



Research article

Cu/SiO₂-Pr-NH-Benz as a novel nanocatalyst for the efficient synthesis of 1,4-disubstituted triazoles and propargyl amine derivatives in an aqueous solutionMahdiah Darroudi ^{a,1}, Hossein Rouh ^{b,1}, Mohammad Hasanzadeh ^c, Nasrin Shadjou ^{d,*}^a Department of Medical Biotechnology and Nanotechnology, Faculty of Medicine, Mashhad University of Medical Sciences, Mashhad, Iran^b Department of Organic Chemistry, Faculty of Chemistry, K. N. Toosi University of Technology, Tehran, Iran^c Pharmaceutical Analysis Research Center, Tabriz University of Medical Science, Tabriz, Iran^d Department of Nanotechnology, Faculty of Science and Chemistry, Urmia University, Urmia, Iran

ARTICLE INFO

Keywords:

Copper nanoparticle
Multicomponent reaction
Click reaction
A³-coupling reaction
Silica nanocatalyst

ABSTRACT

In this work, an innovative nanocatalyst (Cu/SiO₂-Pr-NH-Benz) was synthesized and applied to coupling and click reaction in an aqueous solution. This work reports an efficient and straightforward approach for synthesizing diverse propargylamine and 1,2,3-triazole derivatives in excellent yield and short-time reaction. Also, a novel method involving the Cu NPs supported on the SiO₂ nanocatalyst as a heterogeneous novel catalyst for the “one-pot” three-component A³-coupling of aldehyde, amine, and alkynes and “one-pot” click reaction between alkyne, benzyl halide, and sodium azide in the water at room temperature was developed. Significant advantageous such as enhanced catalytic activity with efficient recycling for the one-pot synthesis of 1,4-disubstituted triazoles and propargyl amine derivatives and in green condition were observed. Also, after five successive reactions, the catalytic activity of recycled Cu/SiO₂-Pr-NH-Benz remained high without significant loss in its intrinsic activity.

1. Introduction

The heterogeneous catalysts have attracted considerable attention because of their wide industrial applications, including cost-effective, acceptable lifetime, fragility, thermal instability, and easy removal compared to homogenous catalysts [1]. Despite their widespread use, design, and synthesis of heterogeneous catalysts as increasingly selective, efficient, and active, it is still a challenging topic [2]. In recent years, diverse heterogeneous and homogenous catalysts have been applied as catalysts for organic reactions. The heterogeneous catalyst can be used for nanomaterial resulting in a significantly high catalytic activity, a high surface area to volume ratio, excellent selectivity, and exhibit novel characteristics of quantum size effects [3]. The nanomaterial was implemented in the optical, electronic, coating, medical, catalytic, and sensor applications [4, 5] because of their exclusive properties. Although nanomaterials displayed an excellent catalytic activity, they cannot be separated from the reaction conveniently. Therefore, different solid supports have been applied to synthesized heterogeneous catalysts based on nanoparticles such as silica, graphene, zeolites, and carbon nanotubes

[4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. Among all, SiO₂ is contemplated as one of the most promising support materials owing to diverse morphology, cost-effective, high specific surface area, thermal stability, and conducting properties. Besides, transition metal ions could be anchored or coordinated with a good dispersion on the functioning surface of SiO₂ [14]. The highly dispersed copper catalyst has been under intensive study and revealed a promising role in a wide range of catalytic reactions, particularly in complicated reactions such as click and coupling reactions [15].

The azide-alkyne cycloaddition reaction, known as the click reaction, is a promising tool for pharmaceutical and molecular biology applications [16]. The original Huisgen cycloaddition of azide and alkyne could be effectively used for triazole scaffold synthesis but had several demerits, including prolonged reaction time, harsh reaction conditions, and low regioselectivity [17, 18]. The application of Cu(I) catalyst can yield product in high atom economy, exclusive regioselectivity, shortened reaction, broad substrate scope, and under mild reaction conditions. Cu-catalyzed azide-alkyne cycloaddition (Cu-AAC) reaction has been reported for triazole synthesis as an alternative catalyst for click reaction

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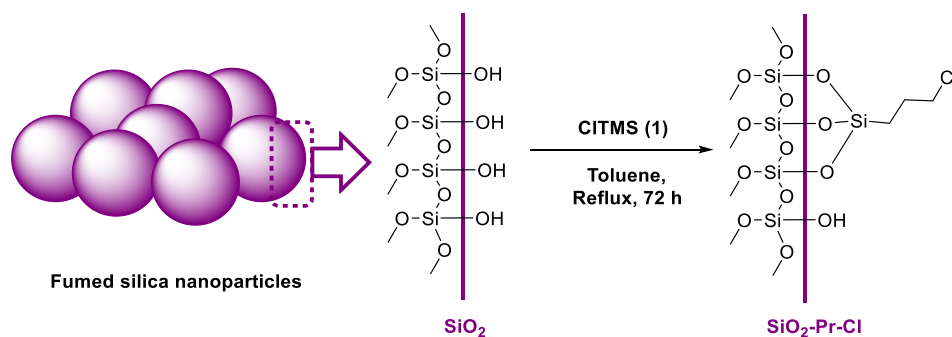


Figure 1. Synthetic approach for preparation of $\text{SiO}_2\text{-Pr-Cl}$.

[19, 20, 21]. Nowadays, incredible efforts have been made to develop catalytic processes to achieve a greener synthesis by reducing chemical waste and the number of synthetic steps and using an eco-friendly solvent to result in target product in good yields and highest rates [22, 23].

Today, the multicomponent and one-pot reaction in which various starting substrates are amalgamated to provide various scaffolds has been utilized significantly. The multicomponent coupling reaction of amines, aldehydes, and alkynes to synthesize propargylamine as a valuable synthon in preparation of diverse biologically active and natural product compounds has become an exciting challenge in organic synthesis [24]. It was performed in different reaction conditions and solvents such as

water, organic media, ionic liquid, or solvent-free conditions to afford various propargylamine. A wide range of different catalysts was utilized in these reactions, including silver, copper, gold, iron, zinc, iridium, and other propargylamine [25, 26, 27].

Copper plays an essential role as a promoter and catalyst in numerous organic reactions such as cycloaddition, coupling, click reactions as well as sigmatropic rearrangements [24, 28, 29]. Copper nanoparticles have been anchored on different silica supports such as MCM and Fumed silica and used for antibacterial and electrochemical applications. However, the potential of these composites in organic catalytic reactions has not been investigated thoroughly. A recent report on copper induction in the

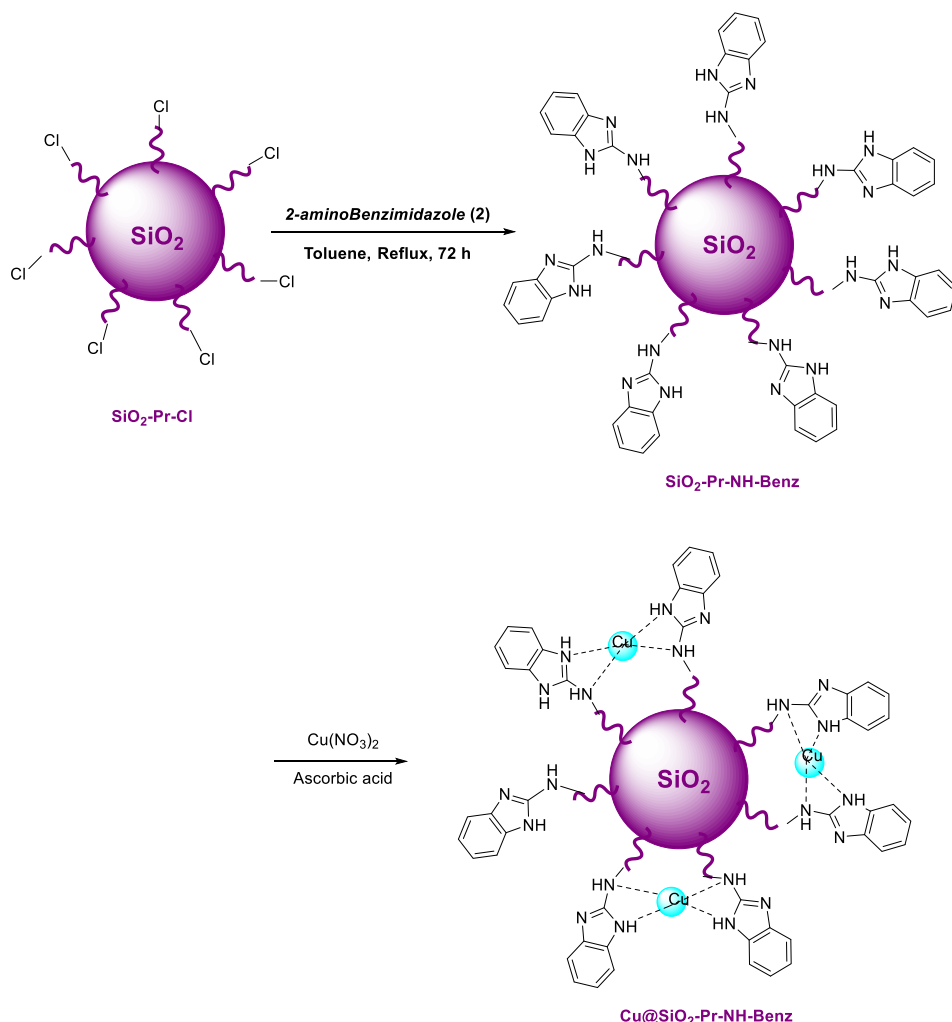


Figure 2. Synthetic approach for preparation of $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$.

