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Green synthesis of predominant (1 1 1) facet CuO nanoparticles: Heterogeneous and recyclable catalyst for *N*-arylation of indoles

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ABSTRACT

Well faceted CuO nanoparticles were synthesized by thermal-assisted green strategy at reflux temperature in a short period of time. A possible growth mechanism of such highly faceted nanostructures based on typical biomolecule-crystal interactions in aqueous solution is tentatively proposed. The large surface area (223.36 m^2/g) and rich exposed active sites are expected to endow such nanostructures with excellent performances in catalysis as demonstrated here for remarkable catalytic activity with respect to the *N*-arylation of indoles. Nanoparticles were characterized by X-ray diffraction, scanning electron microscopy and transmission electron microscopy. Both the activity and selectivity of the *N*-arylation reactions could be tuned by varying the concentration of CuO nanoparticles. Nanoparticles catalyst were recycled and reused for further catalytic reactions with minimal loss in activity. A variety of indole derivatives afforded corresponding *N*-arylation product with excellent yields (up to 98%).

1. Introduction

Catalyst plays a significant role in the production of chemicals today and nanomaterials have the potential for improving efficiency, selectivity, and yield of catalytic process. The higher surface to volume ratio means that much more catalyst is actively participating in the reaction. The potential for cost saving is tremendous from a material, equipment, labour, and time standpoint. Higher selectivity means less waste and fewer impurities, which could lead to safer and reduced environmental impact. It was reported that catalytic performance of nanocrystals finely tuned either by their composition or by their shape which mediates the electronic structure [1,2]. The composition of nanocrystals was useful in determination of surface atomic arrangement and coordination [3–5]. When nanocrystals with different shapes were applied to electron transfer reaction the average rate constant of reaction increased exponentially with the percentage of surface atoms at the corners and edges increases [6,7]. Several groups intensively investigated the effect of shape of nanocrystals on their catalytic activity and stability and found that some specific facets are believed to be most catalytically active [8,9].

CuO nanoparticles as a catalyst for C–N, C–S, C–O cross-coupling reactions and *C*-arylation reaction have been well-documented because it is safe, cheap, having high theoretical capacity and environmental benignity [10–12]. How to improve catalytic performance is become more important and ranks as one of the hot topic. A fundamental goal of materials science is to design and synthesize materials with controllable shape, size and tailored functionality. The preparation of high purity, monodispersed nanocrystalline CuO using sonochemical [13], microwave irradiation [14], and precipitation-pyrolysis [15] methods were well reported. Major drawback of these methods was the formation of multifaceted CuO nanoparticles. Hence, in this paper, a facile one-step synthetic route is describe to construct face-centred-cubic (fcc) CuO nanostructures assisted by starch as a stabilizer at reflux temperature in a short reaction time. In comparison with reported protocols our method is green, environment-friendly, facile and time-saving. These particles have spherical morphology having predominant (1 1 1) facets, which are expecting to be chemically and dynamically active, therefore catalytically active. To the best of our knowledge, no studies have investigated the catalytic activity of predominant (1 1 1) facet nanometre sized CuO in *N*-arylation of indoles.

2. Experimental

2.1. Preparation of predominant (1 1 1) facet spherical shape CuO nanoparticles

All the reagents used in this synthesis were of analytical grade and used without further purification. CuO nanoparticles were prepared by decomposition of copper ammonia complex. The experimental procedure is briefly described as follows. The blue

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Table 1
Optimization of reaction condition for the *N*-arylation of indole with iodobenzene.

Entry	CuO quantity (mol%)	Base (1 equiv.)	Solvent	Reaction time (h)	Yield[a] (%)
1	10	K_2CO_3	CH_2Cl_2	24	31
2	10	K_2CO_3	CH_3CN	24	59
3	10	K_2CO_3	DMSO	9	97
4	10	K_2CO_3	Toluene	24	76
5	2.5	K_2CO_3	DMF	12	65
6	05	K_2CO_3	DMF	8	98
7	05	–	DMF	24	13
8	00	K_2CO_3	DMF	24	00
9	05	KOH	DMF	24	65
10	05	DBU	DMSO	10	81
11	05	Et_3N	DMSO	10	73
12	03	K_2CO_3	DMSO	10	88

[a] Isolated yield.

solution of copper ammonia complex was stirred with 4 g starch as a stabilizing agent for 1 h followed by addition of 100 ml of 0.25 M $NaBH_4$ solution and resultant solution was refluxed for 1 h. During reflux the color of solution changed from blue to colorless and then it turned slowly to brick red which indicated the formation of CuO nanoparticles. The nanoparticle separated out by centrifuge at 3000 rpm and washed with water two to three times.

