

Preparation and characterization of Ca-modified Co/ Al_2O_3 and its catalytic application in the one-pot synthesis of 4H-pyrans

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Abstract

In this research, Co/Ca–Al₂O₃ composite as a heterogeneous nanocatalyst was synthesized by the co-precipitation method. The effect of Ca addition on the textural properties and the catalytic activity was investigated. The results show that the specific surface area and the particle size of the catalyst were influenced by the addition of Ca as well as the catalytic activity of the Co/Al₂O₃ oxide catalyst was increased. The catalyst was characterized by XRD, SEM, EDS, TEM and BET surface area analysis. The catalytic activity of Co/Ca–Al₂O₃ was investigated in the synthesis of 4H-pyrans. The Co/Ca–Al₂O₃ showed better catalytic activity than Al₂O₃ and Co/Al₂O₃. The catalyst can be recycled and reused without a significant structural change or considerable decrease in its activity.

Graphic abstract



Keywords Co/Ca $-Al_2O_3$ nanocatalyst \cdot 4H-pyrans \cdot Multicomponent reactions \cdot Co-based catalyst \cdot Heterogeneous catalysis

Introduction

4H-pyrans and their derivatives are found in the structure of a series of heterocyclic compounds with biological and pharmacological properties [1]. It has been reported that these compounds have significant biological activities such as antibacterial [2], antiviral [3] and anticancer activities [4]. Furthermore, some of the 4H-pyrans have been used for the treatment of Alzheimer's and Parkinson's disease [5]. A number of pyran derivatives are photoactive compounds and used in light-emitting diodes and fluorescent materials [6, 7].

Multicomponent reactions (MCRs) are considerable interest in organic and combinatorial chemistry [8]. One-pot synthesis of complex molecules with several functional groups through applying simple molecules is one of the benefits of multicomponent reactions. Besides these features, the MCRs have some advantages such as simplicity of reactions without separation of intermediates, reducing time and saving energy [9–11]. One type of MCRs is the synthesis of 4H-pyran derivatives by the one-pot, three-component condensation reaction of aldehydes and malononitrile with active methylene compounds. Various catalysts have been reported for the multicomponent synthesis of 4H-pyrans such as 1-methylimidazolium tricyanomethanide [12], P4VPy-CuI [13], Ca(OTf)₂ [14], gold nanoparticles [15], ionic liquids [16], SnCl₂ [17], L-valine [18], PEG-400 [19], SO₃H-dendrimer [20], KF-Al₂O₃ [21], sodium alginate [22], H₅BW₁₂O₄₀ [23], thiamine hydrochloride [24], Mg/La [25], KOH/CaO [26], visible light [27, 28] and meglumine [29].

In recent years, many research has been carried out to use heterogeneous catalysts because of their easy separation and recyclability [30]. One important type of heterogeneous catalysts is metal oxide nanoparticles that are widely used as a catalyst or as a support [31]. Due to the high catalytic activities, metal oxides have found many applications as a catalyst. They have been used in various reactions, such as oxidation [32, 33], hydrogenation [34], alkylation [35] and esterification [36].

A survey shows that numerous reactions have been examined in the presence of cobalt-based catalysts [37–39]. Cobalt catalysts are generally deposited on suitable supports to improve the activity and reusability of the catalyst [40]. Based on previous reports, the interactions between Co nanoparticles and support have a great effect on the physicochemical properties of the Co catalysts [41]. Among Co-based catalysts, Co/Al₂O₃ catalyst has been used widely in steam reforming of ethanol [41] and Fischer–Tropsch reaction [42]. Al₂O₃ has been used as a support in commercial catalysts due to its thermal stability for industrial applications, high surface area and large pores [43, 44]. One method to increase the catalytic stability of cobalt-based catalysts is to add additives such as transition metals, alkaline and alkali earth metals [45]. Moreover, Ca has been used as a promoter in various catalysts because it can improve the reducibility of the metal species and increase the metal dispersion and metal–support interactions [40, 41]; in addition, Ca is a metal with basic properties. Since the γ -Al₂O₃ has inherent acidity, its application as a catalyst support in acid-sensitive reactions has limitations. The alkaline or alkaline earth metal oxides can modify γ -Al₂O₃ and make it suitable as a support for many catalysts [44]. In continuation of our interest in regards to the synthesis and applications of green catalysts in multi-component reactions [46–48], herein, we report the preparation and characterization of Co₃O₄/CaO–Al₂O₃ (named Co/Ca–Al₂O₃) through the co-precipitation method as a heterogeneous and recyclable nanocatalyst. Then, the catalytic activity of the synthesized nanocatalyst was evaluated on the synthesis of 4H-pyran derivatives (Scheme 1).