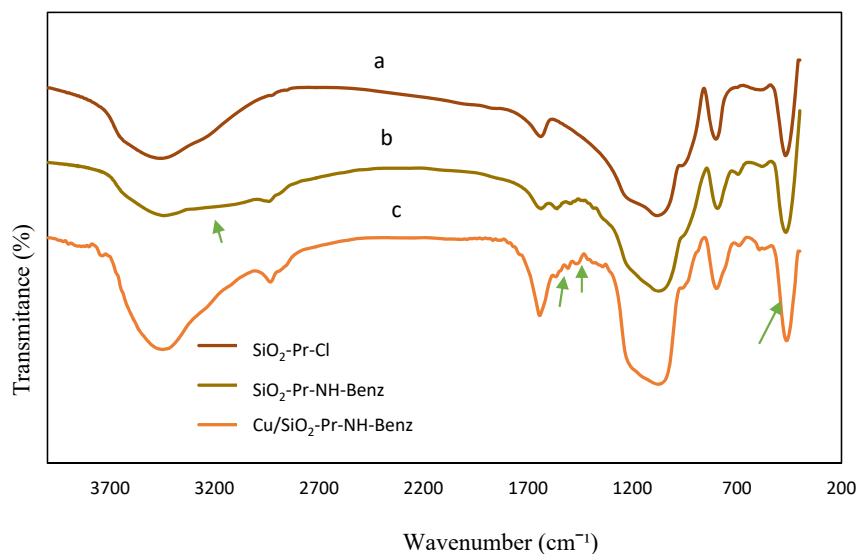


Figure 3. FT- IR spectra of (a) SiO₂-Pr-Cl, and (b) SiO₂-Pr-NH-Benz, and (c) Cu/SiO₂-Pr-NH-Benz.

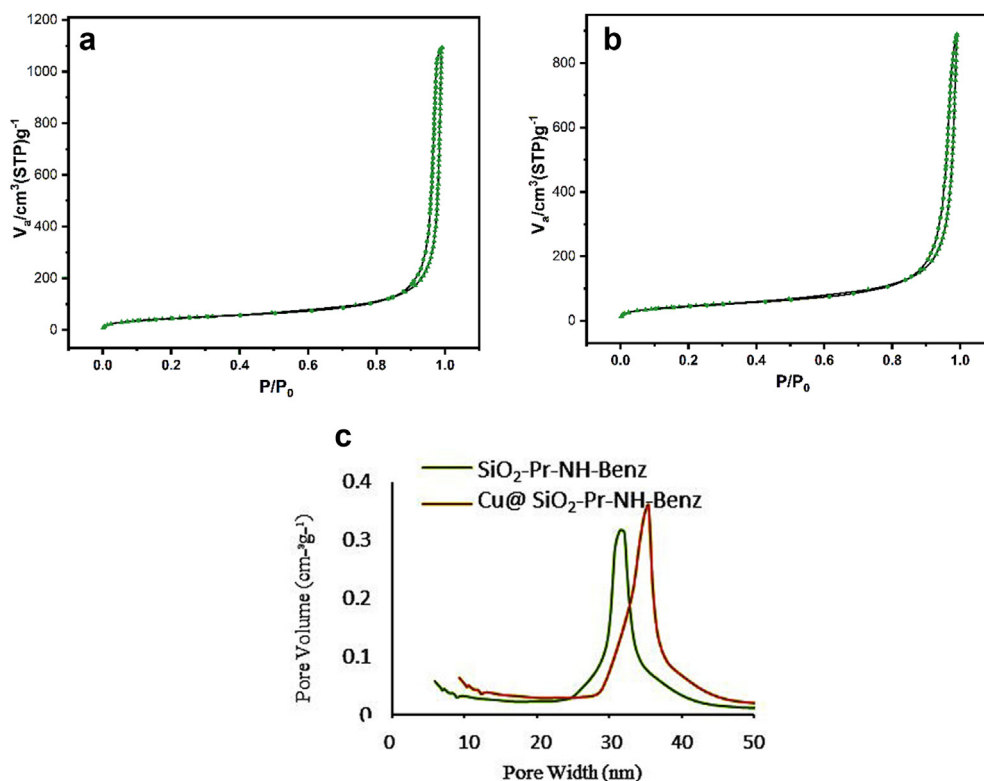


Figure 4. Curves of N₂ adsorption-desorption isotherms of (a) SiO₂-Pr-NH-Benz, and (b) Cu@ SiO₂-Pr-NH-Benz.

Table 1. Physical parameters of SiO₂-Pr-NH-Benz, and (b) Cu@ SiO₂-Pr-NH-Benz.

	Surface area (m ² /g)	Average Pore diameter (nm)	Pore volume (cm ³ /g)
SiO ₂ -Pr-NH-Benz	159.8	30.61	0.316
Cu@SiO ₂ -Pr-NH-Benz	153.5	38.90	0.372

click and A³-coupling reactions prompted us for the present study [30]. This work reports an efficient and straightforward approach for synthesizing diverse propargylamine and 1,2,3-triazole derivatives in eco-friendly condition, excellent yield and short-time reaction. We have designed and developed a method involving the Cu NPs supported on the SiO₂ nanocatalyst as a heterogeneous novel catalyst for the “one-pot”

three-component A³-coupling of aldehyde, amine, and alkynes and “one-pot” click reaction between alkyne, benzyl halide, and sodium azide in the water at room temperature. These routes' unique aspects are the enormous scope, high selectivity, cost-effectiveness, and a single-step method that needs nontoxic reagents and environmentally friendly solvents. Therefore, this technique is safe for environs and humans.