2.2. Sample characterization

The powder X-ray diffraction (XRD) measurements were carried out on a PHILIPS HOLLAND, XRD system using Cu Kα radiation ($\lambda = 1.54056$ Å). The morphology of the CuO nanoparticles was investigated via scanning electron microscopy (SEM), (model JSM-5400, JEOL) and transmission electron microscopy (TEM) (Philips CM200). The BET surface area was determined by specific surface area analyzer (ASAP 2000, micrometrics) with nitrogen gas as an adsorbate.

2.3. Catalytic test

Indole (0.351 g, 3 mmol), iodobenzene (0.673 g, 3.3 mmol), CuO nanoparticles (0.0105 g), K_2CO_3 (0.414 g, 3 mmol) and *N*,*N*-dimethyl formamide (10 ml) was taken in a round bottom flask fitted with a reflux condenser. The resulting mixture was refluxed for the time as mentioned in Table 1. The progress of the reaction was monitored by TLC. After completion of reaction, mixture cooled to room temperature and diluted with 10 ml of water and extracted with ethyl acetate (2× 10 ml). The combined organic extracts were washed with brine and dried on anhydrous sodium sulphate. Solvent was evaporated under reduced pressure and the crude product was purified by flash column chromatography on silica gel using ethyl acetate and petroleum ether (1:9) as eluent to yield analytically pure product. Aqueous layer was centrifuged to recover CuO nanocatalyst.

3. Results and discussion

3.1. Structural analysis

The X-ray diffraction analysis of prepared CuO nanoparticles was carried to identify the product (Fig. 1).

All diffraction peaks are index with the corresponding planes of CuO. The XRD spectra showing an intense peak at 36.4 is having plane (1 1 1), which is the crystal plane of CuO. The low intensity peaks at 29.6, 61.7 which match well with the plane (1 1 0), (1 1 3).

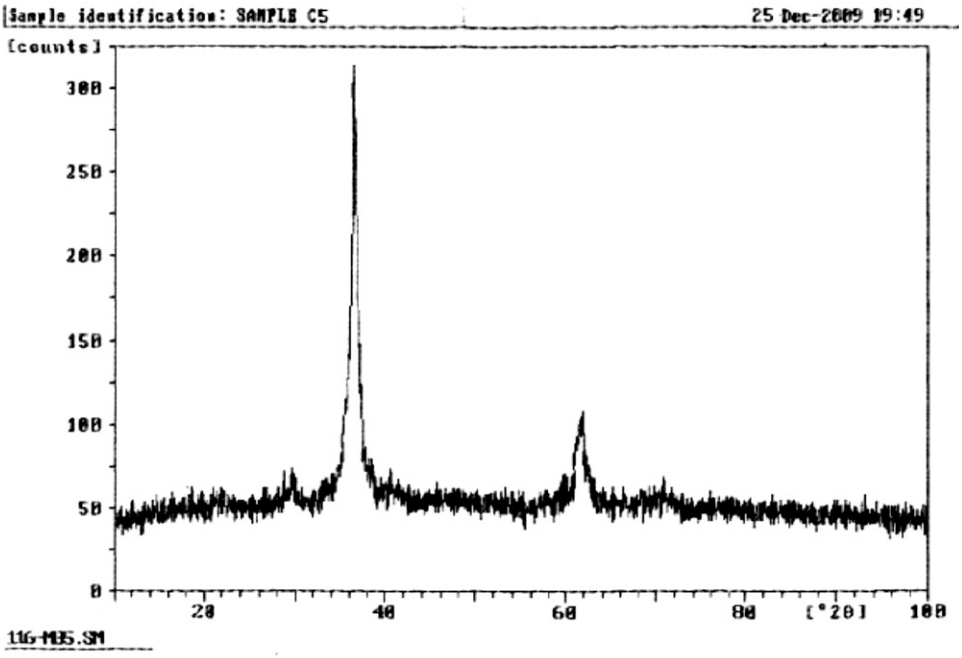


Fig. 1. XRD spectra of CuO nanoparticles.

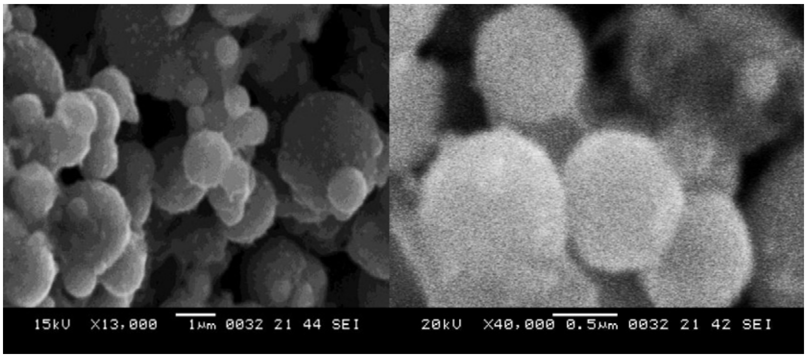


Fig. 2. SEM images of CuO nanoparticles.

