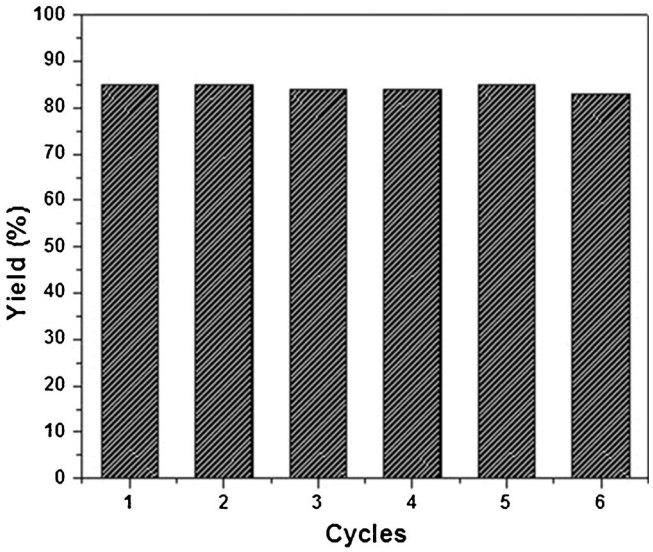


Figure 8. Recycling study of hydromagnesite catalyst for the synthesis of flavanone **2a**.

Conclusions

In conclusion, we have succeeded in the synthesis of hydromagnesite (HM) with flower-like thin-sheet morphology as a novel green catalytic system for the synthesis of biologically active flavanones, flavonol and 1,4-dihydropyridines in water medium for the first time. Moreover, the selective conversion of 2-hydroxychalcone to 2,4-dihydroflavanol was achieved with good yield. The excellent performance of the hydromagnesite catalyst in water medium may be due to flower-like thin-sheet morphology with high surface area and also the presence of hydrophilic interactions of HCO_3^- and OH^- groups on its surface.

Experimental Section

Preparation of the Catalyst

$MgCl_2 \cdot 6H_2O$ (3.76 g) was dissolved in 33 mL of freshly prepared urea solution (6 M) and mixed with 43 mL of ethylene glycol in a 100-mL round-bottom flask. The reaction mixture was heated at 110 °C for 5 h under continuous stirring (600 rpm). The precipitated hydromagnesite was collected by filtration and washed several times with deionized water followed by final washing with ethanol. The thus obtained hydromagnesite was dried at 80 °C for 6 h in oven.

Characterization

TG-DTA analysis (PerkinElmer, Pyris Diamond) with a heating rate of 10 °C min^{-1} in a nitrogen atmosphere was used to study the thermal decomposition behaviour of the as-prepared (dried) sample with respect to α-Al_2O_3 as the reference. X-ray diffraction (XRD) patterns were recorded on Rigaku Rotaflex spectrometer at a 2Θ range of 10–70° with Cu Kα radiation. Specific surface area and pore size analysis of the samples were measured by nitrogen adsorption using a sorptometer (ASAP-2010, Micromeritics). The samples were degassed at 100 °C for 3 h prior to measure-

ments. Fourier transform infrared (FT-IR) spectra were recorded on Perkin-Elmer apparatus and the samples were prepared by mixing the powdered solids with KBr. Scanning electron microscopy (SEM) measurements were performed on a Philips XL30 electron micrograph. Transmission electron microscopy (TEM), EDX and SAED micrographs were obtained on a Joel JEM 2010 transmission electron microscope. The samples were supported on carbon-coated copper grids for the experiments. Melting points were measured with a Büchi B-540 melting-point apparatus and are uncorrected. The ^{1}H and ^{13}C NMR spectra were measured on a Bruker AC-200 instrument using $CDCl_3$ as solvent.

General Procedure for Synthesis of Substituted 2-Phenylchroman-4-ones (2a–k)

A mixture of 2-hydroxychalcone (**1a–k**) (1 mmol) and HM catalyst (50 mol%) was finely powdered by grinding with a pestle and mortar for a few minutes and transferred into a 25-mL round-bottom flask, followed by the addition of solvent (water, 3 mL) and the mixture was refluxed for 3–5 h. After completion of the reaction (as monitored by TLC), the reaction mixture was centrifuged to separate the catalyst which was washed several times with ethanol. The combined organic layers were dried over Na_2SO_4 and the solvent was removed under reduced pressure. The products were purified by recrystallization from $CHCl_3$-petroleum ether.

2-Pyridin-3-yl-chroman-4-one (2b): yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): $\delta = 8.75$–8.65 (m, 2H, Ar-H), 7.96–7.93 (m, 1H), 7.84(d, J=7.3 Hz, 1H), 7.56–7.51 (m, 1H), 7.39 (dd, $J = 8$ Hz, $J = 4.4$ Hz, 1H), 7.10–7.0 (m, 2H), 5.55 (dd, $J = 13.2$ Hz, $J = 2.9$ Hz, 1H, OCH), 3.09 (dd, $J =$ 16.8 Hz, $J = 13.2$ Hz, 1H, -CHCO), 2.93 (dd, $J = 16.8$ Hz, $J =$ 2.9 Hz, 1H, CHCO); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): $\delta = 190.9$ (C=O), 161.0, 150.0, 147.7, 136.2, 134.3, 133.6, 127.0, 123.6, 121.9, 120.8, 117.9, 77.24 (CH), 44.2 (CH_2; IR (KBr): $\nu_{max} = 1695$ cm^{-1} (C=O); anal. calcd. for $C_{14}H_{11}NO_2$: C 74.65, H 4.92, N 6.22; found: C 74.60, H 4.90, N 6.28.

