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ARTICLE TYPE

Polyoxomolybdate-stabilized Cu₂O nanoparticles as an efficient catalyst for the azide-alkyne cycloaddition

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We report a simple methodology for the stabilization of Cu₂O nanoparticles of size 10-30 nm on the polar pore surface of a polyoxomolybdate(NH_4)₁₂[Mo₃₆(NO)₄O₁₀₈(H₂O)₁₆] ({Mo₃₆}). For the first time, a Cu₂O@ ({Mo₃₆} composite has been utilized as a

10 recyclable catalyst for the Huisgen 1,3-dipolar cycloaddition reaction of terminal alkynes, aryl/alkyl halides and NaN₃ for the synthesis of 1,2,3-triazoles.

Introduction

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- The 1,3-dipolar cycloaddition of organic azides and alkynes, a 15 direct route to 1,2,3-triazoles, has inarguably become the most popular ligation reaction that has been widely applied in many areas such as polymers, drug discovery, and advanced material science, etc [1-5]. Early work has been focused on the development of copper(I) catalytic systems for the one-pot
- 20 multicomponent copper-catalyzedazide- alkyne cycloaddition (CuAAC) reaction [6-10]. Cu₂O is also a source of catalytic Cu(I) for these reactions, but direct use of Cu₂O powder in a CuAAC reaction usually requires long reaction times and yet result in incomplete conversion and poor yields [11-13]. In order to
- 25 overcome these drawbacks, several research groups have made enormous efforts to enhance the catalytic efficiency of Cu₂O [14-18]. The most common method employed for the synthesis of Cu₂O nanoparticles is the reduction of metal ions in the presence of NaBH₄ or hydrazine as a reducing agent, which are quite
- 30 expensive and possible hazard to the environment [19-21]. Polyoxometalates (POMs) are well-defined metal- oxygen cluster anions that can be characterized by their ability to undergo stepwise, multielectron redox reactions, whilst their structure remains intact [22-25]. The high anionic charge of POMs causes
- 35 the electrostatic adsorption of metal ions on POMs surface [26]. 60Then POMs can participate in catalytic redox processes as electron relays. Therefore, reduction potentials of POMs make them ideal candidates for the stabilization of nanoparticles [27-30]. This is attributed to their high anionic charge, which prevents
- 40 particle aggregation by electrostatic repulsion. Giant polyoxomolybdate clusters, aside from interest in their enormous they may provide highly symmetric, rigid, nanometer-sized inorganic framework molecules [31-35].
- 45 Herein, we report an alternative, versatile and green-chemistry procedure for the stabilization of Cu₂O nanoparticles on POMs, 7(as a support as well as a reducing agent. By controlling the experimental conditions so as to retain a polyoxometalate structure, specifically, $(NH_4)_{12}[Mo_{36}(NO)_4O_{108}(H_2O)_{16}]$ ({Mo₃₆})

50 [36], we could also address its stabilizing effect on Cu_2O nanoparticles. The {Mo36} polyoxomolybdate skeleton acts as a localized support that gives rise to highly dispersed and stabilized Cu₂O nanoparticles (Scheme 1). Also, a simple, green, and scalable process process for one- pot multicomponent synthesis 55 of 1.2.3-triazoles from aryl/alkyl halides, alkynes, and NaN₃ in water, which are catalyzed by polyoxomolybdate-stabilized Cu₂O nanoparticles is herein reported.



Scheme 1. General procedure for the synthesis of Cu₂O@{Mo₃₆}

Experimental

Material

Chemicals and solvents were purchased from the Fluka and Merck Chemical companies. $(NH_4)_{12}[Mo_{36}(NO)_4O_{108}(H_2O)_{16}]$ structural diversity, are of special importance in this context as 65 ({Mo₃₆}) was prepared according to our previous procedure [36].

Preparation of Cu₂O@{Mo₃₆}

Polyoxomolybdate (NH₄)₁₂[Mo₃₆(NO)₄O₁₀₈(H₂O)₁₆] (0.01 mmol) was suspended in ethyl acetate (10 mL) and then copper nitrate(1) mmol) was added followed by stirring at room temperature for 24

h. During stirring the color of solids was changed to green and then yellow orange which shown the direct reduction of Cu(II) to

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Cu(I) species. The solid was filtered off, washed with ethyl acetate and finally with diethyl ether and dried in air.