Experimental

All chemicals and solvents were purchased from Merck and Sigma-Aldrich Companies. All reagents were used without any further purification. The prepared 4H-pyrans were identified by a comparison of their melting points and IR and NMR data with those reported in the literature. The progress of the reactions was monitored by TLC using silica gel SIL G/UV 254 plates. The melting points were measured with an Electrothermal 9100 apparatus and are uncorrected. FT-IR spectra were recorded with a JASCO 6300 spectrometer in KBr pellets in the range 400-4000 cm⁻¹. ¹H NMR spectra were attained using a Bruker Ultrashield spectrometer at 400 MHz by TMS as an internal standard in DMSO-d₆ or CDCl₃. Powder X-ray diffraction patterns were recorded on a Bruker, D8 ADVANCE with Co $K\alpha$ ($\alpha = 1.5406$ Å) at a voltage of 40 kV and a current of 40 mA. The morphology of the catalyst was studied by scanning electron microscopy (HITACHI S-4160). Transmission electron microscopy (TEM) was performed on a TEM Philips EM 208S instrument. The BET surface area and the BJH pore size analysis of the samples were measured from nitrogen adsorption-desorption analysis at liquid nitrogen temperature (77 K) using a BELSORP-mini II instrument (MicrotracBEL; Japan).



Scheme 1 Synthesis of 4H-pyran derivatives

Inductively coupled plasma optical emission spectrometry (ICP-OES) analysis was performed using a Spectro Genesis ICP-OES instrument.

Catalyst preparation

Co/CaO–Al₂O₃ nanocatalyst was prepared by the co-precipitation method. In a typical procedure, appropriate amounts of $Co(NO_3)_2 \cdot 4H_2O$, $Ca(NO_3)_2 \cdot 4H_2O$ and $Al(NO_3)_3 \cdot 9H_2O$ were dissolved in 100 mL distilled water. Loading amounts of Co and Ca were 15 wt% and 10 wt %, respectively. Then, an aqueous solution of NaOH and Na₂CO₃ (0.15:0.08 molar ratio) was prepared as a precipitating factor. The nitrate salts' solution was heated to 70 °C. Subsequently, the solution of precipitant was added slowly into the aqueous solution of nitrate salts with vigorous stirring at 70 °C until the pH of the solution reached 8. The resulting suspension was aged at 70 °C for 24 h, then filtered and washed with distilled water until the pH becomes 7. The resulting solid was dried at 100 °C overnight and then calcined at 600 °C for 6 h.

General procedure for synthesis of 4H-pyrans

Co/CaO–Al₂O₃ hybrid nanocatalyst (0.02 g), aldehyde (1.0 mmol), malononitrile (1.0 mmol), 1,3-diketone compounds (1.0 mmol) and ethanol (5 mL) were mixed and stirred at reflux conditions (monitored by TLC). After completion of the reaction, the catalyst was removed by filtration and washed with hot ethanol. The filtrate was cooled to room temperature to give a solid product, and the crude product was purified by recrystallization with ethanol/water.

Results and discussion

Today, the use of heterogeneous catalysts has attracted much attention for the synthesis of biologically active molecules. Among various heterogeneous catalysts, metal oxide nanoparticles are widely used as a catalyst in many chemical processes. Cobalt as an inexpensive, nontoxic transition metal has attracted many research attention in sustainable chemistry. Co/Ca $-Al_2O_3$ as a metal oxide nanocatalyst was prepared by the co-precipitation method using nitrate salts as precursors of Co, Ca and Al in basic solution. After precipitation, the obtained powder was dried at 100 °C overnight and then calcined at 600 °C for 6 h. The prepared catalyst is designated here as Co/Ca $-Al_2O_3$ and characterized by XRD, SEM, EDS, TEM and BET analyses.