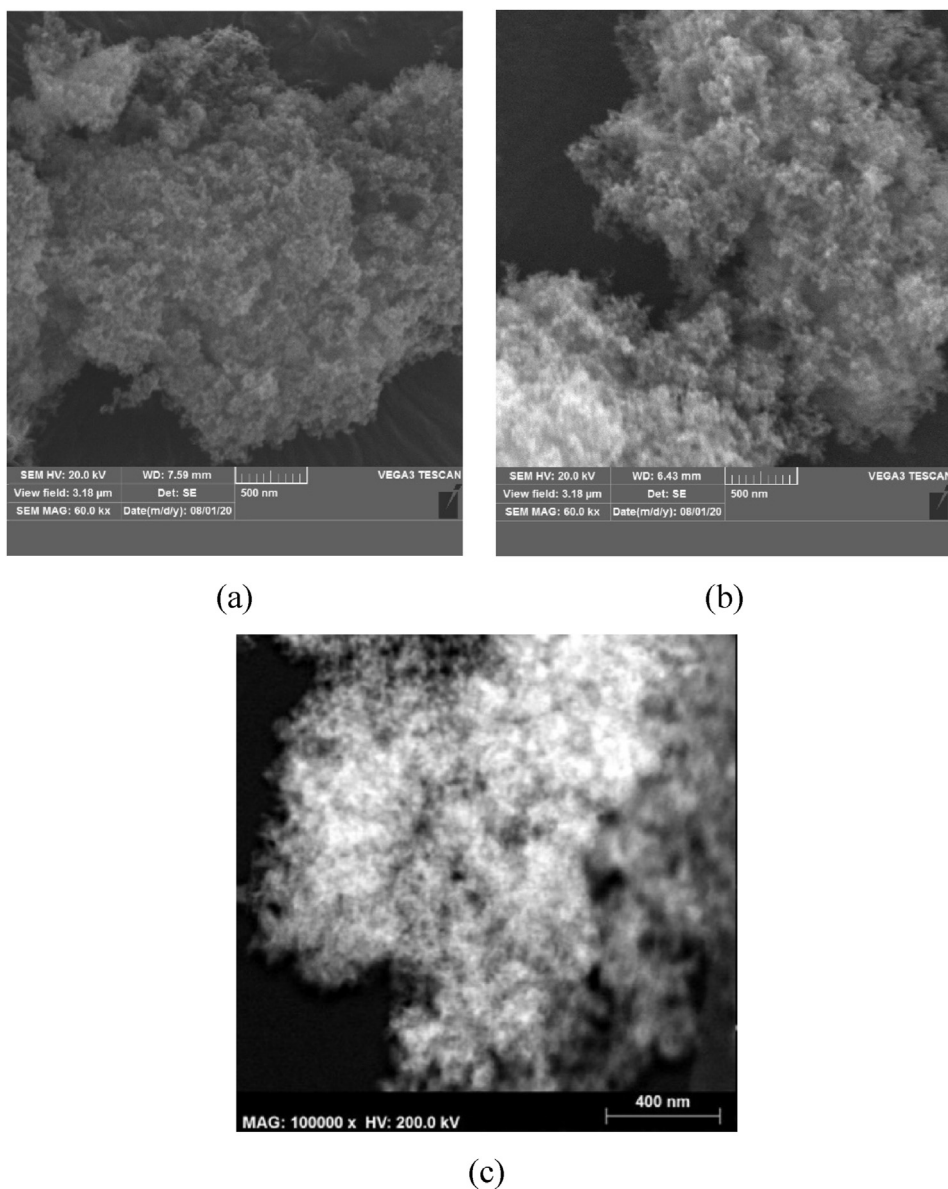


Figure 5. Fe-SEM images of (a) $\text{SiO}_2\text{-Pr-Cl}$, (b) $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ and (c) TEM image of $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$.

2. Experimental

2.1. Synthesis of fumed silica-Pr-Cl nanoparticles

A two-neck round-bottom flask was charged with fumed-silica (2.0 g) and dried out under vacuum at 100 °C. Afterward, dry toluene (50 mL) was added at ambient temperature until a diluted mixture was obtained. Then, the mixture was heated under reflux condition for 30 min, followed by a steady addition of (3-chloropropyl) trimethoxysilane (2 mL) to it and refluxed for 72 h. Finally, the fumed silica-Pr-Cl was filtered and washed frequently with EtOH through the Soxhlet apparatus and dried at ambient temperature for 24 h (Figure 1).

2.2. Synthesis of fumed $\text{SiO}_2\text{-Pr-Pyr-Benzimidazole}$ nanoparticles

Fumed $\text{SiO}_2\text{-Pr-Cl}$ (2.0 g) was dried, and then the pertinent 2-amino-Benzimidazole (1.0 g) and toluene (50 mL) were added, and the mixture was heated under reflux for 72 h. Subsequently, the obtained solid was

filtered and washed well with EtOH using Soxhlet apparatus, then dried at room temperature (Figure 2).

2.3. Preparation of $\text{Cu@SiO}_2\text{-Pr-NH-Benzimidazole}$

The obtained $\text{SiO}_2\text{-Pr-NH-Benz}$ (1 g) were added to a solution of $\text{Cu}(\text{NO}_3)_2$ (1 M, 25 mL), ascorbic acid (0.2 g), and the mixture was stirred for 24 h at 50 °C. The solid was filtrated, washed four times with double-distilled water, and dried under vacuum for 10 h to result in $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$.

2.4. "One-pot" multicomponent A^3 -coupling reaction by $\text{Cu@SiO}_2\text{-Pr-NH-Benzimidazole}$ nanocatalyst

In a typical procedure, phenylacetylene (1.1 mmol), piperidine (1.1 mmol), aldehyde (1.0 mmol), and $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ (0.01 g) were added to a 10 mL flask, and 5 mL H_2O was added. The mixture was subjected to ultrasound irradiation for 1 h at room temperature. After the completion of the reaction, the mixture was separated by filtration and

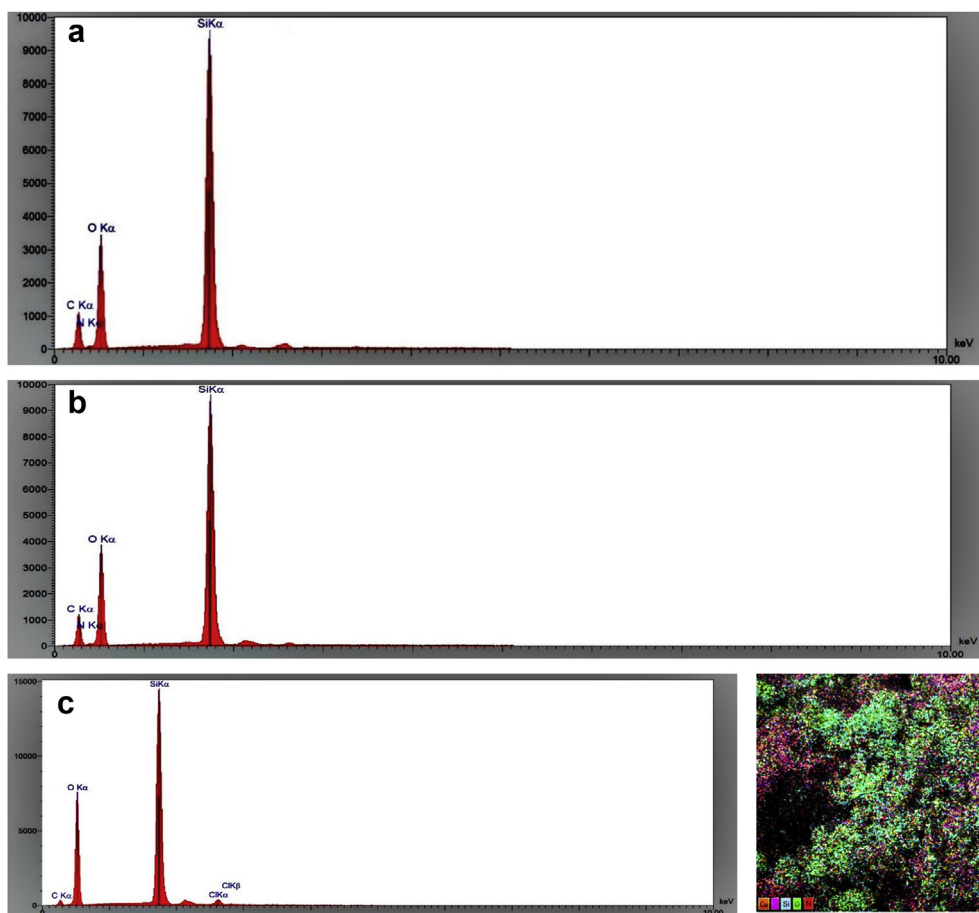


Figure 6. EDX of (a) $\text{SiO}_2\text{-Pr-Cl}$, (b) $\text{SiO}_2\text{-Pr-NH-Benz}$, and (c) $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$.

washed with H_2O and ethanol (310 mL), and filtered. The residue was purified by column chromatography on silica gel using EtOAc/n-hexane as eluent to afford the corresponding pure product (see supporting information; S1–S38).

2.5. “One-pot” multicomponent click reaction by $\text{Cu@SiO}_2\text{-Pr-NH-Benzimidazole}$ nanocatalyst

Phenylacetylene (1 mmol), benzyl bromide derivatives (1 mmol), sodium azide (1 mmol), and $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ nanocatalyst (0.03 g), and 5 mL H_2O were added. The resultant mixture was heated at 70°C , and TLC monitored the progress of the reaction. Upon completion of the reaction, the mixture cooled to room temperature, and the catalyst was separated by filtration. The solvent was removed in a vacuum to afford the pure product.

3. Result and discussion

3.1. Characterization of $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ nanocatalyst

The prepared $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ nanocatalyst was constructed by a three-step procedure to immobilized copper on modified SiO_2 for the click and coupling reactions. The prepared supported catalyst $\text{Cu/SiO}_2\text{-Pr-NH-Benz}$ nanocatalyst was characterized by TGA-DTA, FT-IR, EDX, SEM, and BET analysis. To confirm the preparation of $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ nanocatalyst, FT-IR spectroscopic study was conducted. The FT-IR spectra of $\text{SiO}_2\text{-Pr-Cl}$, $\text{SiO}_2\text{-Pr-NH-Benz}$, and $\text{Cu/SiO}_2\text{-Pr-NH-Benz}$ are shown in Figure 3. The band around 1639 cm^{-1} and broadband at 3265 cm^{-1} are attributed to stretching and bending vibrations of the O–H groups. The silica framework (Si–O–Si) resulted in absorption peaks

around 821 and 1095 cm^{-1} . The silanol group of silica depicted a band at 917 cm^{-1} , representing the Si–O–C formation, which was formed by the reaction of trimethoxy silyl chloride with the silanol group. However, after the functionalization of fumed-silica with 2-amino benzimidazole, a band is depicted at 3375 and 1649 cm^{-1} , which corresponded to the N–H groups, and the band around 1560 cm^{-1} is depicted to C=C groups. After immobilization of Cu, these bands' intensity progressively decreased for the sample due to a decrease in the convenience of free silanol groups. The peaks at 3001 , 2941 , and 1587 cm^{-1} indicate the distinct attachment.

