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Contributed Paper

Comparison of Catalytic Activity of Copper Nanostructures in Friedel-crafts Type Condensation Reactions

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ABSTRACT

The catalytic activity of copper nanostructures in the condensation reaction of selected indoles and aldehydes was investigated. Cu(acac)$_2$, zeolite Y-encapsulated Cu(acac)$_2$, free and zeolite Y-encapsulated CuO nanoparticles, and Cu$_2$O nanoparticles were prepared successfully and characterized by means of UV-Vis spectroscopy, Fourier-transform infrared spectroscopy (FTIR), diffuse reflectance spectroscopy (DRS), X-Ray diffraction analysis (XRD), scanning electron microscopy (SEM), and energy dispersive X-Ray analysis (EDX). Cu$_2$O nanoparticles showed superior activity as a heterogeneous catalyst compared to other catalytic systems. Excellent yields of the desired bis(indolyl)methanes were obtained via condensation reaction of indoles and aldehydes in presence of Cu$_2$O nanoparticles under mild reaction conditions and the catalyst retained activity for six successive catalytic runs.

Keywords: cupric oxide, cuprous oxide, copper(II) acetylacetonate, zeolite Y, nanostructure

1. INTRODUCTION

Catalytic activities of copper compounds have been investigated for decades owing to their unique properties. For example copper (II) acetylacetonate catalyzes carbene transfer, azide-alkyne cycloaddition, Michael addition, and many other reactions [1-3]. The catalytic activity of cuprous and cupric oxide nanoparticles have also been investigated in diverse organic transformations including C-C and C-O bond formation [4], ring opening/coupling cyclization [5] and C-S cross coupling of thiols with iodobenzene [6]. Bis(indolyl)methanes, on the other hand, are known to have diverse biological activities, and their synthesis has received considerable attention during the past two decades [7]. Bis(indolyl)methanes also have been used as precursors for the synthesis of colorimetric chemosensors due to their affinity to a variety of anions and metal ions [8-10]. Condensation of indoles with aldehydes or ketones is a general route for the synthesis of bis(indolyl)methanes in the presence of either protic or Lewis acids [7]. Metal oxide nanoparticles, to a lesser extent, were used in the synthesis of bis(indolyl)methanes. Examples include SiO$_2$ nanoparticles in presence of ultrasound [11], sulfated zirconia nanoparticles [12], $H_5PW_{10}V_2O_{40}$/pyridino-Fe_3O_4 nanoparticles [13], TiO_2 nanoparticles [14] and Fe(ox)-Fe_3O_4 nanoparticles [15]. Each of these methods has limitations such as requirement for special apparatus, long reaction times, organic solvent concerns, and complexity of catalyst preparation. To address some of these issues and to compare copper nanostructures as catalyst in the synthesis of some bis(indolyl)methanes, a research project was undertaken and the results are presented herein.

2. MATERIALS AND METHODS

2.1 Materials

All of the chemicals were purchased from Sigma-Aldrich and used as received. $Cu(acac)_2$ was synthesized according to the literature [16]. Zeolite NaY with the Si/Al ratio of 2.8 was converted to its H^+ form by repeated ion-exchange with 1.0 M ammonium nitrate solution. Cu^{2+}-exchanged zeolite Y, (CuY), was obtained by repeated ion-exchange with 1.0 M copper acetate solution and subsequent Soxhlet extraction with acetonitrile to remove surface Cu^{2+} ions. For preparation of zeolite Y-encapsulated $Cu(acac)_2$, 500 mg of CuY was vacuum dried at 200 °C overnight to remove physically adsorbed water and then acetylacetone (2.0 mL treated with 3.0 M NH_4OH) was diffused into the cages of zeolite Y to coordinate Cu^{2+} ions for 2 h. The obtained light blue solid was then extracted with CH_3CN using Soxhlet to remove unreacted acetylacetonate ions, and the product was dried in an oven at 200 °C overnight. CuO and Cu_2O nanoparticles were synthesized according to the reported methods using a mechanical stirrer rotating at 800 rpm [17, 18]. Zeolite Y-encapsulated CuO nanoparticles were obtained by thermal decomposition of $Cu(acac)_2$ in the supercages of zeolite Y at 800 °C in air. To prepare bis(indolyl)methanes, to a solution of corresponding indole (2.0 mmol) and aldehyde (1.0 mmol) in 5.0 mL of ethanol, 0.1 mmol of catalyst was added and the progress of reaction was monitored by thin layer chromatography (*n*-Hexane/EtOAc, 10:4). All of the bis(indolyl)methane products were insoluble in ethanol, leading to an easy workup step for separation of the catalyst and purification of the desired product by recrystallization from ethyl acetate.