Characterization of Co/Ca-Al₂O₃ catalyst

The XRD patterns of the Al₂O₃, Co₃O₄/Al₂O₃ (named Co/Al₂O₃), fresh Co/ Ca-Al₂O₃ and used catalyst at $2\theta = 10^{\circ}-90^{\circ}$ are shown in Fig. 1. The XRD of Al₂O₃ and Co/Al₂O₃ is used for comparison. There are some peaks in $2\theta = 32.10$, 34.85,



Fig. 1 XRD patterns of catalysts

35.70, 45.30, 46.20, 61.00, 67.15 (Fig. 1a) that correspond to the crystal planes (220), (311), (400) and (440) which are attributed to cubic γ-Al₂O₃ (JCPDS 00-047-1770). Figure 1b shows the XRD patterns for the Co/Al₂O₃ catalysts with 15 wt% cobalt which were prepared by the co-precipitation method. The diffraction patterns show peaks at 2θ =37.50, 45.50, 67.15 corresponding to γ-alumina, and the peaks at 2θ =31.44, 37.07, 45.09, 55.66, 59.65, 65.57 indexed to spinal structure of Co₃O₄ correspond to the crystal planes (220), (311), (400), (422), (511) and (440), respectively (JCPDS 01-078-1969) [42]. XRD pattern for the Co/Ca–Al₂O₃ (Fig. 1c) is much similar to Co/Al₂O₃, with some decrease in the peak intensity in the modified catalyst, which results from the dispersion of cobalt oxide nanoparticles within the catalyst support with the addition of Ca. Moreover, no obvious characteristic diffraction peaks of CaO can be detected; this means that CaO was highly dispersed in an amorphous form on the surface of Al₂O₃. The most intense peak of Co₃O₄ at around 2θ =37 overlaps with a γ-alumina diffraction peak; thus, it cannot be used to

	1	2		
Catalyst	BET surface area (m ² /g)	Total pore volume (cm ³ /g)	Average pore diam- eter (nm)	Crystallite size (nm)
Al ₂ O ₃	154	0.33	106	8.2
Co/Al ₂ O ₃	185	0.65	59	22.5 (19.2) ^a
Co/Ca–Al ₂ O ₃	169	0.49	28	18.5 (19.5) ^a

Table 1 Structural parameters calculated from N₂ adsorption/desorption isotherms and XRD analysis

^aCalculated from the $(2\theta = 31.44)$ diffraction plane of Co₃O₄ with Debye–Scherrer equation



Fig. 2 N₂ adsorption/desorption isotherms of catalysts



Fig. 3 Pore size distribution of catalysts obtained by the BJH method

calculate the accurate size of the cobalt particles. Therefore, the average particle size of Co_3O_4 was calculated based on both the cobalt oxide peak indicated at $2\theta = 31.44$ and $2\theta = 37.07$ and is listed in Table 1.

The textural properties of the catalysts were determined by N_2 adsorption/desorption isotherms and pore size distributions obtained by the BJH method. The N_2 adsorption–desorption isotherms and pore size distribution of Al_2O_3 , Co/Al_2O_3 oxide and $Co/Ca-Al_2O_3$ are shown in Figs. 2 and 3. It can be seen in Fig. 2 that

all samples exhibit type IV isotherms with an H3-type hysteresis loop according to the IUPAC classification, which are in agreement with the mesoporous structures [49].

As shown in Table 1, after the addition of Co, the surface area and the pore volume of the Al_2O_3 were increased. As the BET results show, adding of Co on Al_2O_3 increased the BET specific surface area and pore volume, from 154 m²/g and 0.33 cm³/g for the Al_2O_3 support to 185 m²/g and 0.65 cm³/g for the Co/ Al_2O_3 catalyst. The Ca-modified catalyst has specific surface area and pore volume (169 m²/g, 0.49 cm³/g), smaller than those of the Co/ Al_2O_3 catalyst. It can be resulting from the blocking of some pores of the catalyst. Furthermore, the addition of CaO results in a decrease in the specific surface area of the catalysts; this is due to the small specific surface area of CaO [50]. Figure 3 shows the pore size distribution of the synthesized catalysts. As can be seen, the Co/ Al_2O_3 has a pore size distribution with a pore diameter of about 59 nm. After Ca incorporation, the pore size distribution was changed to 28 nm, which indicates the distribution of CaO on the surface of the catalyst.



