

## FULL PAPER

# Copper(I) stabilized on *N,N'*-methylene bis-acrylamide crosslinked polyvinylpyrrolidone: An efficient reusable catalyst for click synthesis of 1,2,3-triazoles in water

Paulson Mathew | Drishya Sasidharan | Nellickal Purushothaman Rakesh

Department of Chemistry, Centre for Sustainability Science, St. Thomas College (Autonomous), University of Calicut, Thrissur, 680001, Kerala, India

**Correspondence**

Paulson Mathew, Department of Chemistry, Centre for Sustainability Science, St. Thomas College (Autonomous), University of Calicut, Thrissur, 680001, Kerala, India.  
Email: paulson.org@gmail.com

**Funding information**

University Grants Commission, New Delhi, Grant/Award Numbers: No. 2242-MRP/15-16/KLCA019/UGC-SWRO, No.F.14-18/2013 Inno/ASIT

*N,N'*-methylene bis-acrylamide crosslinked *N*-vinyl-2-pyrrolidone (NVP MBA) polymer was prepared via suspension polymerization technique and used as a polymeric support for the reduction of Cu(II) to Cu(I). It was observed that NVP MBA matrix facilitated the stabilization of Cu(I) particles. Furthermore, the copper supported polymer catalyst (CuNVP MBA) was characterized by Fourier transform infrared, X-ray diffraction, scanning electron microscopy (SEM), energy dispersive X-ray analysis, transmission electron microscope (TEM), X-ray photoelectron spectra (XPS), inductively coupled plasma optical emission spectroscopy, and derivative thermogravimetry analysis. SEM showed that both the polymer and CuNVP MBA exhibit a spherical morphology. TEM revealed that copper nanoparticles formed on the polymer surface have an average particle size of 5.14 nm. XPS analysis confirmed the presence of Cu(I) and Cu(II) in the ratio 1:2. The copper content in CuNVP MBA was found to be 1.25 wt%. CuNVP MBA was found to be very effective in promoting the click reaction between terminal alkynes and azides in aqueous media in the absence of ascorbate or external base under mild conditions to form 1,2,3-triazoles in excellent yield with a copper loading as low as 0.2 mol%. The catalyst could be reused and recycled several times without significant loss of catalytic activity.

**KEYWORDS**

Polymer-supported copper, click reaction, 1,2,3-triazole, reaction in aqueous media, *in situ* reduction of Cu(II)

## 1 | INTRODUCTION

1,2,3-Triazoles are an important class of heterocyclic compounds and are widely used in synthetic organic chemistry and materials science.<sup>[1]</sup> They are well known for their potential biological activities such as antibacterial, antiviral, anti-HIV and anticancer

behavior.<sup>[2-4]</sup> Moreover, triazoles and their triazolylidene derivatives are versatile ligands for late transition metals that have special significance in homogeneous catalysis.<sup>[5-7]</sup> 1,2,3-Triazole derivatives are also used in industry as agrochemicals, corrosion inhibitors, and dyes.<sup>[8]</sup> The synthesis of 1,2,3-triazoles has gained significant attention after the Cu(I)-catalyzed azide-alkyne cycloaddition (CuAAC) reaction developed independently by Sharpless<sup>[9]</sup> and Meldal<sup>[10]</sup> in 2002. A plethora of methods have since been developed by various

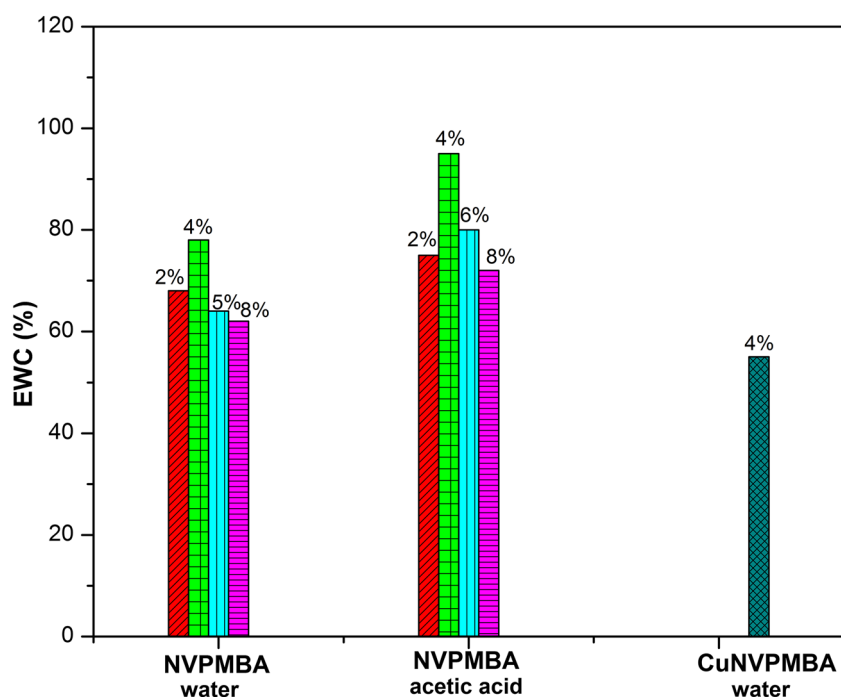
Dedicated to the memory of Rt. Rev. Adolphus E. Medlycott, founder of the college, on the occasion of the centenary year 2019.

researchers to improve its synthetic efficiency.<sup>[11]</sup> These include both homogeneous and heterogeneous systems<sup>[12]</sup> using one-pot procedures,<sup>[13]</sup> magnetic heterogeneous catalysis,<sup>[14]</sup> nanoparticles,<sup>[15]</sup> and reactions in water.<sup>[16]</sup> Although metals like silver, ruthenium, zinc, nickel etc. have been known to catalyze the reaction,<sup>[17]</sup> the Cu(I) catalyzed reaction is the most practical and useful “click” reaction for the regioselective synthesis of 1,4-disubstituted 1,2,3-triazoles.<sup>[18]</sup> To date various ligand systems have been designed and developed to stabilize and modulate the reactivity of the catalytically active Cu(I) species. However, a homogeneous click catalyst add to the problem of removing copper ions from finished products.<sup>[19]</sup> With growing environmental concerns, green protocols requiring the minimum use of catalyst, including its recovery and reuse, are in great demand. To resolve such issues, immobilizing the copper ions on solid supports like carbon, zeolite, silica, polymers etc. has been developed to synthesize the corresponding heterogeneous catalyst.<sup>[20–24]</sup> Such immobilization of copper ions onto various heterogeneous supports can generate an efficient heterogeneous catalyst for the click reaction with good catalytic activity and recyclability.

Recently, polymer-supported catalysts have been explored as recyclable heterogeneous catalysts due to their ease of preparation and post functionalization of the support. It has been observed that the copper-mediated click reaction is accelerated by the presence of certain ligands, such as tris(2-aminoethyl)amine derivatives and acrylamide, and by minimizing the amount of Cu(I) catalyst to an order of less than 1%.<sup>[25]</sup>

Polyvinylpyrrolidone (PVP), a stable, nontoxic commercially available polymer, is widely used as a stabilizer and growth modifier in the synthesis of metal nanoparticles.<sup>[26,27]</sup> It can also act as a mild reducing agent for transforming transition metals in their higher oxidation state to zero oxidation state.<sup>[28]</sup> However, such reduction processes are frequently accomplished in presence of other reducing agents such as NaBH<sub>4</sub>, ethylene glycol,<sup>[29–31]</sup> glucose<sup>[32]</sup> or hydrogen gas.<sup>[33]</sup> The reducing power of PVP is attributed to the presence of a terminal hydroxyl group.<sup>[34]</sup> Metal particles stabilized on PVP show better catalytic activity and selectivity than conventional catalysts.<sup>[35,36]</sup> With this in mind, it was presumed that a copolymer containing a pyrrolidone backbone can perform a dual role of *in situ* reduction of Cu(II) to Cu(I) and stabilization of the latter in the polymer matrix, preventing further reduction to Cu(0).