2.2 Selected Spectroscopic Data for 3, 3′-bis(indolyl)-4-isopropylphenylmethane (Table 2, entry 2)

White solid, mp 154-155 °C. FTIR (KBr, cm^{-1}): 420, 498, 744, 752, 790, 1010, 1089, 1216, 1340, 1456, 1511, 2867, 2962, 3421. ^{1}Hnmr (500 MHz, $CDCl_3$, ppm): 1.29 (d, 6H, *J*= 7.00 Hz), 5.91 (s, 1H), 6.7 (s, 2H), 7.06 (t, *J*= 7.50 Hz, 2H), 7.18 (d, *J*= 8.00 Hz, 2H), 7.21 (t, *J*= 7.51 Hz, 2H), 7.30 (d, *J*= 7.28 Hz, 2H), 7.40 (d, *J*= 8.00 Hz, 2H), 7.46 (d, *J*= 8.00 Hz, 2H), 7.91 (s, 2H). Anal calcd. For $C_{26}H_{24}N_2$: C 85.68, H 6.64, N 7.69; Found: C 85.7, H 6.7, N 7.65.

2.3 Instrumentation

FT-IR spectra were obtained in KBr pellets on a Bruker ALPHA spectrophotometer. X-Ray diffraction patterns were recorded on a Philips diffractometer with mono chromatized Cu Kα radiation (40 KV, 20 mA, Ni filter, step size of 0.05° and count time of 1 s). SEM images were obtained by a Philips XL30 ESEM scanning electron microscope. UV-Vis and DRS spectra were recorded on a UV-2100 Shimadzu spectrophotometer at room temperature.

3. RESULTS AND DISCUSSIONS

X-Ray diffraction patterns (XRD) for $Cu(acac)_2$, zeolite Y-encapsulated $Cu(acac)_2$, zeolite Y-encapsulated CuO nanoparticles obtained by thermal decomposition of $Cu(acac)_2$, CuO nanoparticles and Cu_2O nanoparticles are presented in Figure 1a-e.

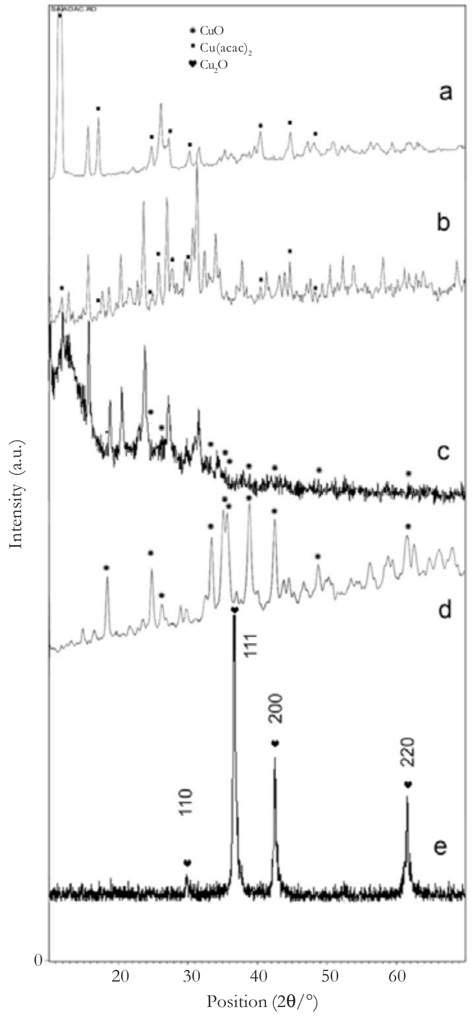


Figure 1. XRD patterns of a: $Cu(acac)_2$, b: zeolite Y-encapsulated $Cu(acac)_2$, c: zeolite Y-encapsulated CuO nanoparticles, d: CuO nanoparticles and e: Cu_2O nanoparticles.