Also, the N_2 adsorption-desorption isotherm was applied to provide insights into pore volume, average pore diameter, specific surface area, and *etc* (Figure 4). The specific surface area (BET) for $\text{SiO}_2\text{-Pr-NH-Benz}$ and $\text{Cu/SiO}_2\text{-Pr-NH-Benz}$ samples were found to be 159.3 and $153.5\text{ m}^2\text{g}^{-1}$, respectively (Figure 4 (a and b)). The BET surface area, pore-volume, and pore size for various samples are represented in Table 1. The nitrogen adsorption/desorption isotherms for $\text{SiO}_2\text{-Pr-NH-Benz}$ and $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ represent a type IV adsorption isotherm characteristic of a type H1 hysteresis loop with relative pressure ranging from 0.8 to 1.0. These characteristics demonstrate that SiO_2 support has a bit mesoporous structure, and still exist after functionalization. The inset figures display the pore size distribution curves for $\text{SiO}_2\text{-Pr-NH-Benz}$, and $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ samples, in which the average pore size is about 30 and 39 nm, respectively, which are consistent with the pore size of Brunauer-Emmett-Teller (Figure 4c). The wide particle size distribution is due to the cluster of SiO_2 particles, which reduces the support's bulk density, forming large fluffy particles. As presented in Table 1, the catalyst-specific surface area diminished gradually along with the surface's functionalization. As the functionalization enhance, the specific surface area of the catalyst reduced slightly because the functionalization of the

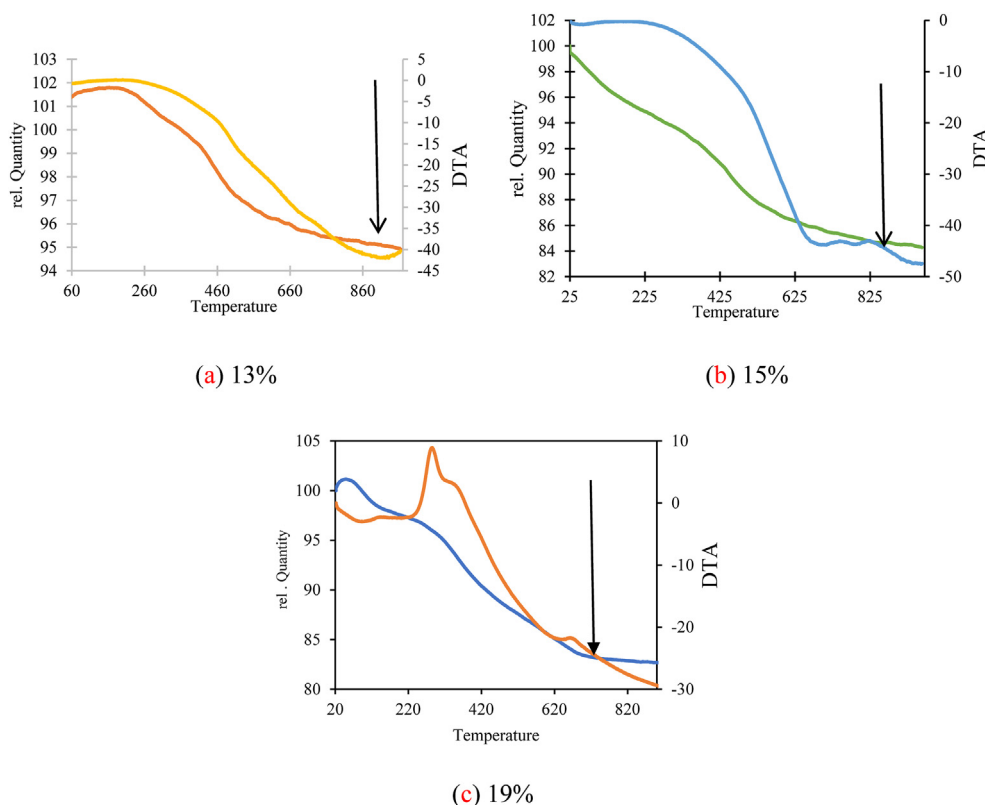


Figure 7. TGA-DTA curves of (a) $\text{SiO}_2\text{-Pr-Cl}$, (b) $\text{SiO}_2\text{-Pr-NH-Benz}$, and (c) $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$.

catalyst support surface occupies a certain surface, but it has a specific surface area [31].

The scanning electron microscopy micrograph (SEM) images of functionalized SiO_2 and the immobilized copper nanoparticles indicate the changes in the catalyst's morphology after the introduction of the Cu. The nanocatalysts' surface is rough, in accordance with the presence of organic groups on the composite surface (Figure 5 (a,b)). The rough surface increases the catalytic activity of nanocatalysts by enhancing the available catalytic sites. Also, the transmission electron microscopy (TEM) analysis shows that the $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ did not agglomerate on the surface of SiO_2 (Figure 5c). Considering the results of SEM-EDX, attachment of the metal on the surface of the $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ solid support can be confirmed. The loading metal was found to be 0.0018 mmol/g of the catalyst (0.020 wt%). The chemical composition of $\text{SiO}_2\text{-Pr-Cl}$, $\text{SiO}_2\text{-Pr-NH-Benz}$, and $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ nanocatalysts were studied through EDX analysis, which confirmed the presence of Cu in the catalyst along with the other elements, indicating the formation of the desired metal complex. As shown in Figure 6 (a-c), the EDX measurement confirmed that the nanocatalyst contains Si, O, C, Cl, Cu.

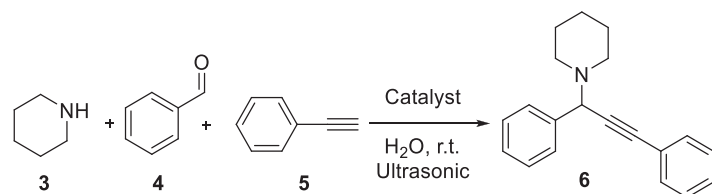
Thermogravimetric analysis (TGA) in nitrogen and synthetic air atmosphere was performed from 25 to 970 °C to predict the catalysts' thermal stability. TGA analysis was applied to study the thermal stability of the $\text{SiO}_2\text{-Pr-Cl}$, $\text{SiO}_2\text{-Pr-NH-Benz}$, and $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$, including the main thermal regions of the polymeric coating decomposition. The TGA results of nanocatalyst demonstrate considerable thermal stability of the catalyst to more than 760 °C, which makes it applicable for implementation in a wide range of reactions with different high temperatures. As shown in Figure 7, the overall weight loss of $\text{SiO}_2\text{-Pr-Cl}$, $\text{SiO}_2\text{-Pr-NH-Benz}$, and $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ was about 13%, 15%, and 19%, which confirmed the functionalization of fumed silica surfaces. The primary decomposition regions determined from TGA-DTA curves exhibited that the organic part's primary decomposition starts from 155 °C, which is

higher than that for organic scaffolds. Obtained data are in line with thermal analysis data reported recently.

3.2. The catalytic activity of $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ for "one-pot" A^3 coupling reaction

The catalytic activity of $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ nanocatalyst was evaluated for the MCR A^3 coupling reaction of amine, aldehyde, and alkyne. The model was performed using phenylacetylene, benzaldehyde, and piperidine to optimize various parameters comprising solvent, temperature, time, and catalyst. The results are listed in Table 2.