General procedure for the azide-alkyne cycloaddition

- 5 Alkyne (0.5mmol), the organic halide (0.55mmol), and NaN₃ (0.55mmol) were added to a solution of Cu₂O@{Mo₃₆} (5 mol%) in H₂O (2mL). The reaction mixture was warmed to 70 °C and monitored by TLC until total conversion of the starting materials. Water (3 mL) was added to the resulting mixture, followed by
- 10 extraction with EtOAc (2×10 mL). The collected organic phases were dried with anhydrous CaCl₂ and the solvent was removed in vaccum to give the corresponding triazoles, which did not require any further purification.

15 Results and Discussion

Preparation of Cu₂O@{Mo₃₆}

Catalyst characterization

To gain insight into the structure of Cu₂O@{Mo₃₆} catalytic system, we have characterized the catalyst by energy dispersive 25 X-ray analysis (EDX), X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). XRD patterns of {Mo₃₆} and Cu₂O@{Mo₃₆} were quite similar (Fig. S1).The morphology and size of the Cu₂O NPs stabilized in the {Mo₃₆} matrix were studied by SEM,

- 30 TEM and HRTEM and representative images are shown in Fig. 1 and Fig. 2 respectively. The TEM images show homogeneous distribution of dark Cu₂O NPs with size 10–30 nm throughout the POM matrix (Fig. 2b). Furthermore, the selected area electron diffraction (SAED) patterns from a larger sample area showed the
- 35 ring-like patterns indexed to the (111), (200) and (220) reflections, suggesting the presence of cubic-phase Cu_2O on the { Mo_{36} }. It is worth noting that the solution impregnation method enables incorporation of metal salts into the pores of the POM matrix, where they interact with polar functional groups through
- 40 electrostatic interactions. The loading of Cu_2O in the surface of catalyst is determined by EDX analysis, and is found to be 4.37% (Fig. S2).



45 Fig. 1 SEM images of a) {Mo₃₆} b) Cu₂O@{Mo₃₆}



Fig. 2 TEM images of a) $\{Mo_{36}\};$ b) $Cu_2O@\{Mo_{36}\};$ c) HRTEM images 50 of $Cu_2O@\{Mo_{36}\}$

To confirm the direct reduction of Cu(II) to Cu(I) species on the POM, the chemical state of the Cu on the surface was analyzed by X-ray photoelectron spectroscopy (XPS). The Cu 2p core-

55 level spectrum shows two intense peaks at 932.2 and 952.1 eV, which can be assigned to Cu 2p3/2 and Cu 2p1/2 spin-orbital components of Cu(I) specials, respectively [37], whereas the satellite peaks associated with Cu(II) species at 934.6 are rather weak, proving that CuO was reduced to form Cu₂O directly by

 $60 \{Mo_{36}\}$ surface [38]. The Cu₂O /CuO ratio by comparing the ratio of satellite to main peaks intensities of Cu 2p3/2 in XPS spectra are estimated to be about 1.82.

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Fig. 3 Cu 2p XPS peaks of Cu₂O@{Mo₃₆}

5 Catalytic effects

The presence of highly mono-dispersed Cu₂O NPs with uniform size on the POM matrix prompted us to study its catalytic activity for Huisgen 1,3-dipolar cycloaddition reactions. Initial reactions were carried out between benzyl chloride with phenylacetylene as

- 10 the model substrates, as shown in Table 1. In this preliminary experiment, the Huisgen cycloaddition reaction was carried out in various solvents, with Cu₂O@{Mo₃₆} as a catalyst, in air at 70 °C for 12 h. The reaction proceeded perfectly in water (entry 3), but yields decreased when the reaction was carried out in other
- 15 solvents (entries 4-8). On the other hand, blank catalytic reactions without catalyst or in the presence of $\{Mo_{36}\}$ showed no conversion, suggesting the role of Cu₂O nanoparticles in catalyzing click reactions (entries 1, 2). Considering to develop an economical and environmentally friendly reaction, using of
- 20 water as a green solvent is clearly the most favorable case in these reactions. As indicated in Table 1, the reaction did not initiate at room temperature under conventional stirring using a magnetic stirrer for 12 h (entry 9), but a significant growth
- 25 (entries 10-12). Also the Cu(II)-catalyzed [3+2] cycloaddition of phenylacetylene and benzyl azide in water with 5mol% of Cu₂O@{Mo₃₆} resulted in 97% of 1-benzyl-4-phenyl-1,2,3traizole.