Figure 1b reveals, in addition to the corresponding reflections of zeolite Y (JCDPS card No. 12-0246), characteristic peaks of $Cu(acac)_2$ encapsulated inside zeolite Y. Those peaks corresponding to the encapsulated species have lower intensity and a minor change in their position is due to possible structural deformation inside the supercages of zeolite Y. A comparison between Figures 1c and 1d also confirms the formation of CuO nanoparticles inside zeolite Y. The corresponding reflections of monoclinic Tenorite CuO nanoparticles are present in both patterns at 32.97°, 35.5°, 38.6°, 48.8°, 53.3°, 61.3°, 65.8°, and 67.7° related to (110), (002), (111), (020), (202), (113), (022) and (311) planes (JCPDS card No. 05-0661). Figure 1e, on the other hand, distinctly illustrates reflections of pure Cuprite Cu_2O nanoparticles. The observed ratio of intensity between the (111) and (200) peaks, which is slightly lower than the conventional values (2.1 vs. 3.105) indicates truncated corners corresponding to (111) facets, which is observable in the SEM image of Cu_2O nanoparticles in Figure 2a. The overall morphology of the nanoparticles is reminiscent of petals that have been stacked as nanosheets. In comparison, CuO nanoparticles were consisted of many ultrafine spherical particles ranging from 10 to 20 nm (Figure 2b). EDX analysis of Cu_2O and CuO nanoparticles are also illustrated in Figures 2c, d.

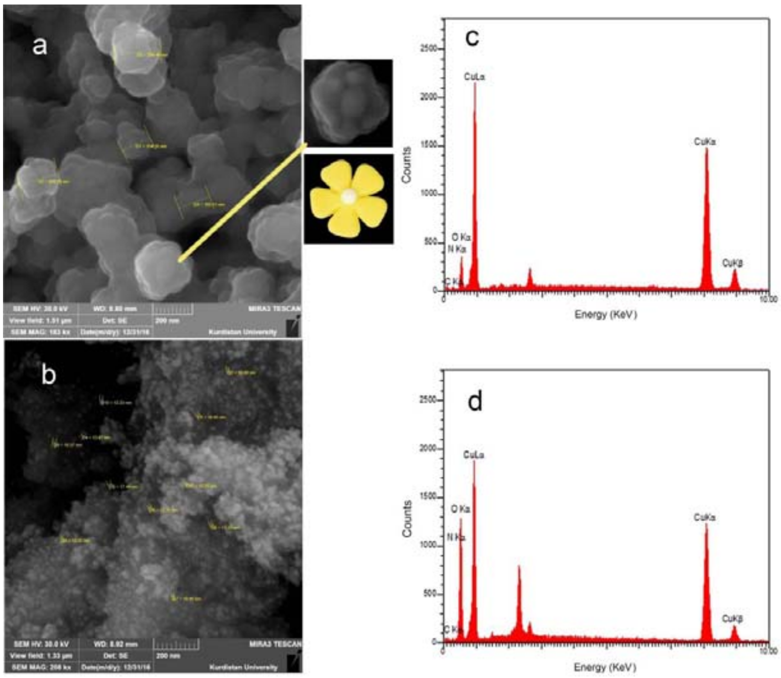


Figure 2. SEM images of Cu_2O and CuO nanoparticles (a, b) EDX analysis data for Cu_2O and CuO nanoparticles (c, d).

Further characterization of the synthesized materials was achieved by UV-Vis spectroscopy. Figure 3 illustrates the absorption spectra of Cu_2O nanoparticles. Surface plasmon resonances from the copper ions on the surface of Cu_2O nanoparticles are responsible for the observed absorption peak with maximum peak intensity at 504 nm [19].