In this context, an *in situ* reduction of Cu(II) to Cu(I), from inexpensive and easily available reagent, that is, copper sulfate, using the copolymer *N,N'*-methylene bisacrylamide crosslinked with *N*-vinyl-2-pyrrolidone (NVP MBA), is reported in the present work. Subsequently, the copper-supported polymer catalyst (CuNVP MBA) was used for the click synthesis of 1,2,3-triazoles in water with very low catalyst loading. Unlike previous reports, no post functionalization of the support was required and reduction of Cu(II) to Cu(I) could be carried out without external reducing agents or an additional base.<sup>[37–41]</sup> The crosslinking agent with its basic character could provide additional stability to the Cu(I) ions and prevent further reduction to Cu(0). This catalyst was highly efficient in terms of low metal



**FIGURE 1** Swelling properties of the polymer (NVP MBA) with different degrees of crosslinking

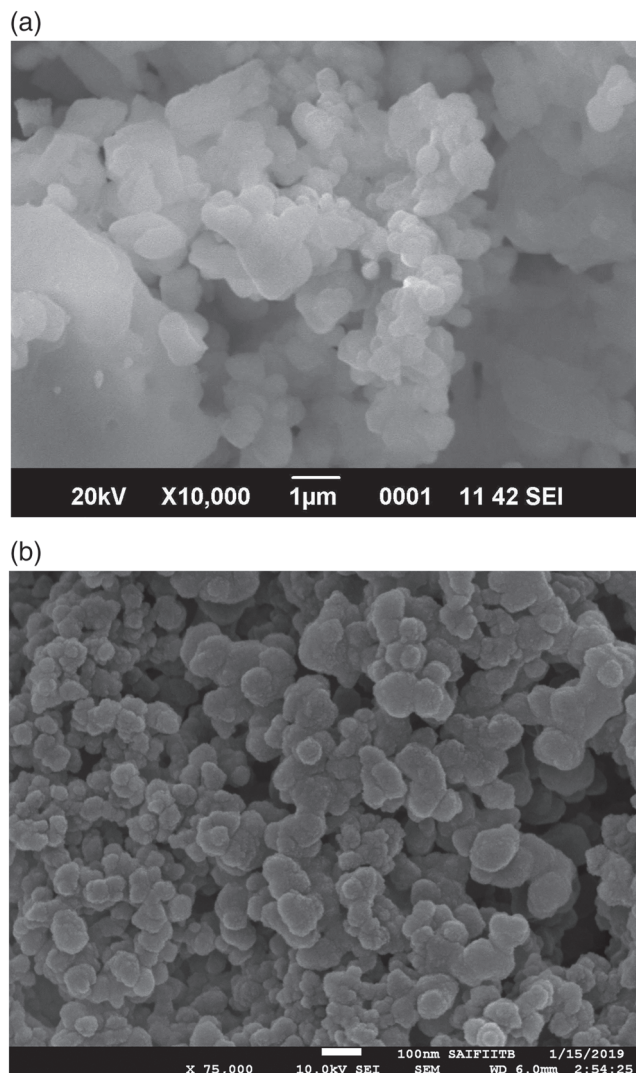
loading, reaction in water, recyclability, and robustness. It is noteworthy that with a very low amount of catalyst being loaded and exceptional efficiencies, the CuAAC reactions in aqueous solution under mild reaction conditions can effectively contribute to the pursuit of “green chemistry” with potential industrial applications.

## 2 | EXPERIMENTAL SECTION

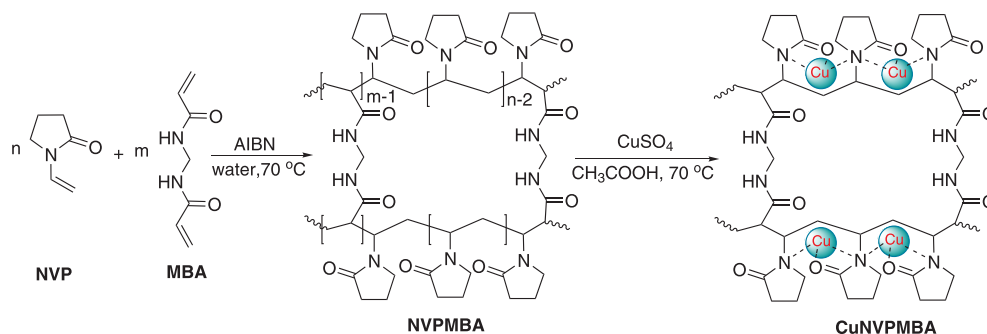
### 2.1 | Materials and methods

All the chemicals were purchased from Sigma Aldrich, Bangalore, India and used as received. All the organic solvents were obtained from Spectrochem India and were used without further purification. Double-distilled water was used in all experiments. Fourier transform infrared (FT-IR) spectra were recorded on a Perkin Elmer L160000A (USA) instrument by the attenuated total reflection method. Scanning electron microscopy (SEM) images were collected using a JEOL JSM-6390LV (Japan) instrument operated at 2–10 kV. An ultrathin window energy dispersive X-ray (EDX) analysis and a Gatan imaging filter attached to the microscope were used to determine the chemical composition of the sample. Transmission electron microscopy (TEM) images were used to study the microscopic properties of the copper-supported polymer catalyst and were recorded using a JEOL 4000EX high-resolution transmission electron microscope operated at 400 kV using an LaB6 source. The powder X-ray diffraction (PXRD) patterns were recorded on a AXS, D8 Advance X-ray diffractometer (Bruker, Germany) operated at 20 kV using Cu-K $\alpha$  radiation ( $\lambda = 0.1542$  nm). The measurements were performed over a diffraction angle range of  $2\theta = 15\text{--}80^\circ$ . The X-ray photoelectron spectra (XPS) were collected in an ultra-high vacuum chamber attached to a Thermo Electron Iris Intrepid II XSP Duo system (Thermo Electron Corporation, USA). Inductively coupled plasma optical emission spectroscopy (ICP-OES) analysis was carried out using a Thermo Fisher Scientific iCAP 7000 series (USA)

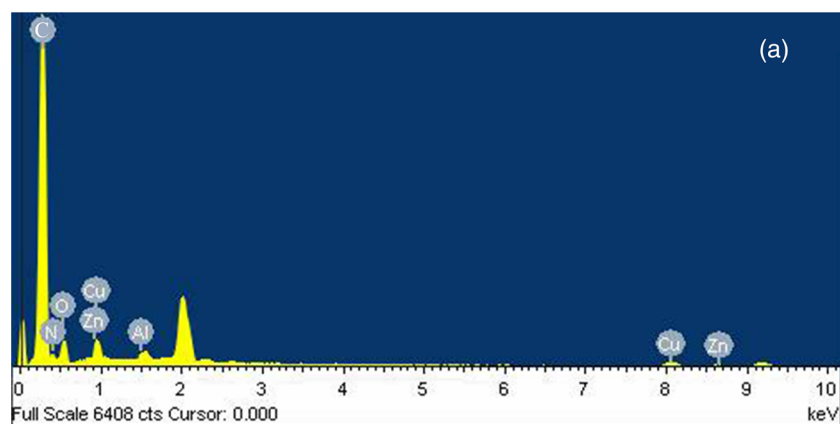
instrument.  $^1\text{H}$  NMR and  $^{13}\text{C}$  NMR spectra were recorded on a Bruker Advance III, 400 instrument (400 MHz for  $^1\text{H}$  and 100 MHz for  $^{13}\text{C}$  in  $\text{CDCl}_3$ ). Thermogravimetric (TG) analysis and derivative thermogravimetry (DTG) results were obtained from a Perkin Elmer, Diamond Thermogravimetric/Differential



