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Synthesis and characterization of active cuprous oxide particles and their catalytic application in 1,2,3-triazole synthesis via alkyne-azide cycloaddition reaction in water

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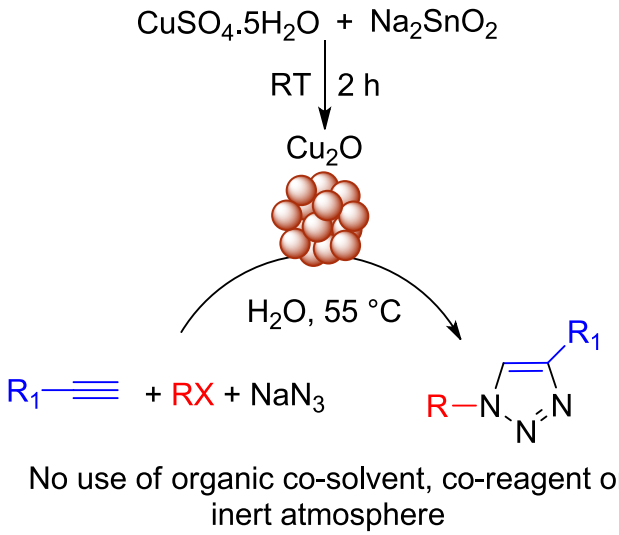
Abstract

Active cuprous oxide materials are synthesized from $CuSO_4.5H_2O$ using sodium stannite as reducing agent in the presence of various stabilizers, viz., cetyl trimethyl ammonium bromide, sodium dodecyl sulphate, and polyvinyl pyrrolidone. The synthesized cuprous oxide materials are well characterized by powder X-ray diffraction and Fourier transform infrared spectroscopy to ascertain their identity, while field emission scanning electron microscopy and energy-dispersive spectroscopy analysis were used to study their morphology and composition, respectively. We have compared the catalytic prowess of the various cuprous oxide materials in the cycloaddition reaction of alkynes and azides to synthesize 1,4-disubstituted-1,2,3-triazoles. A wide variety of substitutions can nicely be tolerated in our optimized reaction conditions to produce very good to excellent yields of the corresponding triazoles in water at 55 °C. The reactions are carried out in water without any assistance of organic cosolvent or other additives, which renders the catalytic method as economical and environment friendly.

1 | INTRODUCTION

The 1,2,3-triazole derivatives are found in several pharmaceutical compounds,[1] which show various biological properties such as antiallergic,[2] antiviral,[3] anticancer,[4] anti-HIV,[5] and antimicrobial[6] activities. Furthermore, the 1,2,3-triazole based compounds are also used as agrochemicals, corrosion inhibition (of copper and copper alloys), dyes, photographic materials, and photostabilizers, etc.[7] Commonly, these compounds are synthesized via the 1,3-dipolar cycloaddition reaction of organic azides with terminal alkynes. With the pioneering contributions by Sharpless et al[8] and Meldal et al[9] independently, on Cu(I) catalyzed alkyne-azide cycloaddition (CuAAC) reaction, the regiospecific synthesis of 1,4-disubstituted-1,2,3-triazoles became a very powerful tool to the synthetic chemists. Inspired by the above mentioned pioneering works on CuAAC reaction, many research groups have conferred their interests in developing new methodologies for the construction of 1,2,3-triazole moieties in both the homogeneous and heterogeneous reaction medium.[10] In this context, the application of copper-based nanocatalysts in heterogeneous CuAAC reaction has gone through paramount expansion in recent times.[11] It is now well understood that the nanocatalysts show superior catalytic efficiency compared with bulk catalytic materials because of the high surface-to-volume ratio of the nanoparticles.[12] Our continuing efforts in developing new methods of synthesizing active metal(0) species from their respective metals salts for their applications in C—C bond forming reactions[13] led us to develop an alternate route to synthesize active Cu_2O particles from



SCHEME 1 Synthesis of active Cu_2O particles and their applications in CuAAC reaction [Color figure can be viewed at wileyonlinelibrary.com]

copper (II) salt using sodium stannite as the reducing agent for catalyzing the CuAAC reaction (Scheme 1). Four different Cu_2O materials have been synthesized via the reduction of $CuSO_4$ solution by freshly prepared sodium stannite (Na_2SnO_2) solution in the presence of stabilizers such as cetyl trimethyl ammonium bromide (CTAB), sodium dodecyl sulphate (SDS), and polyvinyl pyrrolidone (PVP) and in absence of any stabilizer. After characterizing the four cuprous oxide materials using powder X-ray diffraction (XRD), Fourier transform infrared (FTIR), field emission scanning electron microscopy (FESEM), and energy-dispersive spectroscopy (EDS), we have compared their potential as a catalyst in the alkyne-azide cycloaddition reaction. In this regard, excellent yields of 1,4-disubstituted-1,2,3-triazoles were obtained in water under an air atmosphere in a few hours. In addition to developing an alternative approach to synthesize cuprous oxide materials, the present work also demonstrates their excellent catalytic efficiency in alkyne-azide cycloaddition reaction. The use of water as a solvent without the assistance of organic co-solvent, additives, or inert atmosphere in the Cu_2O-catalyzed protocol reported here makes it an attractive alternative for laboratory synthesis of triazoles.

2 | RESULTS AND DISCUSSION

Our investigation started with the synthesis of active Cu_2O materials in both the absence and presence of stabilizers (such as CTAB, SDS, and PVP) via a redox-driven path (Scheme 1). Cu_2O materials synthesized in presence of CTAB is hereafter referred to as Cu_2O-CTAB, and likewise, Cu_2O materials synthesized in presence of SDS or PVP will be referred to as Cu_2O-SDS and Cu_2O-PVP, respectively. The synthesis of cuprous oxide particles proceeded by a wet chemical reaction between $Cu_2SO_4.5H_2O$ solution and freshly prepared Na_2SnO_2 solution as the reducing agent (standard reduction potential of Cu^{2+}/Cu^{+} = +0.153 V and standard reduction potential of SnO_2^{-3}/SnO_2^{-2} = −0.93 V). The reduction completes in 2 hour resulting a brick-red precipitate of Cu_2O materials (Figure 1), which is confirmed by several characterization technique such as powder XRD, FTIR, FESEM, and EDS.