Fig. 4 SEM images (a, b), FESEM mapping (c) and FESEM-EDX analysis (d) of the Co/Ca-Al₂O₃

The morphology and chemical composition of the prepared catalyst were investigated by SEM, EDX and TEM. The SEM images in Fig. 4a show the morphology of Co/Ca–Al₂O₃. The morphological structure unit of Co/Ca–Al₂O₃ is a rodlike structure with the sizes of nanometer. Figure 4d shows the EDX spectra of the catalyst. The spectra show the presence of only Co, Ca, Al and oxygen, which indicates the purity of the synthesized Co/Ca–Al₂O₃ mixed metal oxide. The weight of the Co, Ca, Al and oxygen content from EDX results is about 14.38, 7.45, 44.17 and 33.99%, respectively, on the catalyst surface. According to the elemental mapping analysis (Fig. 4c), all of the elements have good distribution in the Co/Ca–Al₂O₃ catalyst. Figure 5 shows the TEM image for Co/Ca–Al₂O₃. The cobalt and calcium oxides with various sized particles less than 100 nm were well dispersed on the Al₂O₃ support.

Catalytic activity of Co/Ca-Al₂O₃

After characterization of Co/Ca-Al₂O₃ nanocatalyst, its catalytic activity was studied in the synthesis of 2-amino-3-cyano-4H-pyran derivatives. To optimize the reaction conditions, the condensation of 4-nitrobenzaldehyde, malononitrile and ethyl acetoacetate was selected as the model reaction. The efficiency of various reaction parameters such as the effect of solvent, temperature and the amount of the catalyst on the reaction time and yield of the product was investigated (Table 2). First, the reaction was performed without the catalyst in neat conditions; it was found that no desired product was obtained at room temperature and at 100 °C after 2 h. The reaction was carried out by 0.01 g of catalyst; the corresponding product was obtained in low yield. Then, the reaction was investigated in different solvents. As shown in Table 2, among them, ethanol was the best solvent for this reaction. In view of the fact that reaction temperature has a significant effect at the time of the reaction and the product yield, the model reaction was performed at different temperatures. As shown in Table 2, the increase in temperature resulted in a significant increase in the reaction rate and the product yield; thus, the reflux conditions were chosen for the reactions. In order to investigate the effect of the amount of the catalyst, the model reaction was performed under optimal conditions with various amounts of catalyst from 0.01 to 0.1 g. The



Fig. 5 TEM images (a, b) of the Co/Ca-Al₂O₃

Entry	Catalyst (g)	Solvent	Temp. (°C)	Time (min)	Yield (%) ^a
1	_	_	r.t.	120	_
2	_	_	100	120	_
3	_	H ₂ O	r.t.	120	Trace
4	_	H ₂ O	Reflux	120	10
5	0.01	_	100	120	60
6	0.01	CHCl ₃	Reflux	120	28
7	0.01	<i>n</i> -hexane	Reflux	120	Trace
8	0.01	CH ₃ CN	Reflux	120	60
9	0.01	H_2O	r.t.	120	40
10	0.01	H_2O	Reflux	120	82
11	0.01	EtOH	r.t.	120	50
12	0.01	EtOH	Reflux	60	85
13	0.02	EtOH	Reflux	15	95
14	0.05	EtOH	Reflux	15	95
15	0.1	EtOH	Reflux	15	92
16	0.02	EtOH	r.t.	60	55
17	0.02	EtOH	40	60	70
18	0.02	EtOH	60	60	86

 Table 2
 Optimization of the reaction conditions for the preparation of 4H-pyran-3-carboxylate derivatives

Reaction conditions: 4-nitrobenzaldehyde (1.0 mmol), malononitrile (1.0 mmol), ethyl acetoacetate (1.0 mmol), solvent (3 mL) and required amount of the catalyst

^aThe yields are related to the isolated products

results showed that increasing the catalyst from 0.01 to 0.02 g caused the reaction time to considerably decrease. An increase in the catalyst amount to 0.1 g did not have a considerable effect on the yield and the reaction time; therefore, 0.02 g of Co/Ca–Al₂O₃ nanocatalyst was selected as the best amount of catalyst in respect of reaction times and yields of the products.