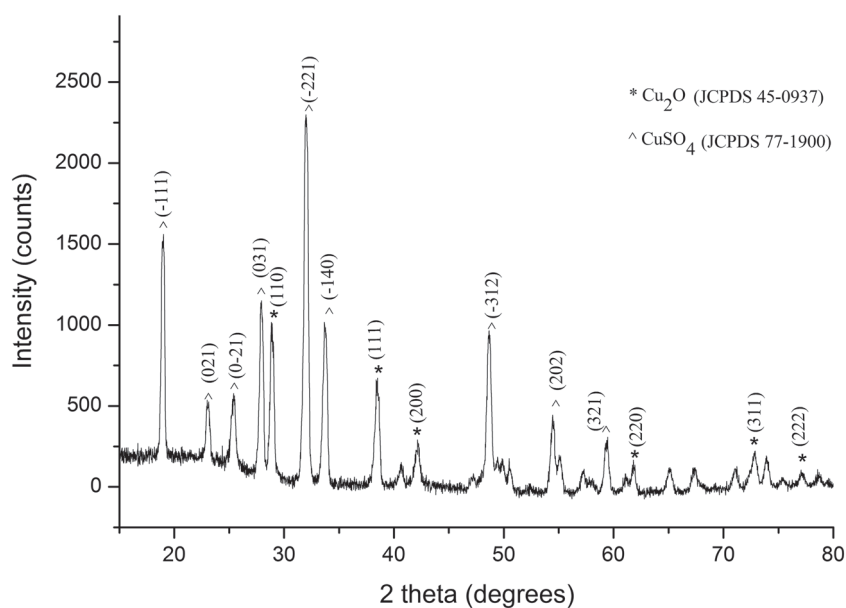
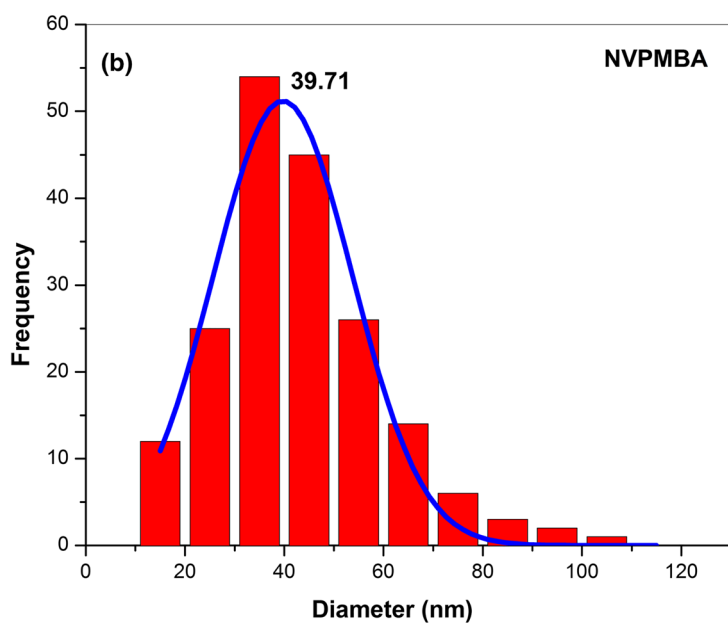
**FIGURE 2** SEM images of (a) NVPMBAs and (b) Cu NVPMBAs catalyst



**SCHEME 1** Synthesis of NVPMBAs and plausible copper coordination



**FIGURE 3** (a) EDX spectrum and (b) particle size histogram of CuNVPMB



**FIGURE 4** PXRD pattern of CuNVPMB catalyst

Thermal Analyzer (Perkin Elmer, USA). Elemental analysis was performed on an on a Vario EL III (Elementar, Germany) and gas chromatography-mass spectrometry studies were conducted on an ISQ LT GC-MS Thermo Fisher Scientific instrument.

## 2.2 | Synthesis of *N,N'*-methylene bis-acrylamide crosslinked polyvinylpyrrolidone

*N,N'*-methylene bis-acrylamide crosslinked (4%) polyvinylpyrrolidone (NVPMBAs) was prepared via suspension polymerization of the monomers in water. To a solution of 0.23 g of sodium dibasic phosphate and 20 g of sodium sulfate in 120 ml of water, a mixture of the monomers *N*-vinyl-2-pyrrolidone (10.5 ml), *N,N'*-methylene bis-acrylamide (0.62 g) and 2,2'-azobisisobutyronitrile (AIBN) (0.12 g) were added under nitrogen atmosphere. The mixture was then stirred at 70°C for 4 hr. The mixture was cooled to room temperature and the product was filtered, washed with water (4 × 25 ml) followed by acetone and dried at 60°C in a vacuum oven to obtain 10.4 g of the polymer beads. These beads were then subjected to Soxhlet extraction using an acetone/methanol (1:1) mixture to remove linear polymers. Beads with mesh size 120–200 were separated by sieving and used in the study.

## 2.3 | Complexation of copper ions with NVPMBAs

To a 100 ml round-bottomed flask containing 20 ml of acetic acid, 2 g NVPMBAs was added and kept for 4 hr until it had swelled up. Copper sulfate (1.5 g, 6 mmol) dissolved in water (10 ml) was added to the solution and the resultant mixture was stirred at 70°C for 2 hr. After cooling to room temperature, the copper complexed polymer (CuNVPMBAs) was filtered, washed with ethanol and dried at 60°C in a vacuum oven.

## 2.4 | General procedure for the azide-alkyne cycloaddition

Alkyne (10 mmol), halide (10 mmol), and sodium azide (730 mg, 12 mmol) were placed in a 100 ml round-bottomed flask. Subsequently, 10 mg (0.2 mol%) of the catalyst CuNVPMBAs and 10 ml water were added. The resultant mixture was heated at 60°C for 5 hr and cooled to room temperature to form a white solid. The same product can be obtained by stirring the reaction mixture for 8 hr at room temperature. The solid formed was filtered, washed with water, and recrystallized from alcohol to get 1,2,3-triazoles in excellent yields. These triazoles