XRD measurements of the synthesized Cu_2O materials were performed to know the crystalline nature of the different Cu_2O samples. Figure 2 shows the XRD pattern of Cu_2O-CTAB, Cu_2O-SDS, Cu_2O-PVP, and Cu_2O materials. The observed diffraction peaks at 2θ = 30.33, 36.47, 42.41, 52.29, 61.47, 73.80, and 77.46° correspond to (110), (111), (200), (211), (220), (311), and (222) planes, respectively, of the cuprous oxide present in the Cu_2O-CTAB sample (Figure 2A). The diffraction peaks at 2θ = 29.70, 36.54, 42.54, 52.64, 61.67, 73.88, and 77.76° corresponds to (110), (111), (200), (211), (220), (311), and (222) planes, respectively, of the cuprous oxide present in the Cu_2O-SDS sample (Figure 2B). The diffraction peaks at 2θ = 29.62, 36.52, 42.54, 52.64, 61.67, 73.73, and 77.69° corresponds to (110), (111), (200), (211), (220), (311), and (222) planes, respectively, of the cuprous oxide present in the Cu_2O-PVP sample (Figure 2C). The diffraction peaks at 2θ = 29.62, 36.49, 42.29, 52.72, 61.57, 73.73, and 77.59° corresponds to (110), (111), (200), (211), (220), (311), and (222) planes, respectively, of the Cu_2O sample (Figure 2D). The above mentioned XRD patterns of the four samples are in good agreement with the crystalline Cu_2O with JCPDS Card No. 05-0667 and are phase pure.[14]

We have recorded the FTIR spectra (Figure 3) of all the four varieties of Cu_2O samples to ascertain the formation of Cu(I)—O bond. As per the literature, the stretching mode of the Cu(I)—O bond of cuprous oxide absorbs at 630.3 cm^{-1} in the infrared region.[15] With minor differences, we have noticed a strong absorption peak corresponding to the stretching vibration of the Cu(I)—O bond in all the four varieties of Cu_2O samples, as shown in Figure 3.

After confirming the identity of Cu_2O, we have analyzed the morphology of the synthesized samples using FESEM technique (Figure 4). We have observed that the Cu_2O-CTAB sample predominantly exhibits flake morphology with the thickness of the flakes being around 20 to 30 nm and the lateral size of around 200 to 300 nm (Figures 4A and 4B). All the other three samples namely Cu_2O-SDS, Cu_2O-PVP, and Cu_2O predominantly exhibit spherical morphology (with the spheres having a diameter of 1-2 μm), while a minor fraction of the material also shows flake structure (Figures 4C-4E). This may be due to the reason that the reduction of Cu (II) salt is kinetically

FIGURE 1 Digital images showing the formation of brick-red colored Cu_2O materials from $CuSO_4.5H_2O$ [Color figure can be viewed at wileyonlinelibrary.com]

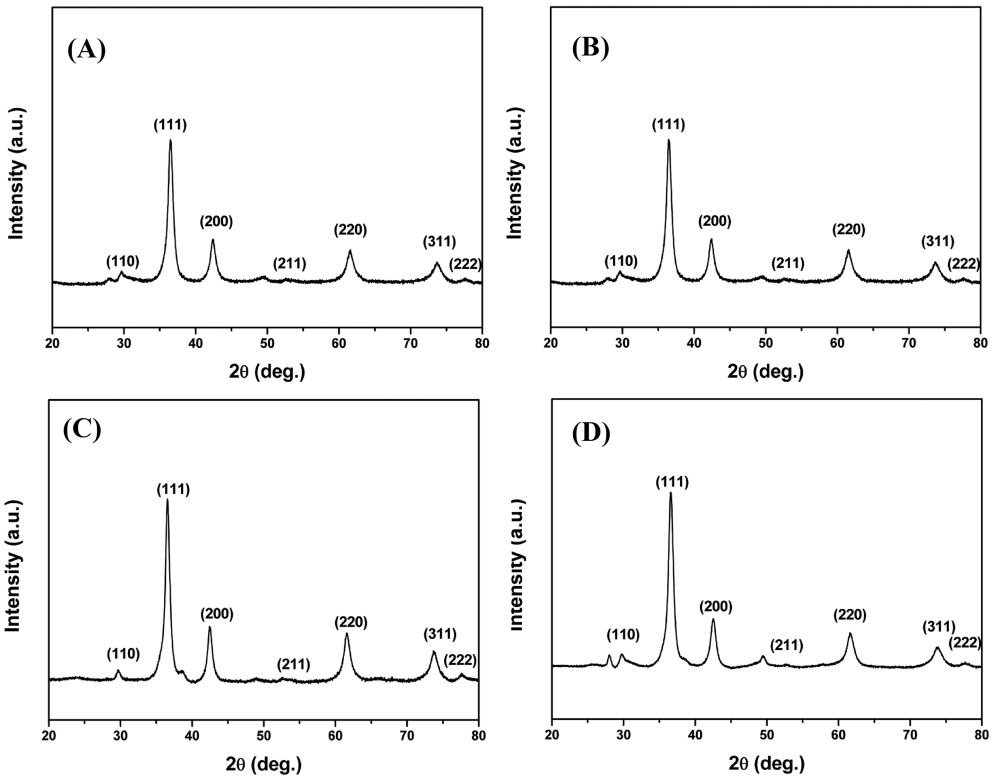


FIGURE 2 X-ray diffraction pattern of the synthesized A, Cu_2O-CTAB, B, Cu_2O-SDS, C, Cu_2O-PVP, and D, Cu_2O particles

controlled by the strong reductant Na_2SnO_2, and hence, the particles turn to preferably have a spherical shape and the stabilizers though controlled the growth to nm range but could not have specific control over their shapes. The elemental compositions of all the synthesized Cu_2O materials were obtained by EDS analysis (Figure 4F). The presence of carbon, nitrogen, and bromine apart from copper and oxygen in the Cu_2O-CTAB sample establishes the presence of the stabilizer (CTAB) on the metal oxide. Similarly, the incorporation of the stabilizers SDS and PVP are also confirmed by EDS analysis of Cu_2O-SDS and Cu_2O-PVP samples, respectively (Figure 4F). The EDS spectra of all the four synthesized cuprous oxides samples are shown in Figure 5.