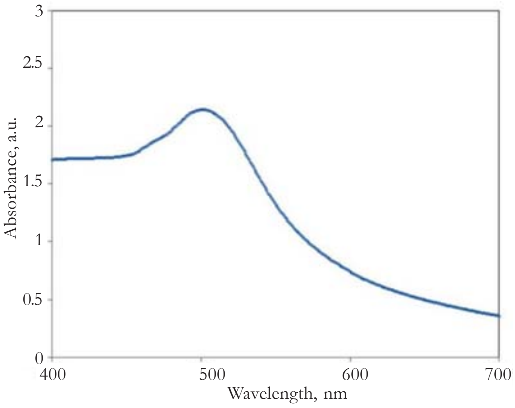


Figure 3. UV-Vis spectrum of Cu_2O nanoparticles dispersed in deionized water.

Diffuse reflectance spectra (DRS) of Cu $(acac)_2$ and zeolite Y-encapsulated Cu $(acac)_2$, are shown in Figure 4. The broad and intense band at about 470 nm, characteristic of d-d transitions in copper central atom in a four coordinate tetrahedral environment, is broadened even more and shifted toward higher wavelengths upon its encapsulation in zeolite Y. (Figure 4).

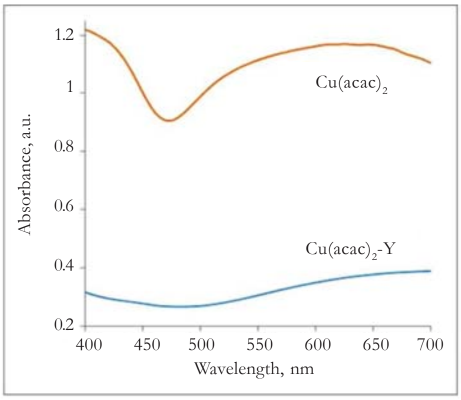
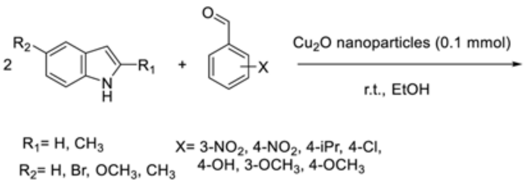


Figure 4. DRS spectra of $Cu(acac)_2$ (top) and zeolite Y-encapsulated $Cu(acac)_2$ (bottom).

After confirming the expected structure of the obtained copper compounds, their ability to catalyze the Friedel-Crafts reaction of indoles with aldehydes (Scheme 1) was compared.



Scheme 1. Cu_2O nanoparticles catalyzed Friedel-Crafts condensation reaction of indoles with aldehydes.

2-methylindole and 3-nitrobenzaldehyde were selected as model substrates to determine the optimized reaction conditions with regards to the catalyst type, catalyst loading, solvent and temperature. The results are summarized in Table 1. The selected substrates were reacted separately in the presence of 0.05 mmol of either CuO nanoparticles or Cu_2O nanoparticles or Cu $(acac)_2$. The best yield for the desired bis (indolyl)methane product was obtained in the presence of Cu_2O nanoparticles (entry 3). Although, $Cu(acac)_2$, as a homogeneous catalyst, showed a promising catalytic activity, (entry 4), due to its solubility in organic solvents, its recycling from the reaction mixture was problematic. Zeolite Y-encapsulated $Cu(acac)_2$ or CuO nanoparticles, on the other hand, were not as effective as Cu_2O nanoparticles (entries 5, 6). Based on these results, optimization continued only for Cu_2O nanoparticles. We noticed that an increase in the amount of Cu_2O nanoparticles up to 0.1 mmol results in an increase of the product yield (entries 7, 8). Higher loads of this catalyst, however, did not increase the yield significantly (entry 9). Elevated temperature, on the other hand, had an adverse effect on the reaction (entries 10, 11), and eventually a suitable solvent for this reaction was found to be ethanol (entry 12).

Table 1. Effects of various parameters on the condensation reaction of 2-methylindole and 3-nitrobenzaldehyde.