All these planes of CuO with FCC crystal structure are very close to those in the JCPDS File No.5-0661. No other diffraction peaks arising from metallic Cu or Cu_2O present in the XRD pattern, which indicate the high phase purity of synthesized sample. The crystal size of products calculated by Scherrer formula was 40 nm.

The BET surface area of the synthesized CuO nanoparticles was determined and found to be 223.36 m^2/g which is significantly higher. The higher surface area of CuO nanoparticles plays the major role in the catalytic activity of CuO nanoparticles.

In order to obtained detail information about the microstructure and morphology of the synthesized sample, SEM and TEM observations were carried out and shown in Figs. 2 and 3. SEM images (Fig. 2) shows the spherical morphology of CuO nanoparticles. Careful observation of these image shows that particle surfaces are not smooth but some small round structures formed on the surface.

The formation of small structures on bigger one may increase its surface area and indirectly the catalytic activity of CuO nanoparticles. TEM images of the CuO nanoparticles are shown in Fig. 3, which shows the synthesized CuO nanoparticles having the size around 40–50 nm match exactly with the XRD analysis.

On the basis of XRD, SEM and TEM analysis we proposed the mechanism of CuO formation.

3.2. Growth mechanism

According to the Gibbs–Curie–Wulff theorem, the shape of a crystal is determined by the relative surface free energy of individual crystallographic faces. The final crystal shape results from minimizing the total free energy of the system [16]. For fcc single crystal, surface energies associated with different crystallographic planes are usually different, and a general sequence may hold, γ (1 1 1) < γ (1 1 0) < γ (1 1 3). Generally, the selective adsorption of surfactants, ions, ligands or polymers on a given crystal plane can inhibit the crystalline growth along one specific direction, leading to a preferential growth along another direction [17–19]. Therefore, the introduction of an additive with a selective adsorption function is widely used for the synthesis of anisotropic nanocrystals in a solution phase. Based on these, a possible mechanism is proposed (Scheme 1). It is believed that the growth of spherical shape completed by two steps, i.e. nucleation and growth respectively. In our synthetic route, starch plays a crucial role in controlling

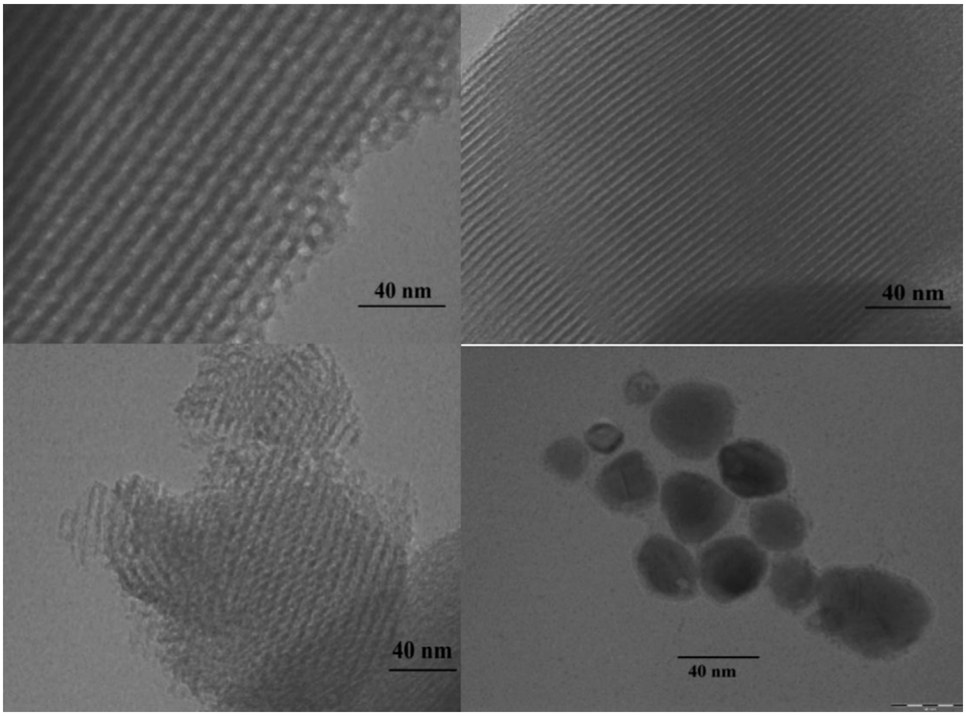
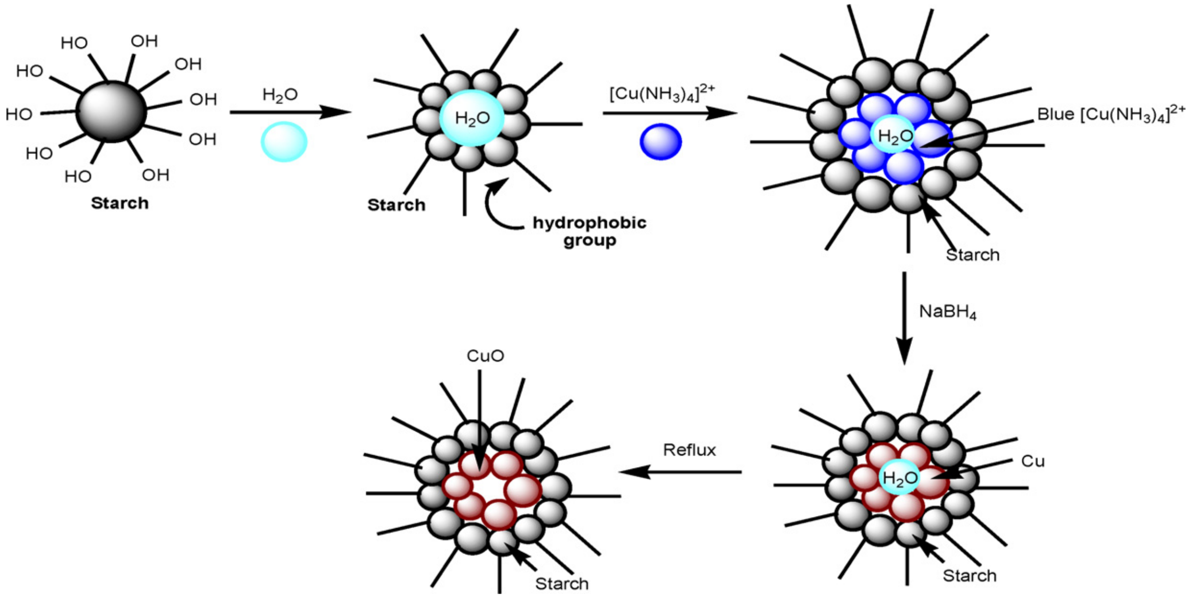