The generality and efficiency of the Co/Ca–Al₂O₃ as the catalyst in the synthesis of 6-amino-5-cyano-4H-pyran-3-carboxylate derivatives were evaluated by the reaction of malononitrile, various aldehydes and ethyl acetoacetate under optimized conditions as shown in Table 3. As presented, aryl aldehydes with electron-donating or electron-withdrawing groups effectively reacted with ethyl acetoacetate, and the desired products were obtained in high yields.

After the synthesis of 6-amino-5-cyano-4-phenyl-2-methyl-4H-pyran-3-carboxylic acid ethyl esters, the efficiency of $Co/Ca-Al_2O_3$ was studied for the synthesis of tetrahydrobenzo[b]pyran derivatives by replacing ethyl acetoacetate with dimedone. The condensation reaction was performed between 4-nitrobenzaldehyde, malononitrile and dimedone as a model to optimize the reaction conditions (Table 4). As shown in Table 4, in the presence of 0.02 g of catalyst, the best results were obtained in ethanol under reflux conditions. The majority of this

Entry	ArCHO	Product ^a	Time (min)	Yield (%) ^b	Mp (°C)	
					Found	Reported
1	4-NO ₂ C ₆ H ₄ CHO	1a	15	95	178–180	173–175 [20]
2	4-CH ₃ OC ₆ H ₄ CHO	1b	35	87	145-147	141–144 [17]
3	2-HOC ₆ H ₄ CHO	1c	25	90	171-173	167–169 [<mark>25</mark>]
4	2-CH ₃ C ₆ H ₄ CHO	1d	30	95	210-212	217–219 [22]
5	4-BrC ₆ H ₄ CHO	1e	20	92	180-182	179–181 [<mark>20</mark>]
6	4-Dimethylaminobenzaldehyde	1f	45	83	216-218	215–217 [22]
7	C ₆ H ₅ CHO	1g	25	90	183-185	188–190 [<mark>22</mark>]
8	4-ClC ₆ H ₄ CHO	1h	15	95	177-179	173–175 [<mark>21</mark>]
9	3-NO ₂ C ₆ H ₄ CHO	1i	30	95	208-210	212–214 [22]
10	4-HOC ₆ H ₄ CHO	1j	40	88	205-207	211–212 [22]
11	2-ClC ₆ H ₄ CHO	1k	20	90	198-200	206–209 [22]
12	Furfural	11	25	85	168–170	173–175 [<mark>21</mark>]

Table 3 Preparation of 4H-pyran-3-carboxylates derivatives catalyzed by Co/Ca–Al₂O₃

Reaction conditions: aryl aldehyde (1 mmol), malononitrile (1 mmol), ethyl acetoacetate (1 mmol) and $Co/Ca-Al_2O_3$ (0.02 g) in ethanol (3 mL) at reflux conditions

^aProducts characterized by comparison of their spectroscopic (NMR and IR) data and melting points with those reported in the literature

^bIsolated yields

reaction was investigated with the use of various aldehydes (Table 5). The desired products were obtained in high yields at short time periods. The aromatic aldehydes with electron-withdrawing substituent reacted faster than aldehydes that have electron-donating groups. Also, in the presence of dimedone in comparison with ethyl acetoacetate, the pyran derivatives were obtained in shorter reaction times.

The catalytic activity of the Co/Ca–Al₂O₃ in the synthesis of ethyl-6-amino-5-cyano-4-(4-nitrophenyl)-2-methyl-4H-pyran-3-carboxylate was compared with Al₂O₃ and Co/Al₂O₃. The results are presented in Table 6. As indicated, the efficiency of Co/Ca–Al₂O₃ is better than others, according to the reaction time and the yield of the product. When the aluminum oxide was used alone, the yield of the product was only 35%. The model reaction was carried out in the presence of Co/Al₂O₃; the reaction yield was improved to 50%, which shows the function of cobalt oxide in catalyst activity. When the Ca-modified catalyst was used, the reaction yield increased to 85%. The better efficiency of the Ca-modified catalyst is thought to be due to a combination of factors such as the surface area of the catalyst, the acid–base properties of the catalyst and the synergistic effect between active components of the catalyst [45].

To show the merit of the present work in comparison with the results reported in the literature, we compared the obtained results using $Co/Ca-Al_2O_3$ with a number of catalysts reported on the synthesis of 4H-pyran derivatives (Table 7). As shown in Table 7, the composite nanocatalyst is comparable to others, in respect of reaction times and yields of the products.