After characterizing of the synthesized Cu_2O materials, we have tested their catalytic prowess in the alkyne-azide cycloaddition reaction. Initially, we took benzyl bromide **1a**, phenylacetylene **2a**, and sodium azide **3** as representative substrates and tested different reaction conditions. At the outset, we have evaluated the potential

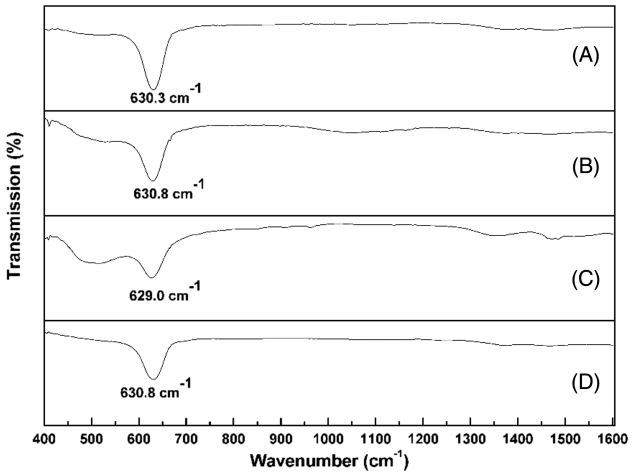
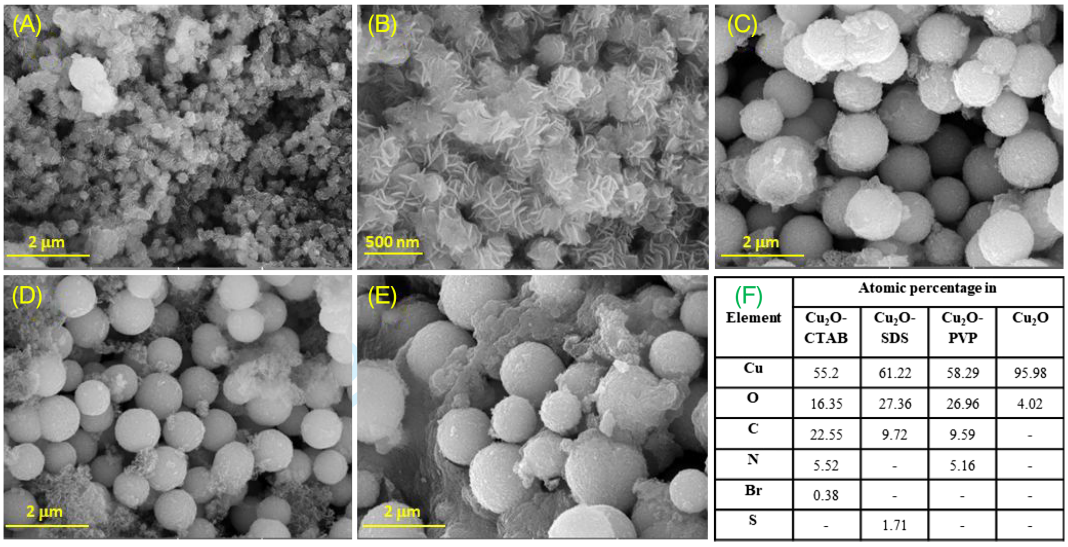


FIGURE 3 Fourier transform infrared spectra of A, Cu_2O-SDS, B, Cu_2O-PVP, C, Cu_2O-CTAB, and D, Cu_2O materials

of all four synthesized Cu_2O materials as catalysts in CuAAC reaction (Table 1, entries 1-4) in EtOH solvent at 25 °C. Out of the four Cu_2O materials, we have noted that the Cu_2O-CTAB shows better catalytic efficiency in alkyne-azide cycloaddition reaction than the other Cu_2O materials. This observation can be explained on the basis of available surface area on the Cu_2O catalysts. Cu_2O-CTAB, predominantly exhibiting flake morphology, offers significantly higher surface area available for catalysis compared with the other varieties showing spherical morphology. Although Cu_2O-CTAB ascended as the catalyst of choice, the underwhelming yield of 64% of the product **4a** obtained at 25 °C in EtOH needs to be addressed. Accordingly, we have changed the solvent to *i*-PrOH and obtained an even lower yield of the desired product **4a** (Table 1, entry 5). When we used aqueous EtOH (1:1), the yield of **4a** improved to 70% (Table 1, entry 6). Encouraged by the results, we have tested water as the only solvent for the CuAAC reaction and obtained 78% yield of the desired product (Table 1, entry 7) at 25 °C. We also studied the effect of temperature and noticed that the reaction proceeds better when the temperature is raised to 55 °C generating a significant 91% yield of **4a** (Table 1, entry 8). Similarly, we checked the effect of temperature on the catalytic efficiency of the other cuprous oxide materials and noted an increase in the yield of the desired product in comparison to the corresponding reaction at room temperature (Table 1, entries 9-11). However, Cu_2O-CTAB remained the catalyst of choice as the yield of the desired product is significantly higher than other cuprous oxide materials. Further increase in the temperature to 80 °C does not improve the yield of the addition product appreciably (Table 1, entry 12). On varying the amount of the catalyst employed in the reaction, we noted that the use of 4 mg catalyst produces optimum results (Table 1, entries 8 and 13-14).

After optimization of the reactions conditions, we have tested the substrate scope of the method using various alkyl halides **1** and alkynes **2**. Initially, we reacted several structurally and functionally diverse alkyl halides (**1a**-**i**) with sodium azide **3** and phenylacetylene **2a** under the optimized reaction conditions to produce triazoles **4a**-**h** (Table 2, entries 1-9). We have noticed that the presence of electron-donating or electron-withdrawing group on the aromatic ring of the benzyl halide does not significantly affect the yield of the corresponding product. We were pleased to find that the reaction proceeds well when



(F)

Element	Atomic percentage in			
	Cu_2O-CTAB	Cu_2O-SDS	Cu_2O-PVP	Cu_2O
Cu	55.2	61.22	58.29	95.98
O	16.35	27.36	26.96	4.02
C	22.55	9.72	9.59	-
N	5.52	-	5.16	-
Br	0.38	-	-	-
S	-	1.71	-	-

FIGURE 4 A, Field emission scanning electron microscopy (FESEM) image of Cu_2O-CTAB sample. B, FESEM image of Cu_2O-CTAB sample at higher magnification. C, FESEM image of Cu_2O-SDS sample. D, FESEM image of Cu_2O-PVP sample. E, FESEM image of Cu_2O sample and F, table showing the atomic percentages of various elements present in the corresponding Cu_2O samples obtained from energy-dispersive spectroscopy analysis [Color figure can be viewed at wileyonlinelibrary.com]