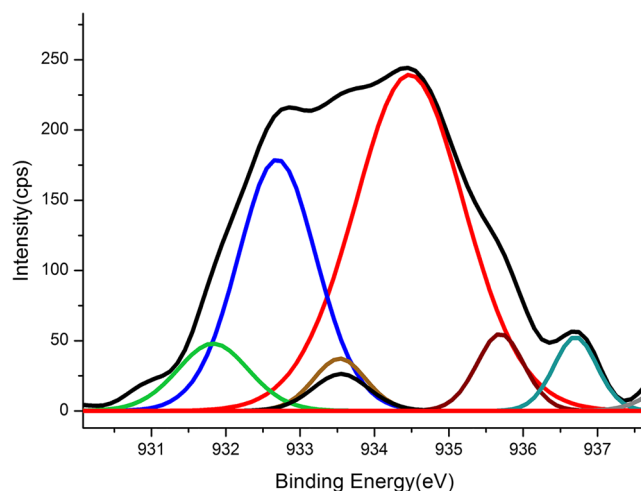


FIGURE 5 Binding energy of CuNVPMBAs as observed in XPS

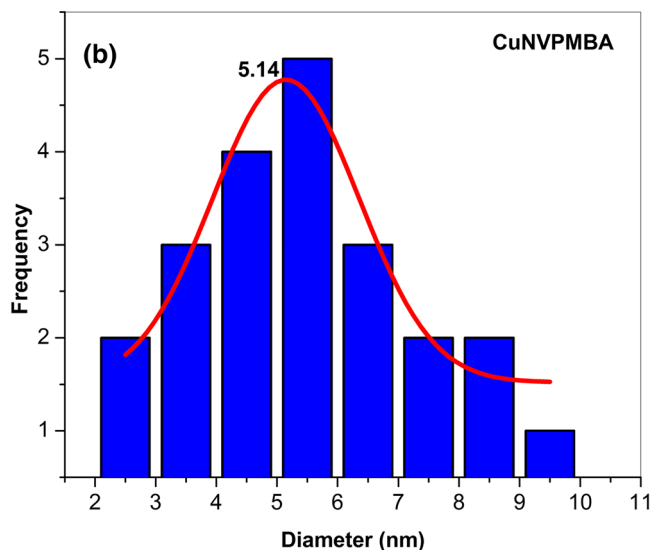
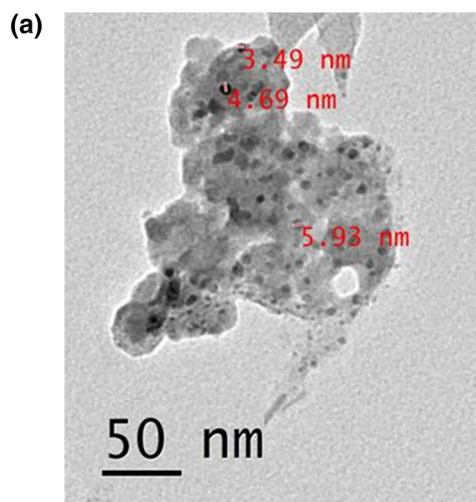


FIGURE 6 (a) HR-TEM image and (b) TEM particle size histogram of CuNVPMBAs



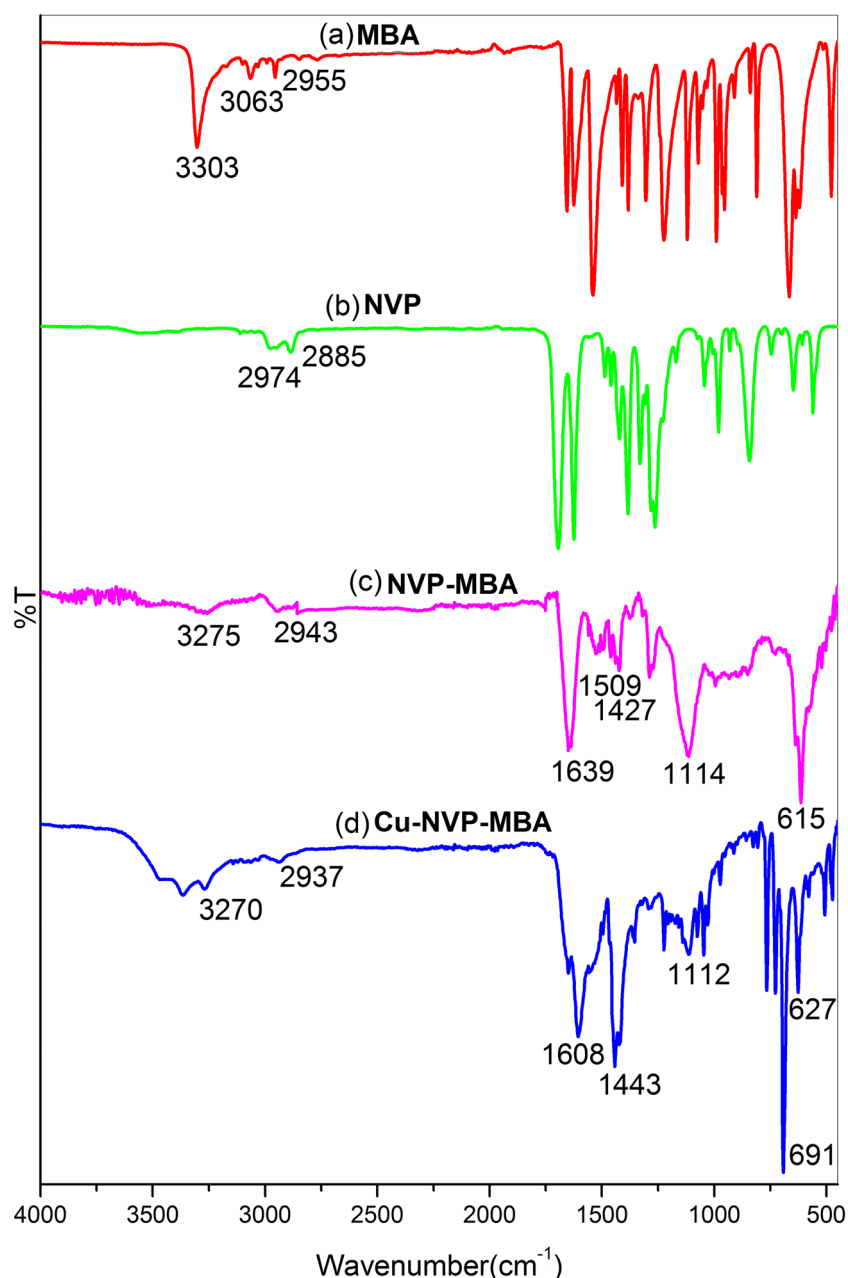
were characterized using  $^1\text{H}$  NMR and  $^{13}\text{C}$  NMR analysis. The values are in good agreement with those reported in the literature (see Supporting Information Data S1).

### 3 | RESULTS AND DISCUSSION

#### 3.1 | Synthesis of the polymer catalyst

*N,N'*-methylene bis-acrylamide (MBA) crosslinked polyvinylpyrrolidone copolymer was prepared by suspension polymerization of the monomers *N*-vinyl-2-pyrrolidone (NVP) and *N,N'*-methylene bis-acrylamide (MBA) using AIBN as the radical initiator. MBA was selected as the crosslinking agent since the amide moiety present on the

molecule can facilitate the coordination of copper.<sup>[42]</sup> Crosslinking agent up to 4% was used to ensure a balance between rigidity and swelling properties. The polymer showed better swelling properties in acetic acid medium compared to water (Figure 1). Immobilization of copper ions into the polymer was achieved by heating it with Cu(II) sulfate in acetic acid as solvent. During this process, Cu(II) ions were adsorbed onto the polymer matrix and subsequently reduced to Cu(I). The polymer support facilitates the immobilization of copper ions within the polymeric voids. This could be attributed to the coordination of Cu(I) with the oxygen atoms of pyrrolidone and chain nitrogen MBA, which can plausibly form an energetically more stable Cu(I) species and prevent further reduction of Cu(I) to Cu(0) (Scheme 1). This mode



**FIGURE 7** FTIR spectrum of (a) MBA, (b) NVP, (c) NVPMBMA, and (d) CuNVPMBMA

of action was further supported by the following characterization techniques.