Entry	Catalyst (g)	Solvent	Temp. (°C)	Time (min)	Yield (%) ^a
1	_	_	r.t.	120	_
2	_	_	100	120	_
3	_	H_2O	r.t.	120	Trace
4	_	H ₂ O	Reflux	120	23
5	0.01	_	100	60	50
6	0.01	CHCl ₃	Reflux	60	40
7	0.01	<i>n</i> -hexane	Reflux	60	10
8	0.01	CH ₃ CN	Reflux	60	65
9	0.01	H_2O	r.t.	60	60
10	0.01	H_2O	Reflux	60	90
11	0.01	EtOH	r.t.	60	75
12	0.01	EtOH	Reflux	10	85
13	0.02	EtOH	Reflux	5	90
14	0.05	EtOH	Reflux	5	92
15	0.1	EtOH	Reflux	5	90
16	0.02	EtOH	r.t.	30	77
17	0.02	EtOH	40	30	80
18	0.02	EtOH	60	30	88

 Table 4
 Optimization of the reaction conditions for the preparation of tetrahydrobenzo[b]pyran derivatives

Reaction conditions: 4-nitrobenzaldehyde (1.0 mmol), malononitrile (1.0 mmol), dimedone (1.0 mmol), solvent (3 mL) and required amount of the catalyst

^aThe yields are related to the isolated products

A probable mechanism for the formation of the 4H-pyrans is depicted in Scheme 2. Initially, catalyst activates the carbonyl group of the aromatic aldehyde and CaO as a base accepts a proton from malononitrile. The Knoevenagel condensation occurred to form the arylidenemalononitrile (I). Subsequently, diketone tautomerized in the presence of CaO, and then nucleophilic addition reaction with arylidenemalononitrile provides the Michael adduct (II). The Michael adduct (II) tautomerizes by CaO to create intermediate (III) which cyclizes and then tautomerizes to provide the 4H-pyran.

Catalyst reusability and stability

Also, the catalyst reusability was investigated in the model reaction. For this purpose, after the reaction was completed, the catalyst was separated by filtration, washed several times with warm ethanol, dried and reused in the next run. The recycled catalyst was used up to five cycles in the reaction without any significant loss in the activity (Table 8). The XRD patterns of the reused catalyst (Fig. 1D) showed that the Co/Ca–Al₂O₃ nanocatalyst structure was maintained after five runs. Furthermore, the adjustment of XRD patterns of the reused catalyst and the

Entry	ArCHO	Product ^a	Time (min)	Yield (%) ^b	Mp (°C)	
					Found	Reported
1	4-NO ₂ C ₆ H ₄ CHO	2a	5	95	185–187	179–181 [21]
2	4-CH ₃ OC ₆ H ₄ CHO	2b	10	90	193–195	198–200 [21]
3	2-HOC ₆ H ₄ CHO	2c	10	85	240-242	247–249 [12]
4	2-CH ₃ C ₆ H ₄ CHO	2d	10	90	203-205	203–205 [24]
5	4-BrC ₆ H ₄ CHO	2e	10	90	210-212	203–205 [15]
6	4-Dimethylaminobenzaldehyde	2f	15	80	211-215	208–210 [15]
7	C ₆ H ₅ CHO	2g	10	90	225-227	229–232 [15]
8	4-ClC ₆ H ₄ CHO	2h	5	92	209-201	214–216 [22]
9	3-NO ₂ C ₆ H ₄ CHO	2i	5	92	212-214	209–211 [20]
10	4-HOC ₆ H ₄ CHO	2j	10	90	228-230	225–227 [<mark>24</mark>]
11	4-CH ₃ OC ₆ H ₄ CHO	2k	10	85	204-206	198–200 [<mark>22</mark>]
12	C ₆ H ₄ CH=CHCHO	21	15	82	175-177	182–184 [<mark>22</mark>]
13	Furfural	2m	15	90	219–220	222–224 [<mark>22</mark>]

Table 5 Preparation of tetrahydrobenzo[b]pyran derivatives catalyzed by Co/Ca-Al₂O₃

Reaction conditions: aryl aldehyde (1 mmol), malononitrile (1 mmol), dimedone (1 mmol) and Co/Ca– Al_2O_3 (0.02 g) in ethanol (3 mL) at reflux conditions