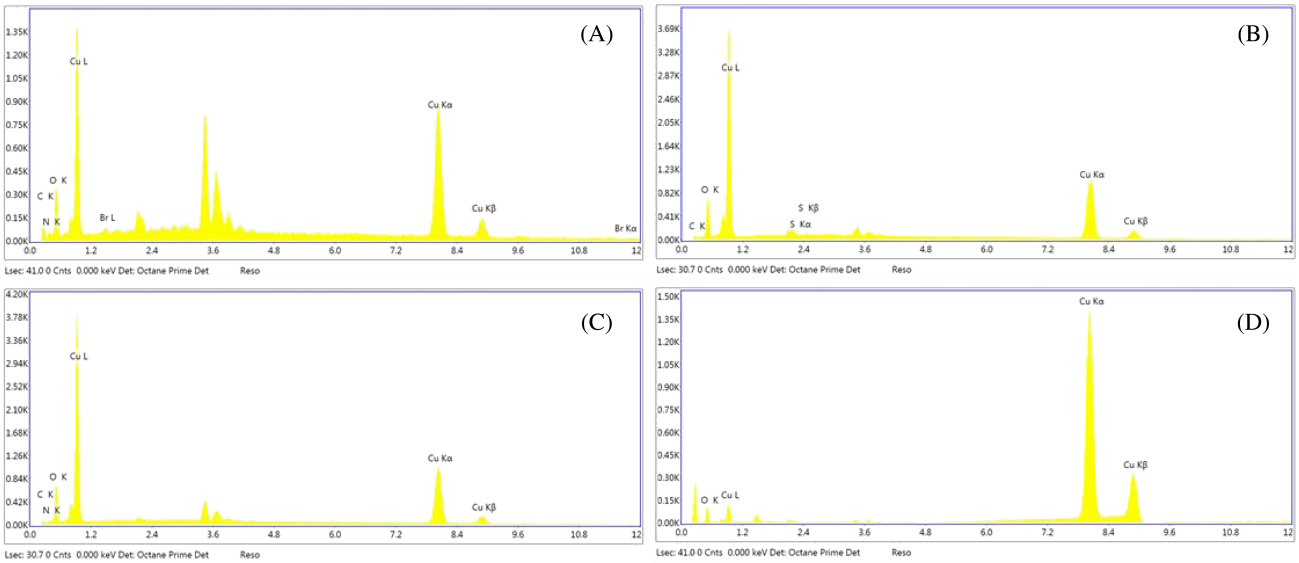
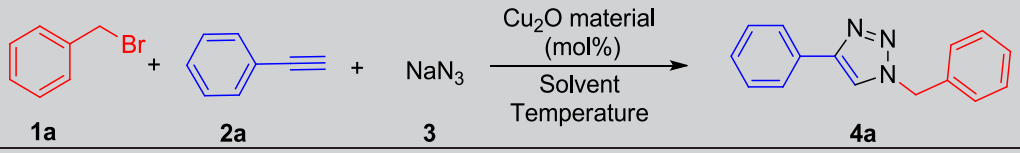


FIGURE 5 Energy-dispersive spectroscopy spectra of A, Cu_2O-CTAB, B, Cu_2O-SDS, C, Cu_2O-PVP. and D, Cu_2O samples [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Optimization of reaction conditions[a]



1a 2a 3 4a

Entry	Solvent	Catalyst	Temperature, °C	Yield of 4a, %[b]
1	EtOH	Cu_2O-CTAB	25	64
2	EtOH	Cu_2O-SDS	25	53
3	EtOH	Cu_2O-PVP	25	50
4	EtOH	Cu_2O	25	40
5	*i*-PrOH	Cu_2O-CTAB	25	60
6	EtOH:H_2O (1:1)	Cu_2O-CTAB	25	70
7	H_2O	Cu_2O-CTAB	25	78
8	H_2O	Cu_2O-CTAB	55	91
9	H_2O	Cu_2O-SDS	55	76
10	H_2O	Cu_2O-PVP	55	71
11	H_2O	Cu_2O	55	52
12	H_2O	Cu_2O-CTAB	80	92
13[c]	H_2O	Cu_2O-CTAB	55	82
14[d]	H_2O	Cu_2O-CTAB	55	93

[a]Reaction conditions: **1a** (1.2 mmol), **2a** (1 mmol), **3** (1.2 mmol), Cu_2O catalysts (4 mg), solvent (3 mL), temperature, time 2 h.

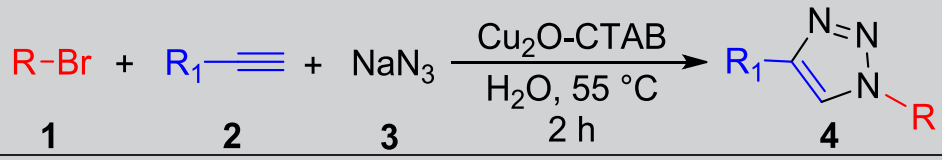
[b]Isolated yields.