General Procedure for Synthesis of the 3-Hydroxy-2-phenylchroman-4-one (3)

A mixture of 2-hydroxychalcone (**1a**) (1 mmol) and HM catalyst (50 mol%) was finely powdered by grinding with a pestle and mortar for a few minutes and transferred to a 25-mL round-bottom flask, followed by addition of 30% hydrogen peroxide (0.6 mL) and water (3 mL), the mixture was then heated at 80 °C for 2 h. After completion of the reaction (as monitored by TLC), the reaction mixture was centrifuged to separate the catalyst which was washed several times with ethanol. The combined organic layers were dried over Na_2SO_4 and the solvent was removed under reduced pressure. The recrystallization of crude product from methanol gave the pure product **3**.

3-Hydroxy-2-phenylchroman-4-one (3): colourless needles; mp 178–180 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): $\delta = 7.95$ (d, $J = 8$ Hz, 1H, Ar-H), 7.61–7.44 (m, 6H), 7.12 (t, $J = 8$ Hz, 1H), 7.06 (d, $J = 8$ Hz, 1H), 5.15 (d, $J = 12.4$ Hz, 1H), 4.65(d, J=12.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): $\delta = 194.2$ (C=O), 161.7, 136.9, 136.2, 129.3, 128.6, 127.5, 127.3, 122, 118.4, 118.1, 83.8 (CH), 73.6 (CH_2); IR (KBr): $\nu_{max} = 3462$ (OH), 1695 cm^{-1} (C=O); anal. calcd. for $C_{15}H_{12}O_3$: C 74.99, H 5.03; found: C 74.96, H 5.01.

General Procedure for Synthesis of 1,4-Dihydropyridines (7a–7k)

A mixture of aldehyde (1 mmol), 1,3-cyclohexanedione (1 mmol), ethyl acetoacetate (1 mmol), ammonium acetate (1.5 mmol) and HM catalyst (30 mol%) in water (2 mL) was heated at 90 °C. After completion of the reaction (as monitored by TLC), organic solvent was added to reaction mixture which was then centrifuged to separate the catalyst. This procedure was repeated for 3–4 times to extract the product from the catalyst surface. The combined organic layers were dried over Na_2SO_4 and the solvent was removed under reduced pressure. Recrystallization of crude product from hot ethanol gave pure products.

Ethyl 4-(3-methoxyphenyl)-2-methyl-5-oxo-1,4,5,6,7,8-hexahydroquinoline-3-carboxylate (7g): off-white solid; mp 197–199 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): $\delta = 9.35$ (brs, 1H, NH), 7.33–7.29 (m, 1H), 6.90 (d, $J = 7.7$ Hz, 1H), 6.89–6.85 (m, 2H), 5.10 (s, 1H), 4.20 (q, $J = 7.3$ Hz, 2H), 3.88 (s, 3H, OCH_3), 2.73–2.68 (m, 3H), 2.44–2.39 (m, 3H), 2.15–1.93 (m, 3H), 1.35 (t, $J = 7.3$ Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): $\delta = 194.6$, 166.9, 158.8, 151.4, 149.2, 144.9, 128.8, 113.6, 110.3, 103.3, 59.0, 54.7, 39.4, 36.7, 35.4, 26.1, 20.8, 18.2, 14.1; ESI-MS: $m/z = 328.15$ $(M+H)^+$; anal. calcd. for $C_{19}H_{21}NO_4$: C 69.71, H 6.47, N 4.28; found: C 69.68, H 6.48, N 4.30.

Ethyl 4-(2,4-dichlorophenyl)-2-methyl-5-oxo-1,4,5,6,7,8-hexahydroquinoline-3-carboxylate (7k): off-white solid; mp 245–247 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): $\delta = 9.42$ (brs, 1H, NH), 7.56–7.55 (m, 1H), 7.49–7.48 (m, 2H), 5.38 (s, 1H), 4.15 (q, $J = 7.3$ Hz, 2H), 2.73–2.66 (m, 4H), 2.43–2.28 (m, 3H), 2.13–2.05 (m, 1H), 1.97–1.88 (m, 1H), 1.30 (t, $J = 7.3$ Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si); $\delta =$ 194.2, 166.6, 151.8, 145.2, 144.5, 132.7, 130.7, 128.1, 127.0, 110.3, 102.7, 59.0, 36.7, 34.6, 26.1, 20.7, 18.1, 14.1; ESI-MS: $m/z = 366.06$ $(M+H)^+$, 367.06 $(M+2)^+$; anal. calcd. for $C_{18}H_{17}Cl_2NO_3$: C 59.03, H 4.68, N 3.82; found: C 59.08, H 4.70, N 3.85.

Supporting Information

SEM and XRD data of recycled catalyst, EDX and TGA data of fresh hydromagnesite catalyst and the HM catalyst loading study as well as ^{1}H and ^{13}C NMR spectra of flavanone **2b**, flavonol **3** and 1,4-dihydropyridines (**7g**, **7k**) are available in the Supporting Information.

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