Herein, we reported a novel Cu-catalyzed one-pot multicomponent coupling reaction. As depicted in Table 2, the investigation was initialized by phenylacetylene, piperidine, and benzaldehyde as model substrates to find the optimal reaction conditions. In order to compare the Cu-catalytic properties, the homocoupling of phenylacetylene has been conducted in H_2O . In the absence of a catalyst at 100 °C after 24 h, no product was obtained (Table 2, entry 1). For comparison, $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-NH}_2\text{-Cu}$, Cu_2O , $\text{Fe}_3\text{O}_4\text{@CuSiO}_3$, Cu/HM , CuFe_2O_4 , $\text{CuSO}_4\text{/SDS}$, $\text{SiO}_2\text{-Pr-NH-Benz}$, and $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ have been synthesized and examined as a heterogeneous catalyst for the one-pot, three-component A^3 coupling reaction to synthesis propargylamine derivatives. When the reaction was repeated in the presence of various catalysts $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-NH}_2\text{-Cu}$, Cu_2O , $\text{Fe}_3\text{O}_4\text{@CuSiO}_3$, Cu/HM , CuFe_2O_4 , $\text{CuSO}_4\text{/SDS}$, and $\text{SiO}_2\text{-Pr-NH-Benz}$ in 5 mL H_2O at room temperature for 12 h, the yield of the corresponding product is negligible for the A_3 coupling reaction while yielded 30, 55, 65, 73, 0% and 90% of aimed propargylamine with catalysts mentioned above respectively (Table 2, entries 2–6). Among the examined copper-catalysts, the $\text{Cu@SiO}_2\text{-Pr-NH-Benz}$ seemed to be the most active catalyst for the A^3 coupling reaction (Table 2, entry 7). In the next step, after optimization of the appropriate catalyst, in order to obtain the best suitable conditions for the synthesis of target propargylamine products, we have optimized the amount of

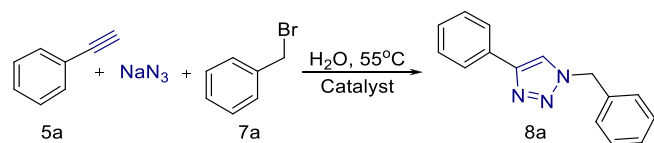
Table 2. Optimization of A³ coupling reaction conditions.

Entry	Catalyst (mg)	Solvent	Catalyst (mol%)	Yield, %	Time	Temp
1	-	H ₂ O	-	-	12 h	rt
2	Cu ₂ O	H ₂ O	10	30	12 h	rt
3	Fe ₃ O ₄ @CuSiO ₃	H ₂ O	10	55	12 h	rt
4	Cu/HM, CuFe ₂ O ₄	H ₂ O	10	60	12 h	rt
5	CuSO ₄ /SDS	H ₂ O	10	63	12 h	rt
6	SiO ₂ -Pr-NH-Benz	H ₂ O	10	-	12 h	rt
7	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	10	75	12 h	rt
8	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	5	78	40 min	rt
9	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	10	82	40 min	rt
10	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	15	87	40 min	rt
11	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	95	40 min	rt
12	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	25	95	40 min	rt
13	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	30	95	40 min	rt
14	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	Trace	100 min	0
15	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	85	35 min	50
16	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	78	40 min	70
17	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	70	50min	100
18	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	80	150 min	rt
19	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	87	24 h	rt
20	Cu@SiO ₂ -Pr-NH-Benz	CH ₃ CN	20	56	40 min	rt
21	Cu@SiO ₂ -Pr-NH-Benz	Solvent-free	20	70	40 min	rt
22	Cu@SiO ₂ -Pr-NH-Benz	DMF	20	75	40 min	rt
23	Cu@SiO ₂ -Pr-NH-Benz	THF	20	60	40 min	rt
24	Cu@SiO ₂ -Pr-NH-Benz	CH ₂ Cl ₂	20	71	40 min	rt
25	Cu@SiO ₂ -Pr-NH-Benz	EtOH	20	82	40 min	rt

Table 3. Copper-catalyzed one-pot multicomponent A³ coupling reaction.

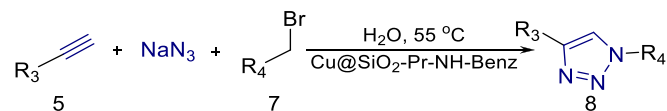
Entry	R ₁	R ₂	R ₃	Product	Yield, %	Time (min)
1	Piperidine	-Ph	Phenyl	6a	97	30
2	Piperidine	3-OH-C ₆ H ₄	Phenyl	6b	80	40
3	Piperidine	4-Me-C ₆ H ₄	Phenyl	6c	92	35
4	Piperidine	2-OH-C ₆ H ₄	Phenyl	6d	90	40
5	Piperidine	2-Me- C ₆ H ₄	Phenyl	6e	81	50
6	Piperidine	4-OMe- C ₆ H ₄	Phenyl	6f	93	15
7	Piperidine	4-Br- C ₆ H ₄	Phenyl	6g	91	8
8	Piperidine	4-Cl C ₆ H ₄	Phenyl	6h	90	34
9	Piperidine	2-naphthaldehyde	Phenyl	6i	93	35
10	Piperidine	CH ₂ O	Phenyl	6j	41	80
11	Diethylamine	-Ph	Phenyl	6k	82	50
12	Morpholine	-Ph	Phenyl	6l	98	35
13	Piperidine	-Ph	2-OMe-C ₆ H ₄	6m	88	24
14	Piperidine	-Ph	4-Me-C ₆ H ₄	6n	93	27
15	Piperidine	-Ph	4-OMe-C ₆ H ₄	6o	91	25

Table 4. Optimization of reaction conditions.



Entry	catalyst	Solvent	Catalyst (mol%)	Yield, %	Time	Temp
1	-	H ₂ O	-	-	12 h	55
2	CuSO ₄ (5mol%)	H ₂ O	5	68	5 h	55
3	MnFe ₂ O ₄	H ₂ O	5	62	3.5 h	55
4	SiO ₂ -Pr-SO ₃ H	H ₂ O	5	-	5 h	55
5	Fe ₃ O ₄ @CuSiO ₃	H ₂ O	5	78	4 h	55
6	SiO ₂ -Pr-NH-Benz	H ₂ O	5	-	8 h	55
7	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	5	85	15 min	55
8	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	10	88	15 min	55
9	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	15	91	15 min	55
10	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	95	10 min	55
11	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	25	95	15 min	55
12	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	30	95	15 min	55
13	Cu@SiO ₂ -Pr-NH-Benz	EtOH	20	84	20 min	55
14	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O/EtOH	20	89	25 min	55
15	Cu@SiO ₂ -Pr-NH-Benz	DMSO	20	69	40 min	55
16	Cu@SiO ₂ -Pr-NH-Benz	THF	20	49	100 min	55
17	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	61	10 min	0
18	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	73	10 min	25
19	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	95	10 min	75
20	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	20	95	10 min	100

Table 5. Copper-catalyzed one-pot multicomponent click reaction.



Entry	R ₃	R ₄	Product	Yield, %	Time (min)	Temp
1	-Ph	-Ph	8a	98	10	55
2	-Ph	3,4-Cl-C ₆ H ₃	8b	92	14	55
3	-Ph	-COPh	8c	91	18	55
4	-Ph	3-Me-C ₆ H ₄	8d	93	13	55
5	-CH ₂ O-C ₆ H ₄ -NO ₂	-COPh	8e	82	23	55
6	Ph	-COPh	8f	91	17	55
7	Ph	4-Br-C ₆ H ₄	8g	94	13	55
8	C ₅ H ₁₁	4-Br-C ₆ H ₄	8h	81	40	55
9	Ph	-Et	8i	73	50	55
10	Ph	2-naphtalene	8j	84	18	55
11	C ₄ H ₉	6-methoxy-naphtalene-	8k	65	33	55
12	-CH ₂ -O-C ₆ H ₄ -NO ₂	4-Cl-C ₆ H ₄	8l	76	26	55

nanocatalyst. Varying the concentration of Cu@SiO₂-Pr-NH-Benz catalyst resulted in yield alteration as expected (Table 2, entry 8–13). We found that 20 mol% of Cu@SiO₂-Pr-NH-Benz nanocatalyst provided a higher yield than 5 mol%, 10 mol%, 15 mol%. However, increasing the amount to 25 mol%, and 30 mol% Cu/SiO₂-Pr-NH-Benz did not provide a better yield. The further screening revealed that a lower or higher reaction temperature proved to be not effective without ultrasonic irradiation (Table 2, entry 14–17). Also, increasing the irradiation time to 150 min resulted in a yield reduction (Table 2, entry 18). A control experiment showed that the propargylamine 6a was obtained in 87% yield after an extended reaction time to 24 h and under ultrasonic irradiation (Table 2,

entry 19). However, it is apparent that the reaction also proceeded in different solvent-free conditions or with solvents such as DMF, THF, CH₃CN, CH₂Cl₂, and EtOH but gave the products in inferior yields (Table 2, entry 11 and 20–24). Notably, no undesirable byproduct could be detected under an optimized reaction condition.