30 Table 1.The Effect of various conditions on the azide-alkyne cycloaddition

| Entry | catalyst | Temperature solvent | | Yield |
|-------|--------------------------------|---------------------|----------------------------------|-------|
| | | (°C) | | (%) |
| 1 | - | 70 | H ₂ O | 0 |
| 2 | {Mo ₃₆ } | 70 | H_2O | 0 |
| 3 | $Cu_2O(a) \{Mo_{36}\}$ | 70 | H_2O | 88 |
| 4 | $Cu_2O(a) \{Mo_{36}\}$ | 70 | C ₂ H ₅ OH | 51 |
| 5 | $Cu_2O(a) \{Mo_{36}\}$ | 70 | CH ₃ CN | 38 |
| 6 | $Cu_2O@{Mo_{36}}$ | 70 | toluene | 11 |
| 7 | $Cu_2O(a) \{Mo_{36}\}$ | 70 | C_6H_6 | 7 |
| 8 | $Cu_2O(a) \{Mo_{36}\}$ | 70 | EtOAc | 15 |
| 9 | $Cu_2O(a) \{Mo_{36}\}$ | r.t. | H_2O | 21 |
| 10 | $Cu_2O(a) \{Mo_{36}\}$ | 40 | H_2O | 35 |
| 11 | $Cu_2O@\{Mo_{36}\}$ | 50 | H_2O | 57 |
| 12 | $Cu_2O(a)$ {Mo ₃₆ } | 60 | H_2O | 73 |

Encouraged by the efficiency of the reaction protocol described 35 above, the scope of the reaction was examined with Cu₂O@{Mo₃₆}under air at 70°C. First, various benzyl chlorides were investigated and reacted with phenylacetylenes. As shown in Table 2, benzyl chlorides and phenyl acetylenes with the 75 The IR spectrum of the recycled catalyst $Cu_2O@\{Mo_{36}\}$ shows substitution of electron withdrawing and electron donating groups 40 on the phenyl ring were suitable cycloaddition partners and did

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not have any appreciable influence on the outcome of the reaction (entries 1-6). Furthermore, steric hindrance due to the ortho substituents on the benzyl chloride affected the reaction progress and therefore benzyl chloride substituted with methyl group at 45 ortho position was less reactive to the cycloaddition reaction than the para derivative (entries 2 and 3). When benzyl bromide was used under the similar reaction conditions, the corresponding products were obtained in higher yields than the case of benzyl chloride (entries 7-9). 50

Table 2. Cycloaddition of benzyl halides with terminal alkynes in the presence of $Cu_2O(a)$ {Mo₃₆}



| Entry | \mathbb{R}^1 | R^2 | Х | R_3 | Yield (%) |
|-------|-----------------------|-------|----|----------|-----------|
| 1 | Ph | Н | Cl | Ph | 88 |
| 2 | 4-Me-Ph | Н | Cl | Ph | 82 |
| 3 | 2-Me-Ph | Н | Cl | Ph | 73 |
| 4 | 4-NO ₂ -Ph | Н | Cl | Ph | 90 |
| 5 | Ph | Η | Cl | 4-MeO-Ph | 86 |
| 6 | Ph | Н | Cl | 4-Me-Ph | 85 |
| 7 | Ph | Н | Br | Ph | 95 |
| 8 | Ph | Н | Br | 4-MeO-Ph | 91 |
| 9 | Ph | Н | Br | 4-Me-Ph | 93 |
| 10 | Ph | Ph | Br | Ph | 64 |
| | | | | | |

55 Repeated use of a catalyst is an important parameter in its evaluation, the reusability of the catalyst $Cu_2O@{Mo_{36}}$ system was investigated. After precipitation and filtration of the azidealkyne cycloaddition products, water solution of the catalyst was reused for new cycle of the reaction. Two recycling experiments increase in the product yield was observed at higher temperatures 60 were carried out with relatively high yield (Fig. 4). Small losses

of catalyst mass during washing procedure may be caused in the low diminution in the activity from the first to the third cycle.