^aAll synthesized compounds are known in the literature

^bIsolated yields

component

Table 6 Influence of catalyst

Entry	Catalyst	Time (min)	Yield (%)
1	Al ₂ O ₃	60	35
2	Co/Al ₂ O ₃	60	50
3	Co/Ca-Al ₂ O ₃	60	85

Reaction conditions: 4-nitrobenzaldehyde (1.0 mmol), malononitrile (1.0 mmol), ethyl acetoacetate (1.0 mmol), ethanol (3 mL) and 0.02 g of the catalyst at reflux conditions

Table 7 Comparison of Co/Ca-Al₂O₃ with other recently reported catalysts

Entry	Catalyst	Conditions	Time (min)	Yield (%)	References
1	L-valine	H ₂ O/40 °C	45-80	78–94	[18]
2	KF-Al ₂ O ₃ (10 mol%)	Ethanol/ r.t.	1.5–5 h	63–91	[21]
3	AuNPs@RGO-SH (0.05 g)	H ₂ O/reflux	30-60	74–86	[15]
4	SO ₃ H-dendrimer (0.05 g)	Ethanol/reflux	40–90	84–90	[20]
5	Sodium alginate (10 mol%)	Ethanol/reflux	40-125	84–96	[22]
6	H ₅ BW ₁₂ O ₄₀ (10 mol%)	Ethanol-H2O/reflux	90-300	77–98	[23]
7	Mg/La (0.05 g)	Methanol/reflux	60-180	55-92	[25]
8	Co/Ca–Al ₂ O ₃ (0.02 g)	Ethanol/reflux	15-45	83–95	This work



Scheme 2 The suggested mechanism for the synthesis of 4H-pyran derivatives using $Co/Ca-Al_2O_3$ catalyst

Table 8	The reusability of the
catalyst	Co/Ca–Al ₂ O ₃ in the
model r	eaction

Run	1	2	3	4	5
Time (min)	15	15	20	20	20
Yield (%)	95	92	90	90	87

Reaction conditions: 4-nitrobenzaldehyde (1.0 mmol), malononitrile (1.0 mmol), ethyl acetoacetate (1.0 mmol), ethanol (3 mL) and 0.02 g of the catalyst at reflux conditions

fresh catalyst indicates that there was no change in the crystal structure of the catalyst. The SEM image of recycled catalyst is presented in Fig. 4b. The comparison between fresh and reused catalysts showed that the morphology of the catalyst was maintained after five cycles. To determine the stability of the catalyst, the amount of calcium leaching from the catalyst was measured by ICP spectroscopy. For this purpose, the catalyst was heated and stirred in ethanol for 2 h; then, the catalyst was removed from the solution. The calcium concentration in ethanol solution was 0.06 ppm. The synthesis reaction of 4H-pyran was then carried out in the residual ethanol solution under similar reaction conditions with the heterogeneous catalyst, but no progress was observed in the reaction. This observation confirmed that the catalytic activity of $Co/Ca-Al_2O_3$ is closely related to the leached CaO. Low concentrations of CaO leached out from the catalyst surface are insufficient for catalyzing the reaction in the homogeneous phase, and the nature of the reaction is heterogeneous.

Conclusion

Co/CaO–Al₂O₃ hybrid nanocatalyst was prepared by the co-precipitation method. The catalytic activity of Co/Ca–Al₂O₃ was investigated for the one-pot synthesis of 4H-pyrans. 4H-pyran derivatives were successfully synthesized in the presence of Co/Ca–Al₂O₃ in high yields. It is found that the addition of CaO can improve the catalytic properties of Co/Al₂O₃. Compared to Al₂O₃ and the bare Co/Al₂O₃, CaO has a considerable effect on the interaction between Co oxide and Al₂O₃ support, and as a result, it increases the catalytic activity of Co oxide supported on Al₂O₃. The CaO leaching does not contribute to the production of 4H-pyrans, and the formation of 4H-pyrans is due to the heterogeneous properties of the catalyst. The catalyst can be recovered and reused without a considerable loss of its catalytic activity for up to five reaction runs. Moreover, easy separation of the catalyst from the reaction mixture, simple workup procedure and short reaction times are some of the other advantages of this method.

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