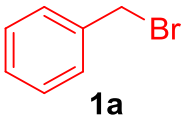
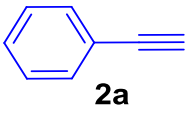
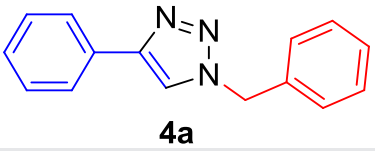
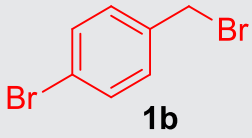
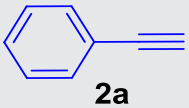
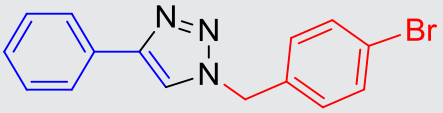
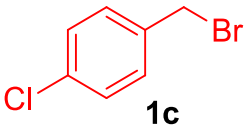
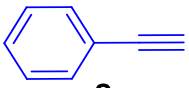
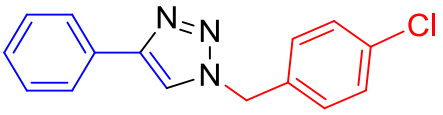
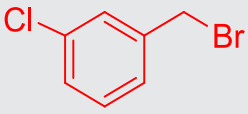
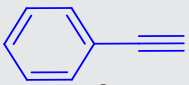
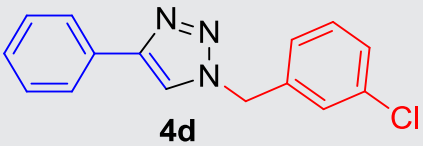
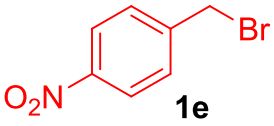
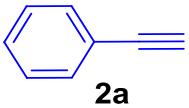
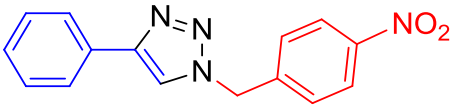
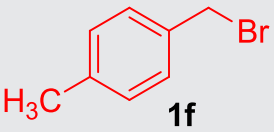
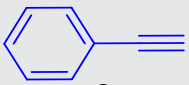
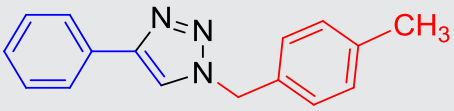
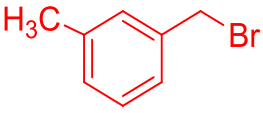
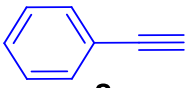
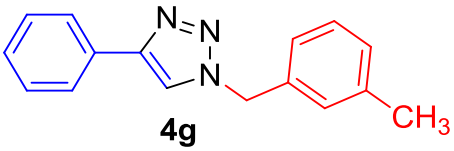
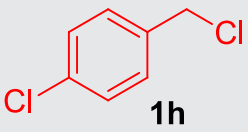
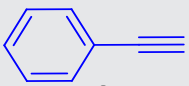
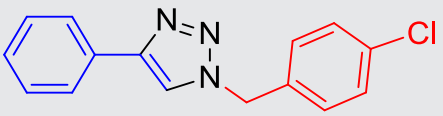
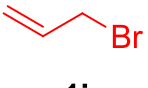
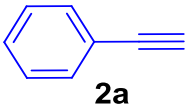
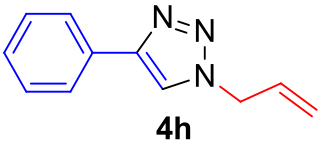
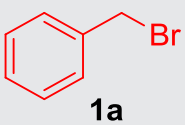
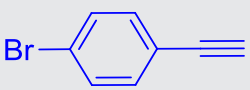
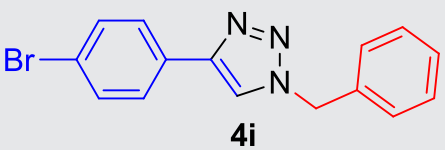
[c]Catalyst 2 mg.

[d]Catalyst 6 mg.

allyl bromide **1i** is used instead of **1a** generating 82% yield of the desired product **4h** (Table 2, entry 9). We have also tested several terminal acetylenes **2b**-**f** to react with benzyl bromide **1a** and sodium azide **3** in our reaction conditions to generate the corresponding triazoles **4** in good to excellent yields (Table 2, entries 10-14). It is to be noted that the hydroxyl group in the propargyl alcohol **2f** was unaffected in our reaction medium (Table 2, entry

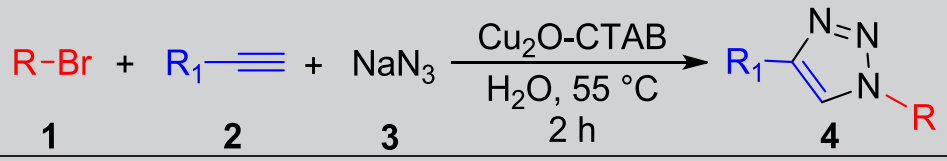
TABLE 2 Cu_2O-CTAB catalyzed synthesis of substituted 1,2,3-triazoles in water[a]



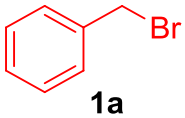
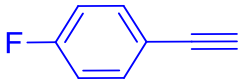
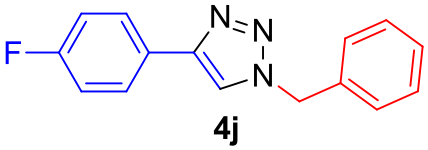
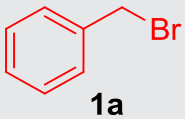
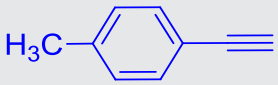
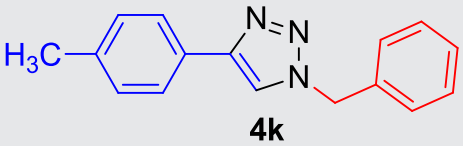
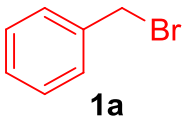
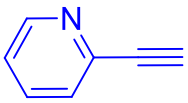
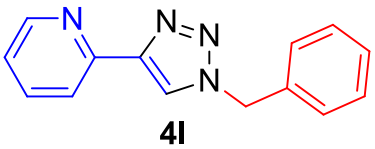
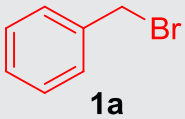
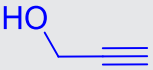
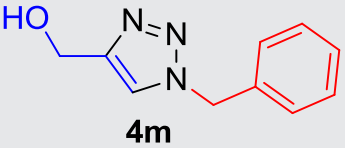
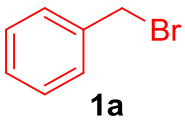
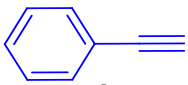
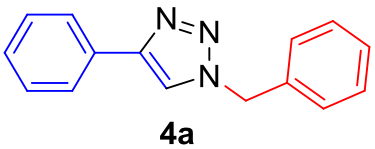
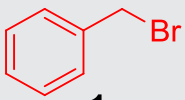
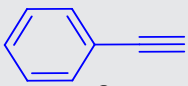
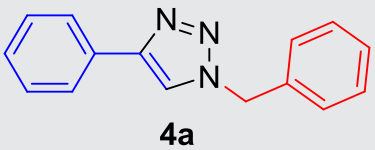
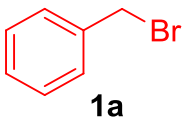
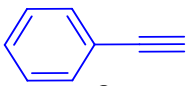
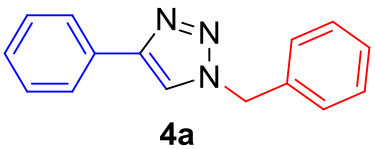
Entry	Alkyl halide 1	Alkyne 2	Product 4	Yield, %[b]
1	 1a	 2a	 4a	91
2	 1b	 2a	 4b	93
3	 1c	 2a	 4c	90
4	 1d	 2a	 4d	91
5	 1e	 2a	 4e	86
6	 1f	 2a	 4f	88
7	 1g	 2a	 4g	90
8	 1h	 2a	 4c	89
9	 1i	 2a	 4h	82
10	 1a	 2b	 4i	89