### 3.2 | Characterization of copper supported polymer catalyst

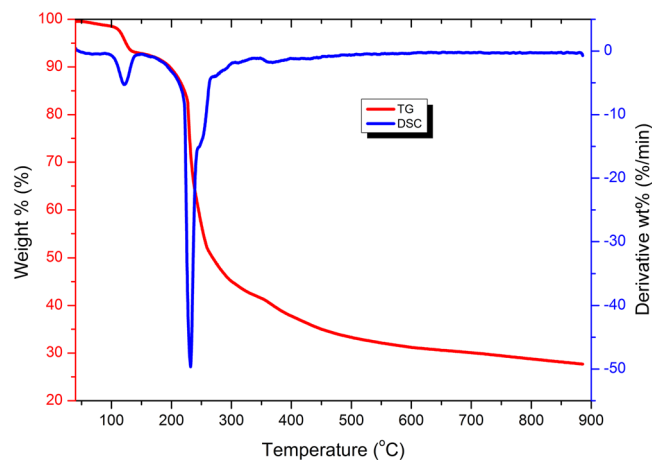
SEM analysis was used to study the surface morphology of NVPMBAs and CuNVPMBAs catalyst (Figure 2). The spherical surface morphology of the polymer remained unchanged even after loading the metal on its surface. A high level of rigidity of the polymer could be deduced from the fact that focusing the high intensity electron beam on the sample did not distort its morphology. EDX spectra were obtained from the electron beam focused onto the CuNVPMBAs sample, which showed peaks at binding energies of 0.85, 8.05, and 8.95 keV. The peaks could be assigned to CuL<sub>1</sub>, CuK $\alpha$ , and CuK $\beta$ , respectively (Figure 3). EDX analysis of the copper-supported NVPMBAs copolymer showed the existence of copper species in different environments and a weight percentage of 1.23 wt%. This was confirmed using ICP-OES analysis and the result showed that percentage of copper in the polymer was 1.25 wt%.

The PXRD pattern of Cu(I) stabilized on the polymer support is shown in Figure 4. The pattern indicates a mixed phase of Cu<sub>2</sub>O and CuSO<sub>4</sub>. Peaks at  $2\theta = 38.4, 42.1, 61.8, \text{ and } 73.6$  were indexed as the (111), (200), (220), and (311) planes of Cu<sub>2</sub>O, which is in good agreement with JCPDS file no. 45-0937 for Cu<sub>2</sub>O. Peaks at  $2\theta = 25.4, 33.7, 48.7, 54.4, \text{ and } 59.3$  were assigned to the (0-21), (-140), (-312), (202), and (321) planes of CuSO<sub>4</sub>, respectively (JCPDS File No. 77-1900). Other peaks at  $2\theta = 18.9, 23, 28, 28.9, 32, \text{ and } 33.7$  were assigned to the crystalline phases present in the NVPMBAs polymer matrix.

The PXRD results were in good agreement with XPS studies which confirmed the presence of Cu(I) and Cu(II) in the polymer matrix (Figure 5). In the figure, peaks at 932.4 eV and 934.8 eV are due to the characteristic Cu 2p<sub>3/2</sub> peaks of Cu(I) and Cu(II) respectively. Shake-up satellite peaks were also observed at higher binding energies, characteristic of compounds having d<sup>9</sup> configuration in the ground state.<sup>[43]</sup> The area under these two main peaks was used to estimate the ratio of Cu(I):Cu(II) and this was found to be 1:2. Since the XPS spectra of Cu(I) and Cu(0) are indistinguishable<sup>[44]</sup> and reduction of Cu(II) to Cu(0) was ruled out in the PXRD analysis, the area of peak at 932.45 was considered to be exclusively due to the presence of Cu(I).

The transmission electron microscopy (TEM) image of the CuNVPMBAs catalyst confirmed the presence of copper oxide nanoparticles dispersed on the polymer support with an average size of 5.14 nm (Figure 6).

The FT-IR spectra of MBA, NVP, CuNVPMBAs, and NVPMBAs are shown in Figure 7. The spectra display characteristic Cu-O stretching vibration of Cu<sub>2</sub>O at



**FIGURE 8** TG and DTG curves obtained for CuNVPMBAs catalyst

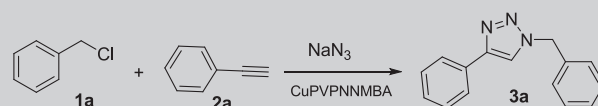
**TABLE 1** Solvent and catalyst optimization studies<sup>a</sup>

Entry	Solvent	Catalyst loading (mg)	Temperature (°C)	Yield (%) <sup>b</sup>
1	<i>t</i> -BuOH	10	RT	70
2	Ethanol	10	RT	65
3	THF	10	RT	84
4	THF/water (1:1 v/v)	10	RT	92
5	Water	10	RT	92
6	Water	10	60	97
7	Water	20	60	98
8	Water	5	60	88
9	Water	No catalyst	RT	0
10	Water	NVPMBAs	RT	0
11	CH <sub>3</sub> CN	10	RT	78
12	DCM	10	RT	75
13	DMF	10	RT	60

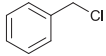

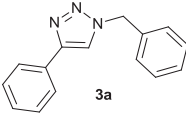
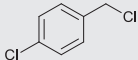

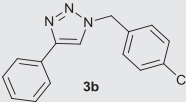
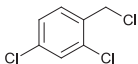

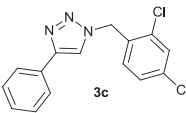
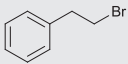

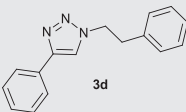


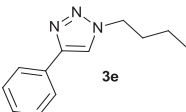


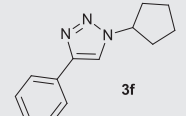


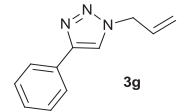
<sup>a</sup>Reaction conditions: benzyl chloride (10 mmol), phenyl acetylene (10 mmol), sodium azide (12 mmol), and catalyst.

<sup>b</sup>Isolated yield after 5 hr of reaction.

Note. DCM, dichloromethane; NVPMBAs, RT, room temperature; THF, tetrahydrofuran.



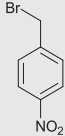

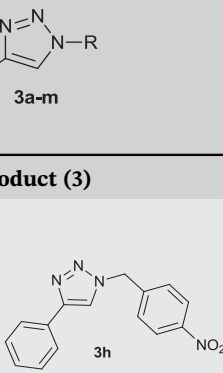
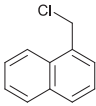

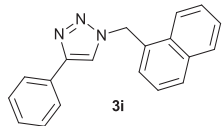
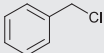
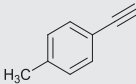
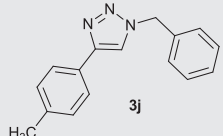
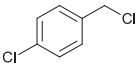
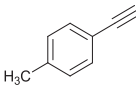
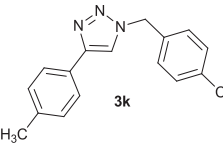
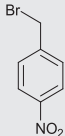
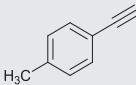
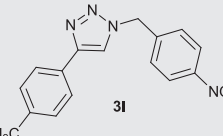

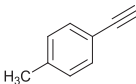
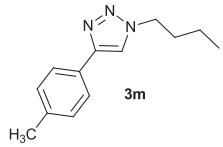
**TABLE 2** CuNVPMBMBA catalyzed one-pot synthesis of 1,2,3-triazoles in water<sup>a</sup>