Fig. 3. TEM images of CuO nanoparticles.



Scheme 1. Possible growth mechanism for single facet CuO nanoparticles.

the shape of nanocrystals. The functional hydroxyl group (—OH) of starch molecules, which is a hydrophilic group can provide coordination sites, namely nucleation sites. When Cu^{2+} ions enter into aqueous solution, there is electrostatic attraction between the positively charged Cu^{2+}–ammonia complex and the negatively charged hydroxyl groups of starch, thus forming complex structure having spherical morphology. The introduction of $NaBH_4$ in a solution leads a rapid redox reaction results in the formation of spherical Cu crystal seeds, followed by CuO conversion after reflux. It has been revealed that a slow reaction is favourable for the formation of anisotropic nanocrystals [20]. Here, the existence of Cu^{2+}–starch complex inside the cavity will reduce the reduction rate of Cu^{2+} ions. Under the slow reaction, as reaction progress forward starch molecules seem to be preferentially adsorbed on the (1 1 0) planes of the nuclei, and consequently the area ratio of (1 1 1) to (1 1 0) increased. An increase in ratio facilitates the formation of spherical shape CuO nanocrystals based on the idea that an increase in the area ratio of (1 1 1) to (1 1 0) results in the evolution of particle shapes to a spherical shape [21].

Besides, the failure of producing spherical shape CuO in the absence of starch further confirmed the special role of starch in the formation of such unique spherical shape CuO as shown in Fig. 4.

3.3. *Catalytic activity*

The formation of C—N bond is one of the most important reactions in numerous syntheses of intermediates and targets with biological and pharmaceutical impact [22–26]. *N*-aryl indoles are of interest as angiotensin, antagonists [27], melatonin receptor, partial agonists [28], antipsychotic agents [29] and synthetic intermediates used in the preparation of other biologically active heterocyclic agents [30]. Various strategies were developed for the *N*-arylation of indoles. The century old copper-catalyzed Ullmann reaction has limitations because of harsh reaction conditions, requirement of stoichiometric amounts of copper reagents, long reaction times, and low yields [31,32]. The palladium-catalyzed *N*-arylation is an alternative method under mild reaction conditions [33]. The copper catalyzed Ullmann reactions have seen a gradual expansion in the past few years and by the correct choice of copper sources, bases, ligands, and other additives, several mild and efficient methods have been reported for the *N*-arylation of indoles [34,35]. Ligands based on diamines [36], oxime-phosphine oxide [37], aminoacids [38], phosphoramidite [39], and proline have been introduced to promote copper-catalyzed *N*-arylation of indoles and other heterocycles [40]. Recently, a transition metal free *N*-arylation of indole using strong base with longer reaction time has been reported [41].