Next, we evaluated the substitute effect of amine and aldehyde (Table 3). In general, good yields were observed with aromatic aldehydes (Table 3, entry 1–8). However, the aliphatic aldehyde afforded product 6j in only 41% yield (Table 3, entry 10). Reaction with aliphatic amines as diethylamine seemed to be working quite well (Table 2, entry 11). The reaction worked efficiently with aliphatic and cyclic amines (Table 3,

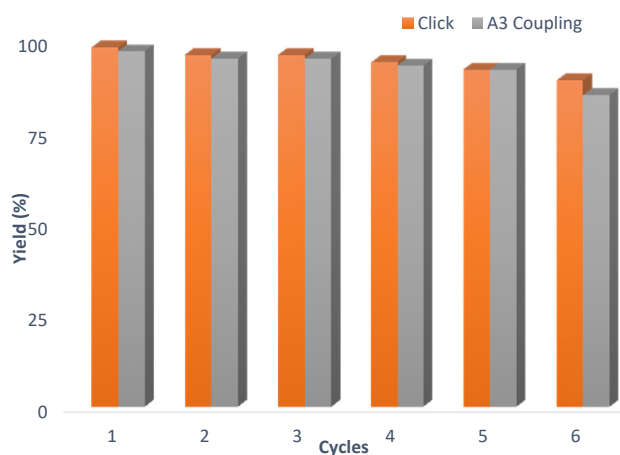


Figure 8. Recyclability of the Cu@SiO₂-Pr-NH-Benz nanocatalyst in the click and coupling reaction.

entry 1–9), affording the desired compound **6** in 80–97% yields. Also, the use of 5-membered ring and 6-membered ring cyclic amine resulted in a good yield of propargylamine **6** (Table 3, entries 1 and 12). Also, alkynes' substituted effect was considered in the reaction with piperidine and benzaldehyde under the optimized condition (Table 3, entries 1 and 13–15). It was exhibited that the different electron-donating groups are bearing -OMe, -Me in the *para* position, and also -OMe in the *ortho* position

were able to produce the corresponding propargyl mine in a good yield and short-reaction time somehow lower than the phenylacetylene group. Incomparable superiorities of our method are quite clear in terms of high yield of synthesized propargylamine, short-reaction time through A³ coupling reaction compared with other previously reported catalysts in a one-pot multicomponent manner and under a green condition with maximum efficiency and activity of nanocatalyst.

3.3. The catalytic activity of Cu@SiO₂-Pr-NH-Benz nanocatalyst for “one-pot” click reaction

The catalytic activity of Cu@SiO₂-Pr-NH-Benz nanocatalyst was investigated by choosing the multicomponent reaction between alkyl halides, terminal alkynes, and sodium azide. To find the optimum reaction conditions, a model reaction was chosen, including a mixture of benzyl bromide (1mmol), phenylacetylene (1mmol), and sodium azide (1mmol). The reaction was carried out under different conditions, and the results are presented in Table 4. In the presence of organic ligands, Cu@SiO₂-Pr-NH-Benz was able to improve the productivity of click reaction under mild and green conditions.

To investigate this catalytic system's generality and utility, the catalytic efficiency of Cu@SiO₂-Pr-NH-Benz was examined in click reaction for the “one-pot” synthesis of 1,2,3-triazoles. The best reaction condition was found as 10 mg catalyst in the water and at 55 °C (Table 4). The results demonstrate that in the absence of catalyst, the reaction could not proceed after 12 h in water and at 55 °C (Table 4, Entry 1). However, employing 5 mol% of homogenous copper sulfates catalyst provided

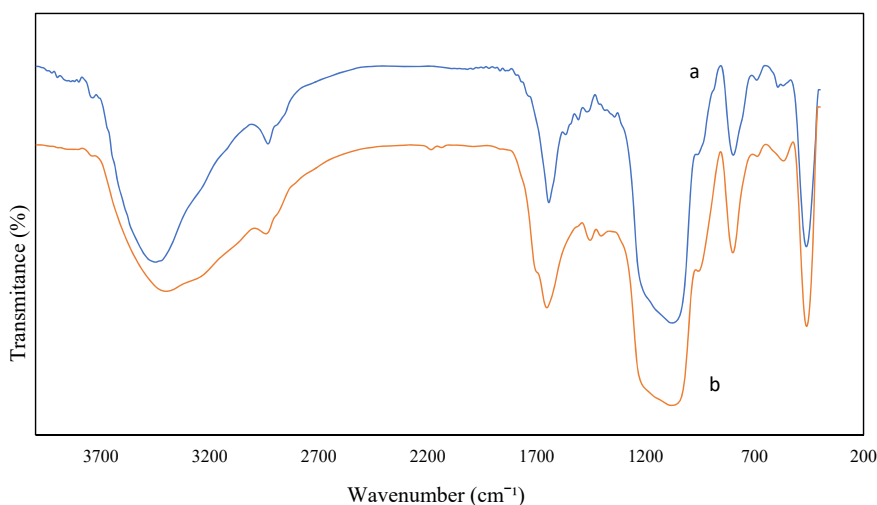


Figure 9. FT-IR spectra of (a) Cu/SiO₂-Pr-NH-Benz, and (b) reused Cu@SiO₂-Pr-NH-Benz after 7 cycles.

Table 6. Comparison of catalyst activity of Cu@SiO₂-Pr-NH-Benz for A³ coupling reaction in comparison with the reported copper content catalyst for the synthesis of **6a**.

Entry	Catalyst	Conditions	Time (min)	Yield (%)
1	Cu/Al	Toluene/100 °C	22 h	94 [25]
2	CuNPs@TiO ₂	Solvent free/70 °C	420	90 [32]
3	Cu NPs	Solvent free/80 °C	420	90 [33]
4	Cu/G	Toluene/100 °C	240	95 [34]
5	Cu@PMO-1L	CHCl ₃ , 70 °C	24 h	96 [35]
6	Cu@GNS	CH ₃ CN, 83 °C	300	89 [36]
7	SiO ₂ @Cu	Toluene, 110 °C	300	94 [37]
8	Cu-MCM-41	Solvent free, 110 °C	150	93 [38]
9	H-Fe ₃ O ₄ @h-Cu@mSiO ₂	Solvent free/110 °C	15	97 [39]
10	CS-MCR-Cu ₂ O	H ₂ O/40 °C	45	95 [30]
11	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O/Ultrasound	30	97 [this work]

Table 7. Comparison of catalyst activity of Cu@SiO₂-Pr-NH-Benz for click reaction in comparison with the reported copper content catalyst for the synthesis of **8a**.

Entry	Catalyst	Conditions	Time (min)	Yield (%)
1	Polymer supported CuI and azide	Reflux, Ethanol	60	92 [40]
2	CuCl ₂ /SiO ₂	H ₂ O, MW/70 °C	10	92 [41]
3	CuSO ₄ /Sodium Ascorbate	DMSO/H ₂ O, 100 °C	40	86 [20,21]
4	Cu/Al ₂ O ₃	Ball-mill	60	92 [42]
5	CuNPs	MeOH, r.t.	480	93 [43]
6	CuNPs/C	H ₂ O, 70 °C	180	98 [43]
7	Cu(I)-zeolite	H ₂ O, 90 °C	15	90 [44]
8	CuSO ₄ -Chitosan	H ₂ O, r.t.	240	99 [45]
9	MnFe ₂ O ₄ @GO@CS/Cu	H ₂ O/EtOH, 50 °C	30	95 [46]
10	CuI-Fe ₃ O ₄ @SiO ₂ (TMS-EDTA)	EtOH	120	97 [19]
11	Cu@SiO ₂ -Pr-NH-Benz	H ₂ O	10	98 [this work]

triazole products in 68% yield (Table 4, Entry 2). As shown in the table, no significant products were observed with SiO₂-Pr-SO₃H, Fe₃O₄@Cu-SiO₃, and SiO₂-Pr-NH-Benz in water after 8 h (Table 4, Entry 4 and 6). It was found that the model reaction in the presence of 5 mol% of Cu@SiO₂-Pr-NH-Benz and after 15 min in H₂O afforded products in 85% yield and at 55 °C (Table 4, entry 7). Therefore, the excellent yield of 1,4-triazole was observed in the presence of Cu@SiO₂-Pr-NH-Benz nanocatalyst and after 15 min.

Increasing the amount of catalyst to 20 mol% improved the yield of model reaction to 95 % in the presence of H₂O as short at 55 °C (Table 4, entry 7–12). The solvent effect was also examined by using the various solvents such as DMSO, EtOH, H₂O and H₂O/EtOH (Table 4, entries 10, 13–16). Table 4, entry 10 depicts that H₂O as the solvent results in the shortest reaction time and highest yield, while for other solvents, the yields are lower even for prolonged reactions. Also, the optimal value of temperature was investigated, which demonstrated decreasing the temperature diminish the yield of the reaction, but raising the reaction temperature more than 55 °C does not affect the yield of reaction (Table 4, entries 17–20).