Entry	RX (1)	Alkyne (2)	Product (3)	Yield (%) <sup>b</sup>
1				97
2				94
3				92
4				97
5				88
6				82
7				92

(Continues)



TABLE 2 (Continued)

Entry	RX (1)	Alkyne (2)	Product (3)	Yield (%) <sup>b</sup>
8				96
9				90
10				93
11				95
12				93
13				88

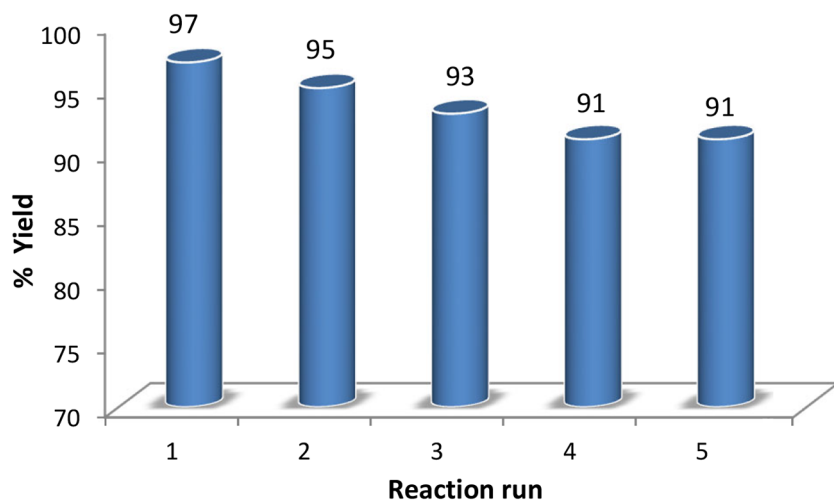
<sup>a</sup>Reaction conditions: Halide **1** (10 mmol), terminal alkynes **2** (10 mmol), sodium azide (12 mmol), catalyst CuNVPMB (10 mg, 0.2 mol%) in water (5 ml) at 60°C for 5 hr.

<sup>b</sup>Yield: isolated yield.

$627\text{ cm}^{-1}$ .<sup>[45]</sup> The C=O groups of pure NVPMBAs show a prominent peak at  $1639\text{ cm}^{-1}$ . This characteristic peak was used to observe the interaction between the polymer and copper ions. CuNVPMBAs showed a strong absorption at  $1608\text{ cm}^{-1}$ , which indicates a strong interaction between copper and the polymer support, possibly through the nitrogen and carbonyl groups present in the polymer. The peak shift towards the low wavenumber direction has been reported previously in PVP-stabilized

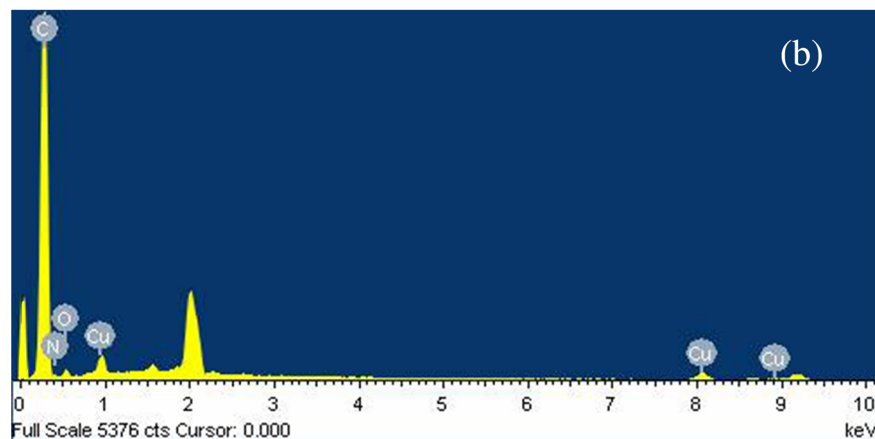
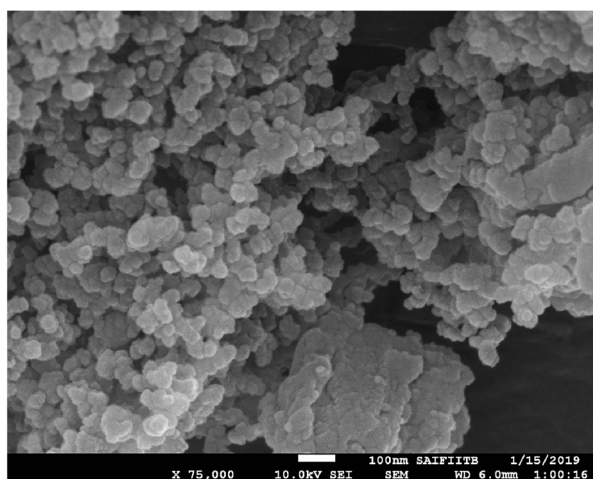
platinum group metals.<sup>[46]</sup> A very small shift in the N–H vibrational frequency indicates feeble interaction between copper and the crosslinking agent (MBA).

The thermal stability of the polymer was monitored using TG and DTG analysis (Figure 8). The thermogram indicated major weight loss at  $240^\circ\text{C}$ . In TGA, the residue at  $900^\circ\text{C}$  indicated a copper weight percentage of  $\sim 1.25\text{ wt\%}$ , which is in good agreement with other analysis.



**FIGURE 9** Reusability study of CuNVPMBAs catalyst in the CuAAC reaction

(a)



**FIGURE 10** (a) SEM image and (b) EDX spectrum of the reused catalyst after the fifth cycle

### 3.3 | Catalytic activity

The as-prepared CuNVPMBAs catalyst was investigated for the click synthesis of 1,4-disubstituted 1,2,3-triazoles using alkyl halide, sodium azide, and alkyne. Optimization of the reaction was performed by taking benzyl chloride, sodium azide, and phenylacetylene as reactants (Table 1). The three-component reaction was carried out by taking the components in water followed by addition of 10 mg of the catalyst and heating at 60°C for 5 hr. The solid that separated out was filtered and recrystallized from ethanol to get pure 1,2,3-triazoles. Increasing the catalyst loading to 20 mg did not significantly affect the overall yield whereas decreasing the catalyst loading to 5 mg reduced the yield of the products (Table 1, entries 7 and 8). In the absence of the catalyst, formation of 1-benzyl-4-phenyl-1*H*-1,2,3-triazole was not observed (Table 1, entries 9 and 10).

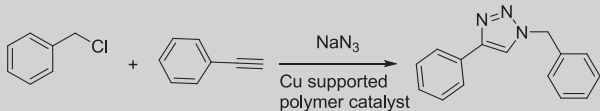
*t*-butanol, ethanol, dichloromethane (DCM), acetonitrile, tetrahydrofuran (THF), *N,N*-dimethylformamide

(DMF), water were tested as solvents, and water was found to be the most effective (Table 1). After optimizing the click reaction, the scope of the reaction was further explored using different alkynes and alkyl halides. It was observed that electron-donating or electron-withdrawing groups had negligible effect on the overall yield of the product (Table 2).

As proposed by Fokin et al.<sup>[47]</sup> for the mechanism of 1,2,3-triazole formation by click chemistry, it has been speculated that Cu(I) present in the polymer wells is responsible for the catalytic activity. During the catalytic process, Cu(I) was oxidized to Cu(II), which in turn was reduced to Cu(I) by the NVP backbone and the catalytic cycle was repeated.