Fig. 4 Recycling studies of the Cu₂O@{Mo₃₆} in the azide-alkyne 65 cycloaddition reaction.

To address the leaching of copper species into solution, the catalytically active particles were removed from the reaction by filtration at half the reaction time in a separate experiment and the 70 filtrate was monitored for continued activity. The results show that the reaction did not proceed significantly upon further treatment of the residual mixture under similar reaction condition for second half of the reaction, indicating that no catalytically active Cu remained in the filtrate.

no vibrational changes indicating a good stability of the catalyst (Fig. 5).



Fig. 5 IR spectrum of fresh (red line) and reused catalyst Cu₂O@{Mo₃₆} 50 (blue line)

- 5 A reaction mechanism proposed for the $Cu_2O@{Mo_{36}}$ catalysed 1,3-dipolar cycloaddition of terminal alkynes with azides is 55 outlined in Scheme 2 on the basis of the previous reports [39]. During the reaction, it is proposed that Cu₂O are attracted towards the phenylacetylene to form a Cu(I)-acetylidine complex
- 10 in the first step. Next, the azide interacts with the copper acetylide through coordination interactions and forms a six- 60 membered copper metallacycle, which forms a copper triazole complex on ring contraction. Finally, protonolysis of the copper triazole complex gives the 1,2,3-triazole product and regenerates
- 15 the catalyst.

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Scheme 2 Proposed mechanism of $Cu_2O@\left\{Mo_{36}\right\}$ catalytic cycle for the formation of 1,2,3-triazole.

20 Conclusions

polar surface In conclusion the of а polyoxomolybdate(NH₄)₁₂[Mo₃₆(NO)₄O₁₀₈(H₂O)₁₆] was used as a 90 support and stabilization scaffold for Cu₂O nanoparticles of 10-30 nm size. This is the first time that such a composite system has

25 been successfully demonstrated as a highly efficient recyclable catalyst for the synthesis of 1,2,3-triazoles by the azide-alkyne 95 cycloaddition.