(Continues)

TABLE 2 (Continued)



1 2 3 4

Entry	Alkyl halide 1	Alkyne 2	Product 4	Yield, %[b]
11	 1a	 2c	 4j	91
12	 1a	 2d	 4k	87
13	 1a	 2e	 4l	83
14	 1a	 2f	 4m	80
15[c]	 1a	 2a	 4a	90
16[d]	 1a	 2a	 4a	78
17[e]	 1a	 2a	 4a	61

[a]Reaction conditions: **1** (1.2 mmol), **2** (1 mmol), **3** (1.2 mmol), Cu_2O-CTAB (4 mg), H_2O (3 mL), 55 °C, time 2 h.

[b]Isolated yields.

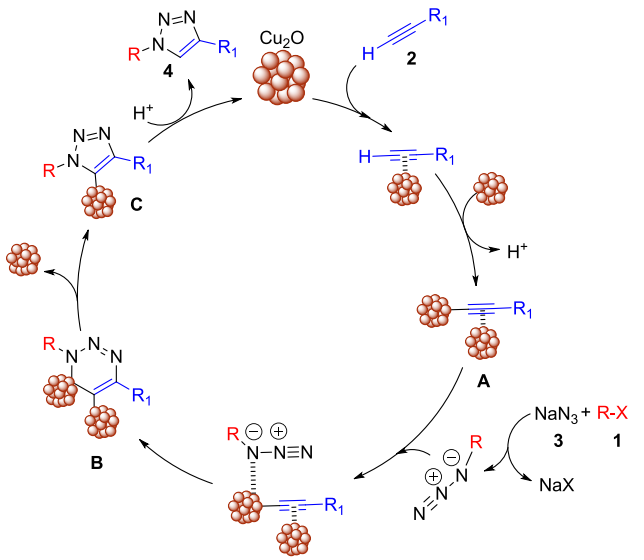
[c]Reaction conditions: **1** (6 mmol), **2** (5 mmol), **3** (6 mmol), Cu_2O-CTAB (20 mg), H_2O (15 mL), 55 °C, Time 2 h.

[d]Cu_2O-CTAB reused after entry 1.

[e]Cu_2O-CTAB reused after entry 16.

14). We also tested the scalability of the developed method by carrying out the reaction in 5 mmol scale where we have obtained 90% (1.06 g) of the desired product **4a**. Furthermore, the catalyst Cu_2O-CTAB can be reused for subsequent alkyne-azide cycloaddition reaction as shown in Table 2 (entry 1, 16-17) although the catalytic efficiency decreases gradually. The decrease in the catalytic activity of the Cu_2O catalyst may be attributed to the slow surface oxidation of the catalyst to CuO as understood by its indicative greenish-brown color after the third cycle.

With the knowledge of relevant literature, we propose the probable reaction mechanism outlined in Scheme 2. The reaction may be initiated with the interaction of active Cu_2O particles and the alkyne **2** to eventually form the copper acetylide intermediate **A**.[10d] Alkyl azide is



SCHEME 2 Probable reaction mechanism of the active Cu_2O catalyzed formation of 1,4-disubstituted-1,2,3-triazole from benzyl halide **1** and terminal alkyne **2** [Color figure can be viewed at wileyonlinelibrary.com]

generated in situ in the reaction medium from the reaction of sodium azide **3** and alkyl halide **1**, which coordinates with the intermediate **A** to form an unusual copper metallocycle **B**. The intermediate **B** immediately undergoes reductive elimination to produce copper triazolide complex **C**, which in the presence of H^+ yields the desired 1,4-disubstituted-1,2,3-triazole releasing the active Cu(I) catalyst in the reaction medium.[10d] However, alternative pathways involving structurally different intermediates cannot be ruled out.

3 | CONCLUSION

In summary, we have synthesized four different types of Cu_2O materials by reduction of copper sulphate with freshly prepared sodium stannite solution in the presence and absence of stabilizers. The as-synthetized Cu_2O materials have been characterized by various analytical techniques, such as powder XRD, FTIR, FESEM and EDS. We have observed that Cu_2O materials when synthesized in presence of CTAB had predominantly flake morphology with the thickness of the flakes being around 20 to 30 nm. In contrast, the absence of stabilizer or the use of PVP and SDS as stabilizers during the synthesis of Cu_2O materials yielded majorly spherical micro-particles of diameters around 1 to 2 μm. We have also studied the catalytic prowess of the four different types of Cu_2O materials in the CuAAC reaction and found that the Cu_2O-CTAB sample shows better catalytic property by virtue of its high surface area. The Cu_2O-CTAB catalyzed optimized reaction conditions revealed that water serves as the best solvent to generate excellent yields of 1,4-disubstituted-1,2,3-triazoles thereby making the developed method environmental friendly. We have demonstrated that the method tolerates wide varieties of alkynes and benzyl halides. Further potential for application of the synthesized Cu_2O materials in the domain of catalysis is currently being explored in our laboratory.