Recyclability of the catalyst was examined using phenylacetylene, benzyl chloride, and sodium azide as reactants and the reaction was performed under the previous reaction conditions. To avoid any loss of catalyst while separating the product by filtration, the product was extracted using ethyl acetate after the first run. The

**TABLE 3** Comparison of click synthesis of 1,2,3-triazoles catalyzed by polymer-supported copper catalyst reported in the literature



Entry	Catalyst	Copper loading (mol%)	Reaction conditions	Time (hr)	Substrate variation	Yield (%) <sup>a</sup>	Ref.
1	Cu(I)NVPMBAs	0.2	Water, 60°C	5	–	97	This work
2	Cu(I)-amberlyst A-21	13	CH <sub>2</sub> Cl <sub>2</sub> , RT	12	–	93	20
3	Cu(I)-AMPS	1	Water, RT	1	Benzyl azide	92	38
4	CuI/SMI-TD	2.2	Water, reflux	0.5	–	80	39
5	Cellulose-CuI	0.3	Water, 70°C	6	Benzyl bromide	94	40
6	Cu(I)C22-PS	0.6	Water, RT	10	–	98	41
7	Cu(II)PolNC	0.5	Water, RT	3	–	96	48
8	Cu@Fe <sub>3</sub> O <sub>4</sub> chitosan	1.54	DCM, RT	12	Benzyl azide	92	49
9	Cu cellulose	0.5	Na ascorbate, 70°C	6	Benzyl azide	91	50
10	Cu(II) cellulosepoly	0.5	Water, 70°C	12	Benzyl bromide	97	51
11	Cu chitosan	0.4	Water, RT	4	Benzyl azide	99	52
12	Cu chitosan PVA	10	EtOH/water, 50°C	6	Phenyl azide	92	53
13	CuI@PMMA-Co-MI	0.36	Water, RT	10 min	–	94	54

<sup>a</sup>Isolated yield.

*Note.* DCM, dichloromethane; NVPMBAs, *N,N'*-methylene bis-acrylamide crosslinked *N*-vinyl-2-pyrrolidone; RT, room temperature. Catalysts: Aminomethylpolystyrene-supportedcopper(I): (Cu(I)-AMPS); Polystyreneresin-supported copper(I) iodide-cryptand-22 complex: (Cu(I)C22PS); Copper(II) poly-5-vinyltetrazolate: (Cu(II)PolNC); CuI-functionalized poly[(methyl methacrylate)-co-maleimide]:(CuI@[PMMA-co-MI]); Coppernanoparticles in hydrogel based on chitosan and poly(vinyl alcohol): (Cuchitosan PVA); Thienebenzodiazepine modified poly (styrene-co-maleic anhydride) supported Cu(I)NPs: (CuI/SMI-TD).

residual catalyst was reused five times under the same conditions and did not show any significant loss of catalytic activity after each successive run (Figure 9).

After the fifth reaction cycle, an SEM image of the catalyst was taken and this did not show any significant change in the morphology (Figure 10). EDX analysis of the recycled catalyst after the fifth run indicated that the copper concentration was 1.22 wt%. After completion of the reaction, the residual solution was subjected to ICP-OES analysis and the absence of copper in the reaction medium was confirmed. Therefore, metal leaching during the process was negligible and facilitated efficient catalyst recycling.

Further investigation of scaling up of the reaction was undertaken by increasing the amount of reactants 10-fold under the same reaction conditions. It was observed that using the same quantity of catalyst, the product was obtained in 97% yield only after 7 hr. However, on increasing the amount of catalyst to 20 mg, the reaction time could be reduced to 5 hr to get quantitative conversion of reactants to product.

A comparative study of the efficiency of CuNVPMBACatalyst with that of recently reported polymer-supported copper catalysts for the click reaction to afford 1,4-disubstituted 1,2,3-triazoles is summarized in Table 3.<sup>[48,49]</sup> It is noteworthy that the CuNVPMBACatalyst is highly efficient in terms of activity, resistance to oxidation, and stability. The reaction involves the *in situ* generation of organic azides which are directly converted into 1,2,3-triazoles. Therefore, handling of hazardous byproducts is completely avoided during this reaction.

## 4 | CONCLUSIONS

To conclude, the present study demonstrates the synthesis and characterization of CuNVPMBACatalyst polymer and its application in catalyzing azide-alkyne cycloaddition in water. The dual function of *in situ* reduction of Cu(II) to Cu(I) and stabilization of the latter on the polymer matrix has been explored in this work. The catalyst was characterized by spectral and analytical techniques. Execution of the catalytic reaction was performed easily using a one-pot, three-component strategy of click reaction between alkyl halide, sodium azide, and alkyne to provide the target compound 1,4-disubstituted 1,2,3-triazoles in a regioselective manner and excellent yields. Inexpensive and easily available copper sulfate was used as the copper source. The process was environmentally friendly and only a very small quantity of catalyst was required. Recyclability of the catalyst without significant loss of efficiency was observed. The possibility

for scaling up the reaction extends the scope for commercialization of the catalyst.

## ACKNOWLEDGMENTS

PM thanks the University Grants Commission (UGC), New Delhi for the generous support for a GCMS system under Innovative Programme (No.F.14-18/2013 Inno/ASIT) and a minor project No. 2242-MRP/15-16/KLCA019/UGC-SWRO for financial support. We thank IIRBS, MG University, Kottayam, Kerala and SAIF, Cochin University of Science and Technology (CUSAT), Kerala, India for providing NMR and other analytical data respectively.

## FUNDING INFORMATION

PM thanks the University Grants Commission (UGC), New Delhi for the generous support for a GCMS system under Innovative Programme (No.F.14-18/2013 Inno/ASIT) and a minor project No. 2242-MRP/15-16/KLCA019/UGC-SWRO for financial support.

## ORCID

Paulson Mathew  <https://orcid.org/0000-0001-6809-3491>

## REFERENCES

- [1] W. Dehaen, V. A. Bakulev, *Chemistry of 1,2,3-triazoles*, Springer International Publishing, Switzerland **2014**.
- [2] S. G. Agalave, S. R. Maujan, V. S. Pore, *Chem. – Asian J.* **2011**, *6*, 2696.
- [3] D. Dheer, V. Singh, R. Shankar, *Bioorg. Chem.* **2017**, *71*, 30.
- [4] R. Alvarez, S. Velazquez, A. San-Felix, S. Aquaro, E. D. Clercq, C. F. Perno, A. Karlsson, J. Balzarini, M. J. Camarasa, *J. Med. Chem.* **1994**, *37*, 4185.
- [5] A. Vivancos, C. Segarra, M. Albrech, *Chem. Rev.* **2018**, *118*, 9493.
- [6] D. Sasidharan, C. V. Aji, P. Mathew, *Polyhedron* **2019**, *157*, 335.
- [7] P. Sharma, J. Rathod, A. P. Singh, P. Kumar, Y. Sasson, *Catal. Sci. Technol.* **2018**, *8*, 3246.
- [8] W. Q. Fan, A. R. Katritzky, 1,2,3-Triazoles, in *Comprehensive Heterocyclic Chemistry II*, (Eds: A. R. Katritzky, C. W. Rees, E. F. V. Scriven), Elsevier Science, Oxford **1996**.
- [9] V. V. Rostovtsev, L. G. Green, V. V. Fokin, K. B. Sharpless, *Angew. Chem. Int. Ed.* **2002**, *41*, 2596.
- [10] C. W. Tornoe, C. Christensen, M. Meldal, *J. Org. Chem.* **2002**, *67*, 3057.
- [11] D. Huang, P. Zhao, D. Astruc, *Coord. Chem. Rev.* **2014**, *272*, 145.
- [12] S. Chassaing, V. Bénétteau, P. Pale, *Catal. Sci. Tech.* **2016**, *6*, 923.
- [13] S. Roy, T. Chatterjee, S. M. Islam, *Green Chem.* **2013**, *15*, 2532.
- [14] Z. Zarnegar, J. Safari, *New J. Chem.* **2014**, *38*, 4555.
- [15] M. Gholinejad, N. Jeddi, *ACS Sustainable Chem. Eng.* **2014**, *2*, 2658.
- [16] R. N. Butler, A. G. Coyne, *Chem. Rev.* **2010**, *110*, 6302.