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Notes and references

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- R. Huisgen, 1,3-Dipolar Cycloaddition Chemistry; Padwa, A., 1. Ed.; Wiley: New York, 1984.
- 2. D. S. Pedersen and A. Abell, Eur. J. Org. Chem., 2011, 2399-2411 3
- K. Nwe and M. W. Brechbiel, Cancer Biother. Radiopharm., 2009, 24, 289-302.
- 4 K. F. Donnelly, A. Petronilho and M. Albrecht, Chem. Commun. 2013, 49, 1145–1159.
- S. G. Agalave, S. R. Maujan and V.S. Pore, Chem. Asian J. 5. 2011, 6, 2696-2718.
- P. Thirumurugan, D. Matosiuk and K. Jozwiak, Chem. Rev., 6 2013. 113. 4905-4979.
- 7. F. Wang, H. Fu, Y. Jiang and Y. Zhao, Green Chem., 2008, 10, 452-456.
- C. R. Becer, R. Hoogenboom and U.S. Schubert, Angew. 8 Chem., Int. Ed., 2009, 48, 4900-4908.
- 9 F. Himo, T. Lovell, R. Hilgraf, V.V. Rostovtsev, L. Noodleman, K. B. Sharpless and V. V. Fokin, J. Am. Chem. Soc., 2005, 127, 210-216.
- J. E. Moses and A. D. Moorhouse, Chem. Soc. Rev. 2007, 36, 10 1249-1262.
- 11. F. Alonso, Y. Moglie, G. Radivoy and M. Yus, Eur. J. Org. Chem., 2010, 2010, 1875-1884.
- E. J. Yoo, M. Ahlquist, S. H. Kim, I. Bae, V. V. Fokin, K. B. 12 Sharpless and S. Chang, Angew. Chem., Int. Ed., 2007, 46, 1730-1733.
- 13 D. Wang, N. Li, M. Zhao, W. Shi, C. Ma and B. Chen, Green Chem., 2010, 12, 2120-2123.
- 14 Z. Zhang, C. Dong, C. Yang, D. Hu, J. Long, L. Wang, H. Li, Y. Chen and D. Kong, Adv. Synth. Catal., 2010, 352, 1600-1604
- 15. C. Shao, R. Zhu, S. Luo, Q. Zhang, X. Wang and Y. Hu, Tetrahedron Lett., 2011, 52, 3782-3785.
- 16. H. López-Ruiz, J. E. de la Cerda-Pedro, S. Rojas-Lima, I. Pérez-Pérez, B. V. Rodríguez-Sánchez, R. Santillán and O. Coreño, ARKIVOC, 2013, 139-164.
- 17. M. N. S. Rad, S. Behrouz, A. Movahedian, M. M. Doroodmand, Y. Ghasemi, S. Rasoul-Amini, A.-R. A. Gandomani and R. Rezaie, Helv. Chim. Acta, 2013, 96, 688-701.
- 18. K. Wang, X. Bi, S. Xing, P. Liao, Z. Fang, X. Meng, Q. Zhang, Q. Liu and Y. Ji, Green Chem., 2011, 13, 562-565.
- 19 I. Prakash, P. Muralidharan, N. Nallamuthu, M. Venkateswarlu and N. Satyanarayana, Mater. Res. Bull. 2007, 42. 1619-1624.
- A. Mateen, J. Pak. Mater. Soc. 2008, 2, 40-43 20.
- 21 L. Gou and C.J. Murphy, Nano Lett. 2003, 3, 231-234.
- 22 R. G. Finke and S. Oezkar, Coord. Chem. Rev., 2004, 248, 135 - 146
- 23. S. Oezkar and R. G. Finke, J. Am. Chem. Soc., 2002, 124, 5796-5810
- 24 R. G. Finke, Metal Nanoparticles, 2002, 17-54.
- A. Troupis, A. Hiskia and E. Papaconstantinou, Angew. 25 Chem. Int. Ed., 2002, 41, 1911-1914.
- V. Kogan, Z. Aizenshtat, R. Popovitz-Biro and R. Neumann, 26. Org. Lett., 2002, 4, 3529-3532
- X. L'opez, J. A. Fern'andez and J. M. Poblet, Dalton Trans., 27 2006, 1162-1167.
- J. J. Borr'as-Almenar, E. Coronado, A. Muller and M. T. 28 Pope, Polyoxometalate Molecular Science, Kluwer Academic Publishers, Dordrecht, 2003.
- 29. M. T. Pope, Heteropoly and IsopolyOxometalates, Springer-Verlag. Berlin, 1983.
- M. Sadakane and E. Steckhan, Chem. Rev., 1998, 98, 219-30 237.
- R. Contant and G. Hervé, Rev. Inorg. Chem. 2002, 22, 63-31 111.
- 32 D-L. Long, R. Tsunashima and L. Cronin, Angew. Chem., Int. Ed. 2010, 49, 1736-1758.
- J. Song, Z. Luo, D. K. Britt, H. Furukawa, O. M. Yaghi, K. I. 33. Hardcastle and C. L. Hill, J. Am. Chem. Soc. 2011, 133, 16839-16846

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- C.-Y. Sun, S-X. Liu, D-D. Liang, K-Z. Shao, Y-H. Ren and Z-M. Su, J. Am. Chem. Soc. 2009, 131, 1883–1888
- H-Y. Liu, G-H. Wang, J. Yang, Y-Y. Liu and J-F. Ma, Inorg. Chem. Commun. 2014, 50, 92-96.
- M. Amini, H. Naslhajian, S.M.F. Farnia and M. Hołyńska, Eur. J. Inorg. Chem. 2015, 2015, 3873–3878.
 - 37. X. Qiu, M. Liu, K. Sunada, M. Miyauchi and K. Hashimoto, Chem. Commun. 2012, 48, 7365–7367.
- X. Qiu, M. Miyauchi, K. Sunada, M. Minoshima, M. Liu, Y. Lu, D. Li, Y. Shimodaira, Y. Hosogi and Y. Kuroda, ACS Nano 2012, 6, 1609–1618.
 - P. Veerakumar, M. Velayudham, K-L. Lu, S. Rajagopal, Catal. Sci. Technol., 2011, 1, 1512–1525.

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Graphical Abstract



A $Cu_2O@$ ({ Mo_{36} } composite has been utilized as a recyclable catalyst for the Huisgen 1,3-dipolar cycloaddition reaction.