The wide scope of CuO nanoparticles catalyst led us to investigate transformations involving less reactive nitrogen nucleophiles such as indoles. It is worth to mention that there was only one example in the literature utilizing commercially available multi-facet CuO nanoparticles for the *N*-arylation of indole with lesser yield (45%) and longer reaction time (23–36 h) [10]. Herein, we describe our progress in the predominant (1 1 1) facet nano CuO-catalysed *N*-arylation of indoles which overcome a number of problems associated with the techniques reported earlier.

The reaction of indole with iodobenzene was considered as a model reaction to find out the optimum reaction conditions for

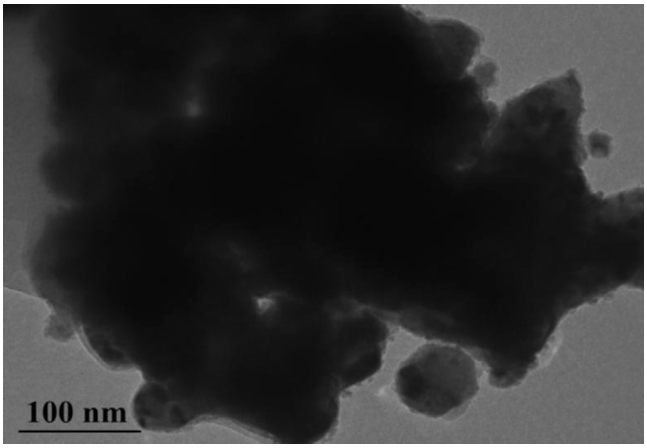
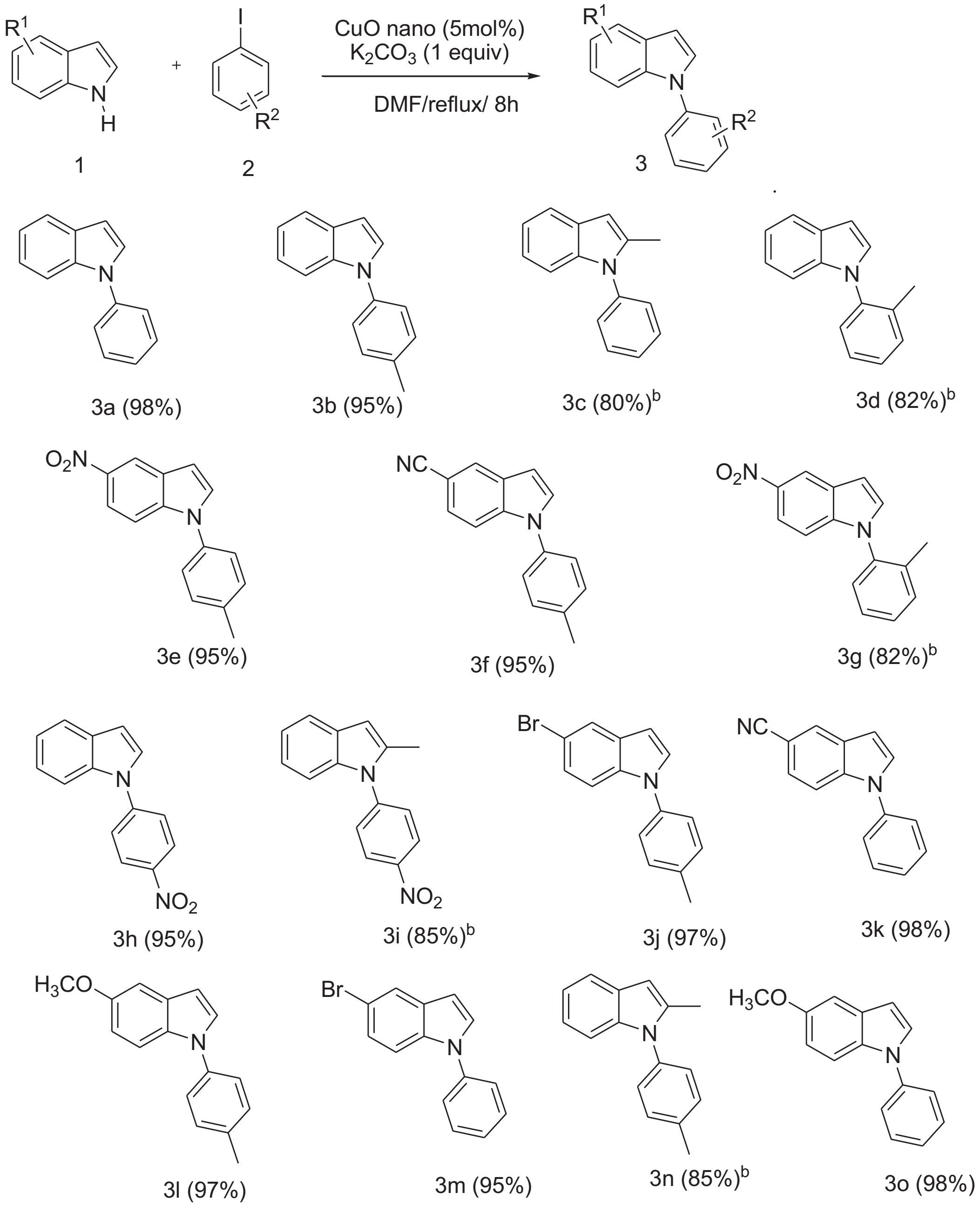