4 | EXPERIMENTAL

4.1 | General remarks

All reagents and solvents are of AR grade and were purchased from Alfa Aesar, Spectrochem, Merck Pvt. Ltd., or Sisco Research Laboratories Pvt. Ltd. and used without further purification unless otherwise stated. All the reactions were done in oven-dried glass apparatus in an air atmosphere. Reactions were monitored by thin-layer chromatography on silica gel 60 F_{254} using UV light as a visualizing agent. Melting points reported are uncorrected. Powder XRD analysis was done in a PW1710 diffractometer (Philips) and processed by JCPDS software. FESEM and EDS analyses were carried out in supra, Carl Zeiss Pvt. Ltd. Instrument and Oxford link (ISIS 300) connected to the FESEM machine, respectively. FTIR studies were done in a PerkinElmer SpectrumTwo instrument using KBr pellets. ^1H and ^{13}C NMR spectra were measured on a Bruker Avance II (^1H NMR: 400 MHz and ^{13}C NMR: 100 MHz) spectrometer. Chemical shifts are reported in ppm from tetramethylsilane (TMS), with the solvent resonance as the internal standard (unless otherwise mentioned, chloroform: δ 7.26 ppm). Data are reported as follows: chemical shifts, multiplicity (s=singlet, d=doublet, t=triplet, q=quartet, br=broad, dd=double doublet, m=multiplet), coupling constant (in Hz), integration. ^{13}C NMR spectra were recorded at 100 MHz with proton decoupling. Chemical shifts are reported in ppm from tetramethylsilane (TMS) with the solvent resonance as the internal standard (unless otherwise mentioned, chloroform: δ 77.0 ppm).

4.2 | Preparation of sodium stannite (Na_2SnO_2) solution

In a 100 mL beaker, 1.5 mmol (338.4 mg) of $SnCl_2.2H_2O$ was dissolved in 15 mL of distilled water to which 3 mL of 5 M NaOH was added and stirred. The milky white suspension turned into a colorless Na_2SnO_2 solution, which was further diluted by adding water to make up the volume up to 50 mL. The as-synthesized Na_2SnO_2

solution is ready to be used for the preparation of cuprous oxide materials.[13]

4.3 | Preparation of different Cu_2O materials

4.3.1 | Preparation of Cu_2O material in the presence of CTAB stabilizer

In a 250 mL beaker, 10 mL of 10 mM aqueous solution of CTAB was added to a solution of 1 mmol (249.7 mg) of $CuSO_4.5H_2O$ in 100 mL of distilled water. The resulting solution was stirred gently at room temperature and 50 mL of the freshly prepared Na_2SnO_2 solution (as synthesized above) was added to it. The light blue solution of Cu_2SO_4 immediately turned to green color upon addition of the alkaline Na_2SnO_2 solution and the stirring was further continued for 2 hour till the entire solution turned to brick-red. Then the solution was centrifuged at 7000 rpm for 10 min, and the brick-red solid material was washed several times with distilled water till the washings were neutral to pH. Finally, the solid material was washed with ethanol and dried under vacuum. The sample is represented as Cu_2O-CTAB.

4.3.2 | Preparation of Cu_2O material in the presence of SDS stabilizer

In a 250 mL beaker, 10 mL of 10 mM aqueous solution of SDS was added to a solution of 1 mmol (249.7 mg) of $CuSO_4.5H_2O$ in 100 mL of distilled water. The resulting solution was stirred gently at room temperature and 50 mL of the freshly prepared Na_2SnO_2 solution (as synthesized above) was added to it. The light blue solution of Cu_2SO_4 immediately turned to green color upon addition of the alkaline Na_2SnO_2 solution, and the stirring was further continued for 2 hour till the entire solution turned to brick-red. Then the solution was centrifuged at 7000 rpm for 10 min, and the brick-red solid material was washed several times with distilled water till the washings were neutral to pH. Finally, the solid material was washed with ethanol and dried under vacuum. The sample is represented as Cu_2O-SDS.

4.3.3 | Preparation of Cu_2O material in presence of PVP stabilizer

In a 250 mL beaker, 10 mL of PVP solution in water (0.4% m/v) was added to a solution of 1 mmol (249.7 mg) of $CuSO_4.5H_2O$ in 100 mL of distilled water. The resulting solution was stirred gently at room temperature and 50 mL of the freshly prepared Na_2SnO_2 solution (as synthesized above) was added to it. The light blue solution of Cu_2SO_4 immediately turned to green color upon addition of the alkaline Na_2SnO_2 solution, and the stirring was further continued for 2 hour till the entire solution turned to brick-red. Then the solution was centrifuged at 7000 rpm for 10 min, and the brick-red solid material was washed several times with distilled water till the washings were neutral to pH. Finally, the solid material was washed with ethanol and dried under vacuum. The sample is represented as Cu_2O-PVP.

4.3.4 | Preparation of Cu_2O material in the absence of a stabilizer

A solution of 1 mmol (249.7 mg) of $CuSO_4.5H_2O$ in 100 mL of distilled water was stirred gently at room temperature, and 50 mL of the freshly prepared Na_2SnO_2 solution (as synthesized above) was added to it. The light blue solution of Cu_2SO_4 immediately turned to green color upon addition of the alkaline Na_2SnO_2 solution, and the stirring was further continued for 2 hour till the entire solution turned to brick-red. Then the solution was centrifuged at 7000 rpm for 10 min, and the brick-red solid material was washed several times with distilled water till the washings were neutral to pH. Finally, the solid material was washed with ethanol and dried under vacuum.

4.4 | Typical procedure for Cu_2O-CTAB catalyzed synthesis of triazole 4a.

A 25 mL round-bottomed flask equipped with a magnetic bar and water condenser was charged with benzyl bromide **2a** (142 μL, 1.2 mmol), sodium azide **3** (78 mg, 1.2 mmol), and 3 mL of distilled water and allowed to stir for 15 min at room temperature. After 15 min, phenylacetylene **1a** (110 μL, 1.0 mmol) and Cu_2O-CTAB materials (4 mg) were added and the reaction mixture was placed in a pre-heated oil bath at 55 °C. The progress of the reaction was monitored by thin-layer chromatography. After completion of the reaction, the reaction mixture was extracted with EtOAc (3 × 10 mL), washed with water (2 × 10 mL) and brine water (2 × 10 mL), and dried over anhydrous Na_2SO_4. The combined organic solvent was evaporated under reduced pressure, and the crude product was purified by crystallization to obtain 91% isolated yield of the corresponding 1,2,3-triazole derivative **4a**.

4.5 | Analytical data of 1,4-disubstituted-1,2,3-triazoles 4

4.5.1 | 1-Benzyl-4-phenyl-1*H*-1,2,3-triazole (4a)[11h]

White solid. M. P. = 120°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.56 (s, 2H), 7.29-7.44 (m, 8H), 7.67 (s, 1H), 7.78-7.80 (m, 2H).^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 54.2, 119.6, 125.7, 128.1, 128.2, 128.8, 128.8, 129.2, 130.5, 134.7, 148.2.