Entry [a]	Catalyst type	Catalyst loading	Temperature	Solvent	Yield (%)[b]
1	No catalyst	0	r.t.	Methanol	13
2	CuO nanoparticles	0.05 mmol	r.t.	Methanol	54
3	Cu_2O nanoparticles	0.05 mmol	r.t.	Methanol	70
4	$Cu(acac)_2$	0.05 mmol	r.t.	Methanol	71
5	Zeolite Y-CuO	50 mg	r.t.	Methanol	32
6	Zeolite Y- $Cu(acac)_2$	50 mg	r.t.	Methanol	35
7	Cu_2O nanoparticles	0.07 mmol	r.t.	Methanol	81
8	Cu_2O nanoparticles	0.1 mmol	r.t.	Methanol	93
9	Cu_2O nanoparticles	0.15 mmol	r.t.	Methanol	94
10	Cu_2O nanoparticles	0.1 mmol	40°C	Methanol	86
11	Cu_2O nanoparticles	0.1 mmol	50°C	Methanol	79
12	Cu_2O nanoparticles	0.1 mmol	r.t.	Ethanol	97
13	Cu_2O nanoparticles	0.1 mmol	r.t.	Acetonitrile	64
14	Cu_2O nanoparticles	0.1 mmol	r.t.	Dichloromethane	49

[a] All of the reactions were performed according to general experimental procedure

[b] Isolated yields

With the optimized conditions in hand, variety of indoles and aldehydes were examined to determine generality and scope of the reaction and the results are summarized in Table 2. Substrates with various functional groups tolerated the reaction conditions and resulted in good to excellent yields in rather short reaction times. Generally, electron-withdrawing nature of substituents on the phenyl ring of the aldehyde moiety, is in favor of formation of bis(indolyl)methanes and this resulted in higher yields for those products having electron-withdrawing functional groups.

Table 2. Cu_2O nanoparticles catalyzed condensation of various indoles and aldehydes.

Entry [a]	R_1, R_2	X	Time (min)	Yield (%) [b]	Reference
1	H, H	3-NO_2	5	92	[20]
2	H, H	4-*i*Pr	3	89	[21]
3	CH_3, H	3-NO_2	3	97	[21]
4	CH_3, H	4-NO_2	3	98	[22]
5	H, CH_3	4-NO_2	5	94	[22]
6	H, CH_3	4-OCH_3	7	92	[22]
7	H, Br	3-NO_2	5	89	[23]
8	H, Br	4-OH	7	88	[20]
9	H, Br	4-NO_2	8	91	[21]
10	H, OCH_3	3-NO_2	10	90	[23]
11	H, OCH_3	4-NO_2	7	93	[23]
12	H, OCH_3	4-OCH_3	12	88	[24]

[a] All of the products were characterized in comparison with authentic samples

[b] Isolated yields

In order to evaluate recyclability of the Cu_2O nanoparticles, the condensation reaction of 2-methylindole and 3-nitrobenzaldehyde was also conducted in the presence of the recycled catalyst. Results from this experiment indicates for 6 successive runs the yields were 97, 97, 93, 88, 82 and 76%, respectively and after six runs, the efficiency of the catalyst was decreased by 21%. Figure 5 represents the recycling results of the catalyst. These results represent Cu_2O nanoparticles as a reusable and efficient catalyst in the condensation reaction of various indoles and aldehydes.

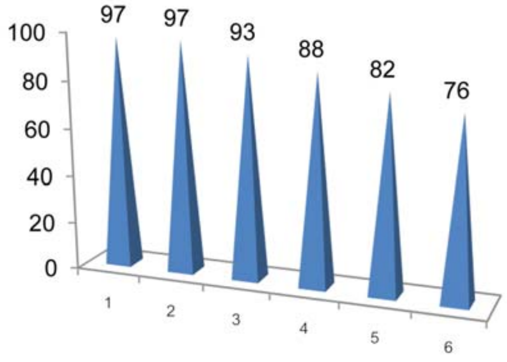


Figure 5. The recycling results of the catalyst during six successive runs.

4. CONCLUSIONS

Cu_2O nanoparticles utility as a versatile catalyst for the Friedel-Crafts condensation reaction between selected indoles and aldehydes was tested. To the best of our knowledge, this is the first report on the application of Cu_2O nanoparticles as a catalyst in the condensation reactions leading to bis(indolyl)methanes. Easy preparation of the catalyst, mild reaction conditions and above all, reusability of the catalyst, are highlights of this study.

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