Fig. 4. TEM images of CuO nanoparticles produced in the absence of starch.

Table 2
CuO nanoparticle catalysed *N*-arylation of indole with iodoarenes.[a,b]



3a (98%)
3b (95%)
3c (80%)[b]
3d (82%)[b]
3e (95%)
3f (95%)
3g (82%)[b]
3h (95%)
3i (85%)[b]
3j (97%)
3k (98%)
3l (97%)
3m (95%)
3n (85%)[b]
3o (98%)

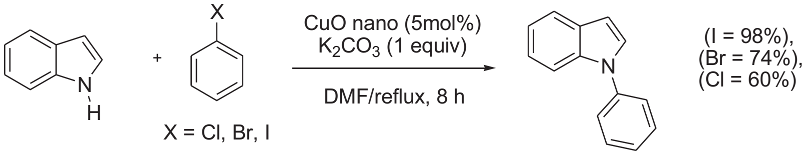
Isolated yields.

[a] Reaction conditions: indole (3 mmol), iodoarene (3.3 mmol), K_2CO_3 (3 mmol), CuO nano 5 mol%, DMF (4 ml) at reflux for 8 h unless noted otherwise.

[b] 12 h.

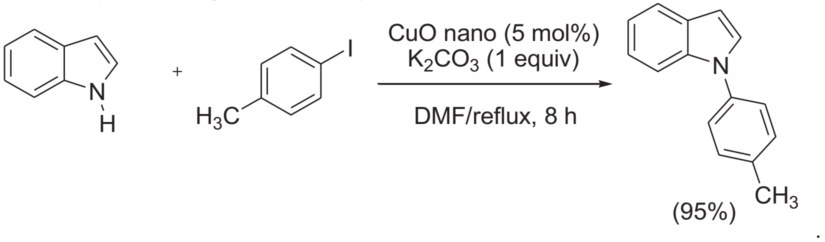
catalytic *N*-arylation process using CuO nanoparticles. The variations in the parameters like solvent, bases and the quantity of nano CuO catalyst were carried out and the results are summarized in Table 1.

The data of Table 1 shows that the *N*-arylation of indole was effectively possible in various solvents with different bases. As the concentration of catalyst was increased from 2.5 mol% to 5 mol%, the yield of the product was increased from 65% to 98% (Table 1,



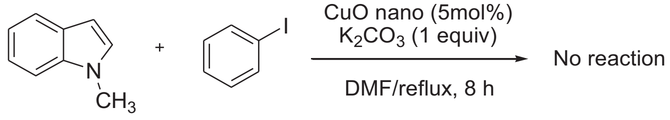
Scheme 2. CuO nanoparticle catalyzed *N*-arylation of indoles using different aryl halide.

Table 3
Recyclability of CuO nanoparticles as a catalyst.



Entry	Cycle	Yield (%)[a]
1	1st	95
2	2nd	94
3	3rd	94
4	4th	90
5	5th	85

[a] Isolated yield.



Scheme 3. Reaction of 1-methyl indole with aryl iodide.

entries 5 and 6). It is important to mention that *N*-arylation of indole did not take place in absence of CuO nanoparticle (Table 1, entry 8). The combination of K_2CO_3 as the base and 5 mol% of CuO nanoparticle as the catalyst in DMF solvent was found to be the best choice to get maximum yield of the product (Table 1, entry 6). With these optimum reaction conditions in hand, the scope and generality of the *N*-arylation method was investigated by the variations of iodoarenes and indoles with different substituent's and the results are summarized in Table 2.

The effect of different aryl halide on the yield of product was also studied. The reactions were performed with bromobenzene and chlorobenzene as a source of aryl halide under optimised reaction conditions (Scheme 2). The order of reactivity of aryl halide was found to be iodobenzene > bromobenzene > chlorobenzene.