4.5.2 | 1-(4-Bromobenzyl)-4-phenyl-1*H*-1,2,3-triazole (4b)[11h]

White solid. M. P. = 139°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.46 (s, 2H), 7.11 (d, J = 8.2 Hz, 2H), 7.25 (t, J = 7.4 Hz, 1H), 7.33 (t, J = 7.5 Hz, 2H), 7.44 (d, J = 8.2 Hz, 2H), 7.60 (s, 1H), 7.72 (d, J = 7.6 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 53.5, 119.4, 122.9, 125.7, 128.3, 128.9, 129.7, 130.3, 132.3, 133.7, 148.4.

4.5.3 | 1-(4-Chlorobenzyl)-4-phenyl-1*H*-1,2,3-triazole (4c)[11p]

Pale yellow solid. M. P. = 98°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.64 (s, 2H), 7.34-7.52 (m, 12H), 8.16-8.19 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 52.2, 102.5, 125.7, 125.8, 126.2, 128.7, 128.8, 129.1, 129.50, 129.9, 130.1, 131.6, 133.2, 134.6, 148.2.

4.5.4 | 1-(3-Chlorobenzyl)-4-phenyl-1*H*-1,2,3-triazole (4d)[11q]

White solid. M. P. = 99°C.^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.55 (s, 2H), 7.18 (d, J = 6.8 Hz, 1H), 7.30-7.35 (m, 4H), 7.41 (t, J = 7.5 Hz, 2H), 7.71 (s, 1H), 7.80-7.82 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 53.6, 119.6, 125.7, 126.1, 128.1, 128.3, 128.9, 129.0, 130.3, 130.5, 135.0, 136.6, 148.4.

4.5.5 | 1-(4-Nitrobenzyl)-4-phenyl-1*H*-1,2,3-triazole (4e)[11h]

Pale yellow solid. M. P. = 149°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.71 (s, 2H), 7.33-7.46 (m, 5H), 7.77-7.83 (m, 3H), 8.24 (d, J = 8.4 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 53.2, 119.7, 124.4, 125.7, 128.5, 128.55, 128.9, 130.1, 141.8, 148.1, 148.7.

4.5.6 | 1-(4-Methylbenzyl)-4-phenyl-1*H*-1,2,3-triazole (4f)[11h]

White solid. M. P. = 113°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 2.35 (s, 3H), 5.52 (s, 3H), 7.20-7.41 (m, 7H), 7.64 (s, 1H), 7.79 (d, J = 7.7 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 21.2, 54.01, 119.6, 125.7, 128.2, 128.8, 129.8, 130.5, 131.6, 138.8, 148.1.

4.5.7 | 1-(3-Methylbenzyl)-4-phenyl-1*H*-1,2,3-triazole (4g)[16]

White solid. M. P. = 102°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 2.34 (s, 3H), 5.53 (s, 2H),), 7.11 (d, J = 6.4 Hz, 2H), 7.17 (d, J = 7.6 Hz, 1H), 7.26-7.33 (m, 2H), 7.40 (t, J = 7.6 Hz, 2H), 7.66 (s, 1H), 7.79-7.81 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 21.4, 54.2, 119.5, 125.2, 125.7, 128.2, 128.8, 128.8, 129.0, 129.6, 130.5, 134.6, 139.1, 148.2.

4.5.8 | 1-Allyl-4-phenyl-1*H*-1,2,3-triazole (4h)[17]

White solid. M. P. = 63°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.02 (d, J = 6.0 Hz, 2H), 5.36 (t, J = 14.1 Hz, 2H), 6.01-6.12 (m, 1H), 7.33 (t, J = 7.3 Hz, 1H), 7.42 (t, J = 7.6 Hz, 2H), 7.77 (s, 1H), 7.83 (d, J = 7.7 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 52.8, 119.5, 120.2, 125.7, 128.2, 128.8, 130.6, 131.3, 148.0.

4.5.9 | 1-Benzyl-4-(4-bromophenyl)-1*H*-1,2,3-triazole (4i)[10c]

White solid. M. P. = 149°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.57 (s, 2H), 7.32 (d, J = 7.4 Hz, 2H), 7.40 (d, J = 6.3 Hz, 3H), 7.52 (d, J = 8.4 Hz, 2H), 7.67 (d, J = 8.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 54.3, 119.6, 122.1, 127.2, 128.1, 128.9, 129.2, 129.5, 131.9, 134.5, 147.2.

4.5.10 | 1-Benzyl-4-(4-fluorophenyl)-1*H*-1,2,3-triazole (4j)[11p, 11r]

White solid. M. P. = 97°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.57 (s, 1H), 7.06-7.14 (m, 2H), 7.30-7.40 (m, 5H), 7.62 (s, 1H), 7.75-7.78 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 54.3, 115.8 (d, J = 21.8 Hz), 119.2, 127.4 (d, J = 8.1 Hz), 128.1, 128.9, 129.2, 134.6, 147.4, 162.6 (d, J = 247.2 Hz).

4.5.11 | 1-Benzyl-4-(p-tolyl)-1*H*-1,2,3-triazole (4k)[11h]

White solid; M. P. = 151°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 2.37 (s, 3H), 5.58 (s, 2H), 7.22 (d, J = 7.9 Hz, 2H), 7.32 (dd, J = 7.4, 1.9 Hz, 2H), 7.37-7.43 (m, 3H), 7.63 (s, 1H), 7.70 (d, J = 8.1 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 21.3, 54.2, 119.1, 125.6, 127.7, 128.1, 128.8, 129.2, 129.5, 134.7, 138.0.

4.5.12 | 4-(1-Benzyl-1*H*-1,2,3-triazol-4-yl) pyridine (4l)[11h]

Pale yellow solid. M. P. = 99°C. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 5.58 (s, 2H), 7.19-7.38 (m, 5H), 7.75-7.79 (m, 1H), 8.06 (s, 1H), 8.18 (d, J = 7.9 Hz, 1H) 8.53 (d, J = 4.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 54.4, 120.2, 121.9, 122.9, 128.3, 128.9, 129.2, 134.3, 136.9, 148.7, 149.3, 150.2.

4.5.13 | (1-Benzyl-1*H*-1,2,3-triazol-4-yl) methanol (4m)[11p]

Pale yellow gum. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 3.65 (s, 1H), 4.75 (s, 2H), 5.50 (s, 2H), 7.26 (d, J = 7.2 Hz, 2H), 7.36 (d, J = 5.0 Hz, 3H), 7.53 (s, 1H).

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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