To explore the generality and applicability of the catalyst, and also check the feasibility of CuAAC reaction, terminal alkynes (1 mmol) was reacted with primary halides (1 mmol) and sodium azide (1 mmol) in the presence of Cu@SiO₂-Pr-NH-Benz nanocatalyst (20 mol%) at 55 °C in H₂O medium under optimal reaction conditions. A series of benzyl bromide phenylacetylene and sodium azide (Table 5). Though, the exceptional yield of 1,4-triazole was observed in the presence of 20 mol% Cu@SiO₂-Pr-NH-Benz nanocatalysts after 10 min (Table 4). We have applied the optimal condition to various substrates for the multicomponent one-pot click reaction. To this purpose, various types of substituents for alkynes and alkyl bromides with different electron-withdrawing and electron-donating groups were employed, and the results are shown in Table 5. The results indicate that alkyl halides are bearing various functional groups, including -Br, -Cl, -OH, -Me, and -NO₂ were able to produce the corresponding 1,4-disubstituted triazoles (Table 5, Entry 1–8). However, the ethyl halide was less reactive (Table 5, Entry 9). Moreover, it was exhibited that alkyl acetylides had lower yields and resulted in triazole and in longer reaction time (Table 5, Entry 8, and 11). Generally, it has been observed that the aromatic substituted for alkyne and aryl bromide led to high yields for corresponding click reactions.

3.4. Revocability and reusability of the catalyst

The reusability and the recyclability of the heterogeneous catalysts are crucial from an economic perspective. The reusing method of the Cu@SiO₂-Pr-NH-Benz nanocatalyst was deployed to synthesize triazole scaffolds **8** and propargylamine **6** upon optimized condition. After each cycle's accomplishment, the solid catalyst was separated from the reaction mixture by filtration, followed by washing several times with ethanol (5 mL) at 50 °C. After drying through vacuum overnight, it was used again in sequential reactions. This investigation exhibited that the

catalyst could be recovered and reused at least five times, with only an insignificant loss of its catalytic activity (Figure 8). The results exhibit that the supported catalyst was highly recyclable under the studied reaction conditions, preserving almost unaltered its initial catalytic performance after five times use.

To confirm the stability and reusability of nanocatalyst during the reaction, a comparison between the recovered catalyst and the fresh one was performed applying FT-IR analysis (Figure 9), and no significant changes were observed. The observation confirms that the structure of the recovered catalyst did not change during the reaction.

Further investigation of the heterogeneous character of the Cu@SiO₂-Pr-NH-Benz nanocatalyst and the stability was implemented using a hot filtration test. It was examined separating catalysts in half the reaction time; no alter were recognized in the click reaction. The one-pot multicomponent reactions do not proceed significantly after the separation of the solid catalyst. In comparison with other reported catalysts for the click reactions, Cu@SiO₂-Pr-NH-Benz nanocatalyst represented good catalytic performance in reusability and activity for the A³ coupling reaction Click reaction (Respectively, Tables 6 and 7).

4. Conclusion

In conclusion, a novel SiO₂ based nanocatalyst functionalized by benzimidazole scaffolds with immobilized copper nanoparticles as a heterogeneous catalyst was reported. Significant advantageous such as enhanced catalytic activity with efficient recycling for the one-pot synthesis of 1,4-disubstituted triazoles and propargyl amine derivatives and in green condition were observed. The unprecedented broad scope of the products of reaction with this novel catalyst was considerable, and facile synthesis of various heterocyclic compounds could be achieved through this procedure. Moreover, this heterogeneous nanocatalyst is stable without copper leaching and aggregation, and also multiple times racIALIZATION without loss of catalytic activity makes it eco-friendly. Our investigation to find potential applications in green organic chemistry is ongoing.

Declarations

Author contribution statement

Mahdieh Darroudi, Hossein Rouh: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Mohammad Hasanzadeh: Conceived and designed the experiments.

Nasrin Shadjou: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at <https://doi.org/10.1016/j.heliyon.2021.e06766>.