To ensure that there was no *C*-arylation taken place in the reaction, the reaction was carried out with 1-methyl indole and found that there was no product formed (Scheme 3). This shows the high selectivity of CuO nanoparticles as catalyst in the *N*-arylation of indole.

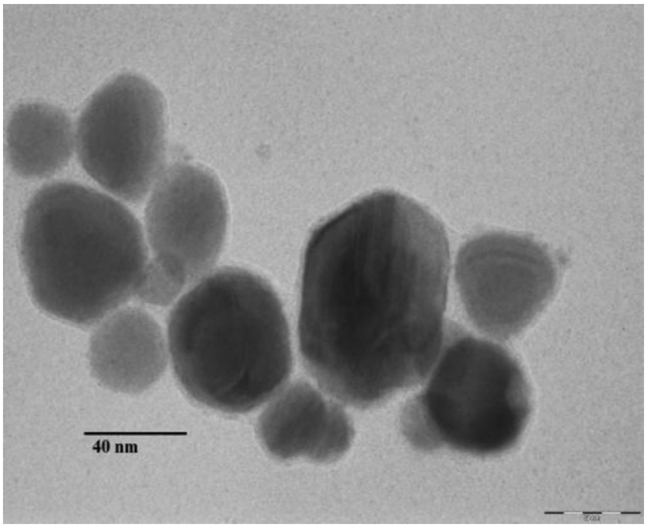


Fig. 5. TEM image CuO nanoparticles after recycled for 4th time in the reaction.

To find out whether any copper traces are in the aqueous solution after reaction, we done ICP study and electrochemical study of aqueous solution after the centrifugation but there were no any traces of copper found in the solution. The absence of Cu traces in the solution confirmed that the reaction was heterogeneous and occurring in the surface of nanoparticle and there was no leaching of metal species involved during the reaction.

3.4. Recyclability of catalyst

Finally the stability and activity of the catalyst was tested in the recycle-use experiments. The CuO nanoparticles recycled for five times without loss of its catalytic activity (Table 3). The used catalyst was then separated by centrifugation and washed with hot water two-three times before recycled in next reaction. It was found that during recycle experiments there was not much loss in yield of the product which shows the recyclability and reusability of catalyst without significant loss of its catalytic activity. In addition, TEM analysis of the CuO nanoparticles, before and after the reaction showed identical particle shape and size (Figs. 5 and 3).

4. Conclusion

In summary, we developed an environment-friendly procedure for rapid synthesis of highly faceted CuO with FCC nanostructures. Compared with the reported protocols, our method is green, environment-friendly, facile, and time-saving. The synthesized CuO nanoparticles with spherical nanostructures featured extremely strong reflection peaks of the (1 1 1) plane and possess small round structures on the bigger one. This kind of morphology endow them with excellent catalytic performance, as demonstrated here for the remarkable catalytic activity with respect to coupling reaction between indole and iodoarene in a ligand free condition. This interesting result highlights the advantage of such CuO nanostructures over the bulk counterpart and places a solid foundation for the feasible and promising application of such highly faceted nanomaterials in catalysis. To the best of our knowledge, it is the first report on nanometre-sized predominant (1 1 1) facet CuO acting as a catalyst for *N*-arylation of indoles and simultaneously is a good example for the combination of green chemistry and functional materials.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molcata.2012.03.017.