- [17] C. Wang, D. Ikhlef, S. Kahlal, J. Saillard, D. Astruc, *Coord. Chem. Rev.* **2016**, *316*, 1.
- [18] P. Thirumurugan, D. Matosiuk, K. Jozwiak, *Chem. Rev.* **2013**, *113*, 4905.
- [19] C. Deraedt, N. Pinaud, D. Astruc, *J. Am. Chem. Soc.* **2014**, *136*, 12092.
- [20] C. Girard, E. Onen, M. Aufort, S. Beauviere, E. Samson, J. Herscovici, *Org. Lett.* **2006**, *8*, 1689.
- [21] M. Nasrollahzadeh, M. Sajjadi, H. Alikhonakdar, *J. Mol. Struct.* **2018**, *1161*, 453.
- [22] M. Nasrollahzadeh, M. Maryami, M. Sajjadi, E. Mehdipour, *Appl. Organomet. Chem.* **2019**, *33*, e4730.
- [23] M. Nasrollahzadeh, S. M. Sajadi, A. Rostami-Vartooni, M. Khalaj, *J. Colloid Interface Sci.* **2015**, *453*, 237.
- [24] M. Nasrollahzadeh, B. Jaleh, P. Fakhri, A. Zahraei, E. Ghadery, *RSC Adv.* **2015**, *5*, 2785.
- [25] Y. M. A. Yamada, S. M. Sarkar, Y. Uozumi, *J. Am. Chem. Soc.* **2012**, *134*, 9285.
- [26] K. M. Koczur, S. Mourdikoudis, L. Polavarapu, S. E. Skrabalak, *Dalton Trans.* **2015**, *44*, 17883.
- [27] T. C. Deivaraj, N. L. Lala, J. Y. Lee, *J. Colloid Interface Sci.* **2005**, *289*, 402.
- [28] Y. Xiong, I. Washio, J. Chen, H. Cai, Z.-Y. Li, Y. Xia, *Langmuir* **2006**, *22*, 8563.
- [29] M. Tsuji, R. Matsuo, P. Jiang, N. Miyamae, D. Ueyama, M. Nishio, S. Hikino, H. Kumagae, K. S. N. Kamarudin, X.-L. Tang, *Cryst. Growth Des.* **2008**, *8*, 2528.
- [30] M. H. Kim, B. Lim, E. P. Lee, Y. Xia, *J. Mater. Chem.* **2008**, *18*, 4069.
- [31] H. Zhang, X. Ren, Z. Chi, *J. Cryst. Growth* **2007**, *304*, 206.
- [32] M. Jin, G. He, H. Zhang, J. Zeng, Z. Xie, Y. Xia, *Angew. Chem. Int. Ed.* **2011**, *50*, 10560.
- [33] T. Ayvali, P. Lecante, P.-F. Fazzini, A. Gillet, K. Philippot, B. Chaudret, *Chem. Commun.* **2014**, *50*, 10809.
- [34] B. Lim, M. Jiang, J. Tao, P. H. C. Camargo, Y. Zhu, Y. Xia, *Adv. Funct. Mater.* **2009**, *19*, 189.
- [35] A. Sarkar, T. Mukherjee, S. Kapoor, *J. Phys. Chem. C* **2008**, *112*, 3334.
- [36] X. Zuo, H. Liu, M. Liu, *Tetrahedron Lett.* **1998**, *39*, 1941.
- [37] R. U. Islam, A. Taher, M. Choudhary, M. J. Witcomb, K. Mallick, *Dalton Trans.* **2015**, *44*, 1341.
- [38] L. Bahsis, H. B. El Ayouchia, H. Anane, A. Pascual-Álvarez, G. D. Munno, M. Julve, S.-E. Stiriba, *Appl. Organomet. Chem.* **2019**, *33*, e4669.
- [39] F. Ebrahimpour-Malamir, T. Hosseinejad, R. Mirsafaei, M. M. Heravi, *Appl. Organomet. Chem.* **2018**, *32*, e3913.
- [40] P. V. Chavan, K. S. Pandit, U. V. Desai, M. A. Kulkarni, P. P. Wadgaonkar, *RSC Adv.* **2014**, *44*, 2137.
- [41] B. Movassagh, N. Rezaei, *Tetrahedron* **2014**, *70*, 8885.
- [42] B. George, V. N. R. Pillai, B. Mathew, *J. Appl. Polym. Sci.* **1999**, *74*, 3432.
- [43] J. Ghijsen, L. H. Tjeng, J. V. ELP, H. Eskes, J. Westerink, G. A. Sawatzky, M. T. Czyzyk, *Phys. Rev. B* **1988**, *38*, 11322.
- [44] C. D. Wagner, W. M. Riggs, L. E. Davis, J. F. Mouler, in *Handbook of X-Ray Photoelectron Spectroscopy*, (Ed: G. E. Muilenberg), Perkin Elmer Corporation, Physical Electronics Division, Eden Prairie, MN **1979**.
- [45] A. S. Ethiraj, D. J. Kang, *Nanoscale Res. Lett.* **2012**, *7*, 70.
- [46] W. X. Tu, X. B. Zuo, H. F. Liu, *Chin. J. Polym. Sci.* **2008**, *26*, 23.
- [47] B. T. Worrell, J. A. Malik, V. V. Fokin, *Science* **2013**, *340*, 457.
- [48] A. V. Zuraev, Y. V. Grigoriev, V. A. Budevich, O. A. Ivashkevich, *Tetrahedron Lett.* **2018**, *59*, 1583.
- [49] M. Chetia, A. A. Ali, D. Bhuyan, L. Saikia, D. Sarma, *New J. Chem.* **2015**, *39*, 5902.
- [50] B. H. Mandal, M. L. Rahman, M. M. Yusoff, K. F. Chong, S. M. Sarkar, *Carbohydr. Polym.* **2017**, *156*, 175.
- [51] S. Pan, S. Yan, T. Osako, Y. Uozumi, *ACS Sustainable Chem. Eng.* **2017**, *5*, 10722.
- [52] R. N. Baig, R. S. Varma, *Green Chem.* **2013**, *15*, 1839.
- [53] J. F. Souza, G. P. Costa, R. Luque, D. Alves, A. R. Fajardo, *Catal. Sci. Technol.* **2019**, *9*, 136.
- [54] N. Pourmohammad, M. M. Heravi, S. Ahmadi, T. Hosseinejadi, *Appl. Organomet. Chem.* **2019**, *33*, e4967.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Mathew P, Sasidharan D, Rakesh NP. Copper(I) stabilized on *N,N'*-methylene bis-acrylamide crosslinked polyvinylpyrrolidone: An efficient reusable catalyst for click synthesis of 1,2,3-triazoles in water. *Appl Organometal Chem.* 2020;e5642. <https://doi.org/10.1002/aoc.5642>