References

- Giannakakis, M. Flytzani Stephanopoulos, E.C.H. Sykes, Single-atom alloys as a reductionist approach to the rational design of heterogeneous catalysts, *Acc. Chem. Res.* 52 (2019) 237–247.
- J.D.A. Pelletier, J.M. Basset, Catalysis by design: well-defined single-site heterogeneous catalysts, *Acc. Chem. Res.* 49 (2016) 664–677.
- M. Beller, H. Fischer, K. Kühlein, C.P. Reisinger, W.A. Herrmann, First palladium-catalyzed Heck reactions with efficient colloidal catalyst systems, *J. Organomet. Chem.* 520 (1996) 257–259.
- K.X. Yao, X. Liu, Z. Li, C.C. Li, H.C. Zeng, Y. Han, Preparation of a Ru-Nanoparticles/Defective-Graphene composite as a highly efficient arene-hydrogenation catalyst, *ChemCatChem* 4 (2012) 1938–1942.
- N. Zhang, H. Qiu, Y. Liu, W. Wang, Y. Li, X. Wang, J. Gao, Fabrication of gold nanoparticle/graphene oxide nanocomposites and their excellent catalytic performance, *J. Mater. Chem.* 21 (2011) 11080.
- Á. Mastalir, Z. Király, Á. Patzkó, I. Dékány, P. L'Argentiere, Synthesis and catalytic application of Pd nanoparticles in graphite oxide, *Carbon N. Y.* 46 (2008) 1631–1637.
- X. Wu, L. Tan, D. Chen, X. Meng, F. Tang, Icosahedral gold–platinum alloy nanocrystals in hollow silica: a highly active and stable catalyst for Ullmann reactions, *Chem. Commun.* 50 (2014) 539–541.
- X. Pan, X. Bao, Reactions over catalysts confined in carbon nanotubes, *Chem. Commun.* (2008) 6271.
- K.P. De Jong, J.W. Geus, Carbon nanofibers: catalytic synthesis and applications, *Catal. Rev. Sci. Eng.* 42 (2000) 481–510.
- P. Mondal, N. Salam, A. Mondal, K. Ghosh, K. Tuhina, S.M. Islam, A highly active recyclable gold-graphene nanocomposite material for oxidative esterification and Suzuki cross-coupling reactions in green pathway, *J. Colloid Interface Sci.* 459 (2015) 97–106.
- M.A. Islam, I.A.W. Tan, A. Benhouria, M. Asif, B.H. Hameed, Mesoporous and adsorptive properties of palm date seed activated carbon prepared via sequential hydrothermal carbonization and sodium hydroxide activation, *Chem. Eng. J.* 270 (2015) 187–195.
- N. Gokulakrishnan, G. Peru, S. Rio, J.F. Blach, B. Léger, D. Grosso, E. Monflier, A. Ponchel, A direct novel synthesis of highly uniform dispersed ruthenium nanoparticles over P6mm ordered mesoporous carbon by host–guest complexes, *J. Mater. Chem. A* 2 (2014) 6641–6648.
- W.M.H. Sachtler, Metal clusters in zeolites: an intriguing class of catalysts, *Acc. Chem. Res.* 26 (1993) 383–387.
- L. Armelao, D. Barreca, G. Bottaro, A. Gasparotto, S. Gross, C. Maragno, E. Tondello, Recent trends in nanocomposites based on Cu, Ag and Au clusters: a closer look, *Coord. Chem. Rev.* 250 (2006) 1294–1314.
- A. Sandoval, A. Aguilar, C. Louis, A. Traverse, R. Zanella, Bimetallic Au-Ag/TiO₂ catalyst prepared by deposition-precipitation: high activity and stability in CO oxidation, *J. Catal.* 281 (2011) 40–49.
- J. Sultana, D. Sarma, Ag-catalyzed azide-alkyne cycloaddition: copper free approaches for synthesis of 1,4-disubstituted 1,2,3-triazoles, *Catal. Rev. Sci. Eng.* 62 (2020) 96–117.
- M. Darroudi, M. Hamzehloueian, Y. Sarrafi, An experimental and mechanism study on the regioselective click reaction toward the synthesis of thiazolidinone-triazole, *Heliyon* 7 (2021), e06113.
- W. Bihlmaier, J. Geittner, R. Huisgen, H.U. Reissig, Stereospecificity of diazomethane cycloadditions, *Heterocycles* 10 (1978) 147–152. https://scholar.google.com/scholar?q=Bihlmaier%2C+W.%3B+Geittner%2C+J.%3B+Huisgen%2C+R.%3B+Reissig%2C+H.+U.+Heterocycles%2C+1978%2C+10%2C+147&btnG=&hl=en&as_sdt=0%2C5. (Accessed 22 December 2016).
- M. Darroudi, S. Ranjbar, M. Esfandiari, M. Khoshneviszadeh, M. Hamzehloueian, M. Khoshneviszadeh, Y. Sarrafi, Synthesis of novel triazole incorporated thiazolone motifs having promising antityrosinase activity through green nanocatalyst CuI-Fe 3 O 4 @SiO₂ (TMS-EDTA), *Appl. Organomet. Chem.* (2020).
- M. Darroudi, Y. Sarrafi, M. Hamzehloueian, An efficient synthesis of novel triazoles incorporating barbituric motifs via [3+2] cycloaddition reaction: experimental and theoretical study, *J. Serb. Chem. Soc.* 83 (2018) 821–835.
- S. Ranjbar, P. Shahvaran, N. Edraki, M. Khoshneviszadeh, M. Darroudi, Y. Sarrafi, M. Hamzehloueian, M. Khoshneviszadeh, 1,2,3-Triazole-linked 5-benzylidene (thio)barbiturates as novel tyrosinase inhibitors and free-radical scavengers, *Arch. Pharm.* (2020) (Weinheim).
- F. Ebrahimpour-Malamir, T. Hosseinejad, R. Mirsafaei, M.M. Heravi, Synthesis, characterization and computational study of CuI nanoparticles immobilized on modified poly (styrene-co-maleic anhydride) as a green, efficient and recyclable heterogeneous catalyst in the synthesis of 1,4-disubstituted 1,2,3-triazoles via click reaction, *Appl. Organomet. Chem.* 32 (2018), e3913.
- V.V. Nemmara, V. Subramanian, A. Muth, S. Mondal, A.J. Salinger, A.J. Maurais, R. Tilvawala, E. Weerapana, P.R. Thompson, The development of benzimidazole-based clickable probes for the efficient labeling of cellular protein arginine deiminases (PADs), *ACS Chem. Biol.* 13 (2018) 712–722.
- M.N. Chen, L.P. Mo, Z.S. Cui, Z.H. Zhang, Magnetic nanocatalysts: synthesis and application in multicomponent reactions, *Curr. Opin. Green Sustain. Chem.* 15 (2019) 27–37.
- J. Dulle, K. Thirunavukkarasu, M.C. Mittelmeijer-Hazeleger, D.V. Andreeva, N.R. Shiju, G. Rothenberg, Efficient three-component coupling catalysed by mesoporous copper-aluminum based nanocomposites, *Green Chem.* 15 (2013) 1238–1243.
- N. Salam, A. Sinha, A.S. Roy, P. Mondal, N.R. Jana, S.M. Islam, Synthesis of silver-graphene nanocomposite and its catalytic application for the one-pot three-component coupling reaction and one-pot synthesis of 1,4-disubstituted 1,2,3-triazoles in water, *RSC Adv.* 4 (2014) 10001–10012.
- X. Huo, J. Liu, B. Wang, H. Zhang, Z. Yang, X. She, P. Xi, A one-step method to produce graphene-Fe₃O₄ composites and their excellent catalytic activities for three-component coupling of aldehyde, alkyne and amine, *J. Mater. Chem. A* 1 (2013) 651–656.
- Y. Han, M. Zhang, Y.Q. Zhang, Z.H. Zhang, Copper immobilized at a covalent organic framework: an efficient and recyclable heterogeneous catalyst for the Chan-Lam coupling reaction of aryl boronic acids and amines, *Green Chem.* 20 (2018) 4891–4900.
- M. Zhang, Y.H. Liu, Z.R. Shang, H.C. Hu, Z.H. Zhang, Supported molybdenum on graphene oxide/Fe₃O₄: an efficient, magnetically separable catalyst for one-pot construction of spiro-oxindole dihydropyridines in deep eutectic solvent under microwave irradiation, *Catal. Commun.* 88 (2017) 39–44.
- A. Shaabani, M. Shadi, R. Mohammadian, S. Javanbakht, M.T. Nazeri, F. Bahri, Multi-component reaction-functionalized chitosan complexed with copper nanoparticles: an efficient catalyst toward A3 coupling and click reactions in water, *Appl. Organomet. Chem.* 33 (2019).
- B. Wang, B. Dai, M. Zhu, Application of fumed silica as a support during oxidative desulfurization, *ACS Omega* 5 (2020) 378–385.
- M.J. Albaladejo, F. Alonso, Y. Moglie, M. Yus, Three-component coupling of aldehydes, amines, and alkynes catalyzed by oxidized copper nanoparticles on titania, *Eur. J. Org. Chem.* 2012 (2012) 3093–3104.
- A. Shouli, S. Menati, S. Sayyahi, Copper(II) chelate-bonded magnetite nanoparticles: a new magnetically retrievable catalyst for the synthesis of propargylamines, *Compt. Rendus Chem.* 20 (2017) 765–772.
- S. Frindy, A. El Kadib, M. Lahcini, A. Primo, H. García, Copper nanoparticles supported on graphene as an efficient catalyst for A3 coupling of benzaldehydes, *Catal. Sci. Technol.* 6 (2016) 4306–4317.
- M. Gholinejad, B. Karimi, A. Aminianfar, M. Khorasani, One-pot preparation of propargylamines catalyzed by heterogeneous copper catalyst supported on periodic mesoporous organosilica with ionic liquid framework, *Chempluschem* 80 (2015) 1573–1579.
- M. Gopiraman, D. Deng, S.G. Babu, T. Hayashi, R. Karvembu, I.S. Kim, Sustainable and versatile CuO/GNS nanocatalyst for highly efficient base free coupling reactions, *ACS Sustain. Chem. Eng.* 3 (2015) 2478–2488.
- H. Guo, X. Liu, Q. Xie, L. Wang, D.L. Peng, P.S. Branco, M.B. Gawande, Disproportionation route to monodispersed copper nanoparticles for the catalytic synthesis of propargylamines, *RSC Adv.* 3 (2013) 19812–19815.
- M. Abdollahi-Alibeik, A. Moaddeli, Copper modified spherical MCM-41 nano particles: an efficient catalyst for the three-component coupling of aldehydes, amines and alkynes in solvent-free conditions, *RSC Adv.* 4 (2014) 39759–39766.
- Z. Elahimehr, F. Nemat, A. Elhampour, Synthesis of a magnetic-based yolk-shell nano-reactor: a new class of monofunctional catalyst by Cu⁰-nanoparticles and its application as a highly effective and green catalyst for A3 coupling reaction, *Arab. J. Chem.* 13 (2020) 3372–3382.
- M. Keshavarz, N. Iravani, A. Ghaedi, A.Z. Ahmady, M. Vafaei-Nezhad, S. Karimi, Macroporous polymer supported azide and nanocopper (I): efficient and reusable reagent and catalyst for multicomponent click synthesis of 1,4-disubstituted-1H-1,2,3-triazoles from benzyl halides, *SpringerPlus* 2 (2013) 1–21.
- C.S. Radatz, L.D.A. Soares, E.R. Vieira, D. Alves, D. Russowsky, P.H. Schneider, Recoverable Cu/SiO₂ composite-catalysed click synthesis of 1,2,3-triazoles in water media, *New J. Chem.* 38 (2014) 1410–1417.
- N. Mukherjee, S. Ahammed, S. Bhadra, B.C. Ranu, Solvent-free one-pot synthesis of 1,2,3-triazole derivatives by the “Click” reaction of alkyl halides or aryl boronic acids, sodium azide and terminal alkynes over a Cu/Al₂O₃ surface under ball-milling, *Green Chem.* 15 (2013) 389–397.
- F. Alonso, Y. Moglie, G. Radivoy, M. Yus, Multicomponent synthesis of 1,2,3-triazoles in water catalyzed by copper nanoparticles on activated carbon, *Adv. Synth. Catal.* 352 (2010) 3208–3214.

- [44] V. Bénéteau, A. Olmos, T. Boningari, J. Sommer, P. Pale, Zeo-click synthesis: Cu-zeolite-catalyzed one-pot two-step synthesis of triazoles from halides and related compounds, *Tetrahedron Lett.* 51 (2010) 3673–3677.
- [45] R.B.N. Baig, M.N. Nadagouda, R.S. Varma, Ruthenium on chitosan: a recyclable heterogeneous catalyst for aqueous hydration of nitriles to amides, *Green Chem.* 16 (2014) 2122–2127.
- [46] M. Mahdavinab, M. Hamzehloueian, Y. Sarrafi, Preparation and application of magnetic chitosan/graphene oxide composite supported copper as a recyclable heterogeneous nanocatalyst in the synthesis of triazoles, *Int. J. Biol. Macromol.* 138 (2019) 764–772.