References

[1] J. Zhang, K. Sasaki, E. Sutter, R.R. Adzic, Science 315 (2007) 220–222.
[2] V.R. Stamenkovic, B. Fowler, B.S. Mun, G. Wang, P.N. Ross, C.A. Lucasand, N.M. Markovíc, Science 315 (2007) 493–497.
[3] R. Narayanan, M.A. El-Sayed, Nano Lett. 4 (2004) 1343–1348.
[4] F.J. Vidal-Iglesias, J. Solla-Gullón, P. Rodríguez, E. Herrero, V. Montiel, J.M. Feliu, A. Aldaz, Electrochem. Commun. 6 (2004) 1080–1084.
[5] N. Tian, Z.Y. Zhou, S.G. Sun, Y. Ding, Z.L. Wang, Science 316 (2007) 732–735.
[6] R. Narayanan, M.A. El-Sayed, Langmuir 21 (2005) 2027–2033.
[7] G.A. Somorjai, F. Zaera, J. Phys. Chem. 86 (1982) 3070–3078.
[8] R. Narayanan, M.A. El-Sayed, J. Am. Chem. Soc. 126 (2004) 7194–7195.
[9] R. Narayanan, M.A. El-Sayed, J. Phys. Chem. B. 108 (2004) 5726–5733.
[10] S. Jammi, S. Sakthivel, L. Rout, T. Mukherjee, S. Mandal, R. Mitra, P. Saha, T. Punniyamurthy, J. Org. Chem. 74 (2009) 1971–1976.
[11] L. Rout, S. Jammi, T. Punniyamurthy, Org. Lett. 9 (2007) 3397–3399.
[12] M. Kidwai, S. Bhardwaj, R. Poddar, Beilstein J. Org. Chem. 6 (2010) 1–6.
[13] Q. Sun, M. Alterawneh, B.Z. Dlugogorski, E. Kennedy, J.C. Mackie, Environ. Sci. Technol. 41 (2007) 5708–5715.
[14] R.V. Kumar, Y. Diamant, A. Gedanken, Chem. Mater. 12 (2000) 2301–2305.
[15] J.G. Li, T. Ishigaki, X.J. Sun, J. Phys. Chem. C. 111 (2007) 4969–4976.
[16] J.W. Mullin, Crystallization, 4th ed., Butterworth-Heinemann, Boston, 2001.
[17] Y.G. Sun, Y.N. Xia, Science 298 (2002) 2176–2179.
[18] B.J. Wiley, Y.J. Xiong, Z.Y. Li, Y.D. Yin, Y.N. Xia, Nano Lett. 6 (2006) 765–768.
[19] A. Tao, P. Sinsermsuksakul, P.D. Yang, Angew. Chem. Int. Ed. 45 (2006) 4597–4601.
[20] C.C. Li, K.L. Shuford, Q.H. Park, W.P. Cai, Y. Li, E.J. Lee, S.O. Cho, Angew. Chem. Int. Ed. 46 (2007) 3264–3268.
[21] Z.L. Wang, J. Phys. Chem. B. 104 (2000) 1153–1175.
[22] D.S. Surry, S.L. Buchwald, Chem. Sci. 1 (2010) 13–31.
[23] A. Klapars, S.L. Buchwald, J. Am. Chem. Soc. 124 (2002) 14844–14845.
[24] T. Hayakawa, R. Goseki, M. Kakimoto, M. Tokita, J. Watanabe, Y. Liao, S. Horiuch, Org. Lett. 8 (2006) 5453–5456.
[25] P. Huang, J. Ramphal, J. Wei, C. Liang, B. Jallal, G. McMahon, C. Tang, Bioorg. Med. Chem. 11 (2003) 1835–1849.
[26] J.R. Dimmock, R.N. Puthucode, J.M. Smith, M. Hetherington, J.W. Quail, U. Pugazhenthi, T. Lechler, J.P. Stables, J. Med. Chem. 39 (1996) 3984–3997.
[27] S.R. Stabler, Synth. Commun. 24 (1994) 123–129.
[28] G. Spadoni, C. Balsamini, A. Bedini, G. Diamantini, B.D. Giancomo, A. Tontini, G. Tarzia, J. Med. Chem. 41 (1998) 3624–3634.
[29] K. Andersen, T. Liljefors, J. Hyttel, J. Perregaard, J. Med. Chem. 39 (1996) 3723–3738.
[30] R. Sarges, H.R. Howard, B.K. Koe, A. Weissman, J. Med. Chem. 32 (1989) 437–444.
[31] F. Ullmann, Ber. Dtsch. Chem. Ges. 36 (1903) 2382–2384.
[32] F. Ullmann, Ber. Dtsch. Chem. Ges. 37 (1904) 853–854.
[33] J.F. Hartwig, M. Kawatsura, S.I. Hauck, K.H. Shaughnessy, L.M. Alcazar-Roman, J. Org. Chem. 64 (1999) 5575–5580.
[34] J.P. Corbet, G. Mignani, Chem. Rev. 106 (2006) 2651–2710.
[35] S.V. Ley, A.W. Thomas, Angew. Chem. Int. Ed. 42 (2003) 5400–5449.
[36] A. Klapars, J.C. Antilla, X.H. Huang, S.L. Buchwald, J. Am. Chem. Soc. 123 (2001) 7727–7729.
[37] L. Xu, D. Zhu, F. Wu, R. Wang, B. Wan, Tetrahedron 61 (2005) 6553–6560.
[38] Q. Cai, W. Zhu, H. Zhang, Y. Zhang, D. Ma, Synthesis 3 (2005) 496–499.
[39] Z. Zhang, J. Mao, D. Zhu, F. Wu, H. Chen, B. Wan, Tetrahedron 62 (2006) 4435–4443.
[40] R. Omar-Amrani, A. Thomas, E. Brenner, R. Schneider, Y. Fort, Org. Lett. 5 (2003) 2311–2314.
[41] R. Cano, D.J. Ramon, M. Yus, J. Org. Chem. 76 (2011) 654–660.