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Cellulose-Supported Poly(Hydroxamic Acid)-Copper(0) Nanoparticles Catalyst for Aza-Michael Reaction †

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Abstract: A green, regenerative and highly active copper(0) catalyst derived from pandanus fruit fibre cellulose-supported poly(hydroxamic acid) was synthesized. The surface of the pandanus hydrolyzed cellulose was undergone chemical modification through graft co-polymerization using purified methyl acrylate. Then the poly(methyl acrylate) was further converted into poly(hydroxamic acid) bidentate chelating ligand via Wilhelm Lossen rearrangement in an alkaline hydroxylamine aqueous solution. At last, the copper was impregnated onto the poly(hydroxamic acid) via the adsorption process forming stable five-member ring complex; Cu(II)NPs@PHA. The Cu(II)NPs@PHA will reduce into Cu(0)NPs@PHA using hydrazine hydride as a reducing agent. The Cu(0)NPs@PHA was fully characterized by spectroscopy analyses. The cellulose-supported Cu(0)NPs@PHA was successfully applied to the Aza-Michael addition reaction with several Michael acceptors and various substituted aryl/heterocyclic/alky amine to afford the corresponding C-N product with excellent yield [aryl amine (50–95%); heterocyclic amine (50–96%); alkyl amine (80–98%)]. The Cu(0)NPs@PHA showed extraordinary stability and it was easy to recover from the reaction mixture and could be reused up to five times without loss of its original catalytic activity.

Keywords: Aza-Michael addition; Cu(0)NPs@PHA; C-N bond; heterogeneous catalyst; poly(hydroxamic acid) and pandanus fruit fiber

1. Introduction

A recyclable biomass-derived heterogeneous catalyst pave the way for significant attention in recent decades [1]. This is due to the broad advantages of a heterogenous catalyst such as low cost, high activity, and easy recovery, potential reusability and tolerance to drastic reaction conditions [2]. Thus environmentally friendly solid supports for the catalysts could be a good choice. Namely, MOF-supported [3], non-magnetic and magnetic supported [4], carbon nanotube [5], MCM-41 supported [6], COF-supported [7] and etc. showed a good catalytic activity to the organic reaction. Nevertheless, they suffer from the viewpoint of economic and sustainable protocols involved in developing green processes. Taking into consideration, biopolymers are an attractive candidate as a solid supported material in the synthesis of heterogeneous catalyst. The biopolymers such as alginate [8], gelatin [9], chitosan [10], and cellulose [11] and etc. Among all of these biopolymers, cellulose could be the most satisfactory material due to its large abundance in nature, low-density, universal availability, low cost and outstanding mechanical properties [12]. Here, we report pandanus cellulose supported poly(hydroxamic acid) copper(0) catalyst as an efficient heterogeneous catalyst for Aza-Michael addition reaction, which can be used for syntheses of medicinal compounds such as antibiotics, auxiliaries, natural products and N-containing heterocycles [13].

In this respect, the cellulose supported catalyst was chosen and we presents the preparation and characterization of effective cellulose-supported poly(hydroxamic acid) copper(0) complex as indicated Cu(0)NPs@PHA for the Aza-Michael addition reaction. Cu(0)NPs@PHA could efficiency promoted the Aza-Michael addition reaction of an aliphatic amine, heterocyclic amine and aryl amine with α,β-unsaturated carbonyl/cyano compound in mild reaction condition.

2. Materials and Methods

2.1. Cellulose Extraction and Hydrolysis (1)

The pandanus fruit was obtained from the seaside near the Papar area, Kota Kinabalu, Sabah. The pandanus fiber was cut into uniform size and dry in the oven for a few days to remove all the pandanus fruit fiber's water. Cellulose was extracted from fibre according to the reported procedure [14]. The hydrolysis process was carried out in 1 L duran bottle in the thermo shaker. The hyrdolyzed cellulose (**1**) was prepared by stirring 5.0 g of pandanus cellulose pulp (**1**) in 250 mL 40% of concentrated sulphuric acid for 2 h with well stirring in 50 °C. After stirring for 2 h, the resultant product directed pours into cold water to stop the reaction. At the same time, it can reduce the acidity of the solution. Then wash the cellulose (**1**) with water until neutralized and dried it in over at 50 °C [15].

2.2. Synthesis of Poly(Methyl Acrylate)-Grafted Nanocellulose (2)

Poly(methyl acrylate)-grafted nanocellulose (PMA-g-nanocellulose) (**2**) was prepared by stirring exactly 6.0 g of pandanus cellulose (**1**) in 600-mL of distilled water overnight. The reaction was carried out according to the procedure described in the reported paper [16]. The desired product (**2**) was precipitating out by the added excess amount of methanol and dried it in over at 50 °C.

2.3. Synthesis of Poly(Hydroxamic Acid) Ligand (3)

Extactly 10.0 g of PMA-g-cellulose (**2**) was placed into a two-neck round bottom flask and fixed with a stirrer and condenser in a thermostat oil bath. The prepared hydroxylamine solution was then added into the bottom flask, and the reaction was carried out at 70 °C for five hours. After the reaction complete, the product (**3**) was separated from the aqueous hydroxylamine solution by filtration and washed using the ethanolic solution. The final product (3) was filtered and washed several times with methanol and dried in an oven at 50 °C to obtain a constant weight (Figure 1a).

2.4. Preparation of Hydroxamic Acid-Copper(II) Metal Catalyst, Cu(II)NPs@PHA (4)

A 1 M of an aqueous solution of copper (II) sulphate solution (9.33 g, 50 mL distilled water) will be added into a stirred suspension of hydroxamic acid ligand (3) (10.0 g) in 50 mL of pH 6.5 buffer solution at room temperature. The white color of the hydroxamic acid ligand (3) was immediately turned into green color hydroxamic acid copper(II) complex (**4**). The hydroxamic acid copper (II) complex (**4**) was filtered out and washed with ammonium chloride and methanol. The ICP-OES analysis was used to determine the amount of copper absorbed onto hydroxamic acid ligand. The ICP-OES analysis showed that 0.02 mmol/g of copper was coordinated with the poly(hydroxamic acid) ligand (Figure 1b).

2.5. *Preparation of Hydroxamic acid-Copper(0) Metal Catalyst, Cu(0)NPs@PHA (5)*

About 5.0 g of Cu(II)NPs@PHA (4) was added into a round bottom flask and added around 10.0 mL of methanol into the flask. Then, 3.0 mL of hydrazine hydride was added into the flask and stirred for two hours. The green color of the Cu(II)NPs@PHA (4) will turn into dark brown color. After that, filter the resultant product (5) and washed with methanol to remove all the hydrazine hydride that retain on the surface of the metal catalyst. The brown color of the Cu(0)NPs@PHA (5) was dried under vacuum and store in inert condition (Figure 1c).

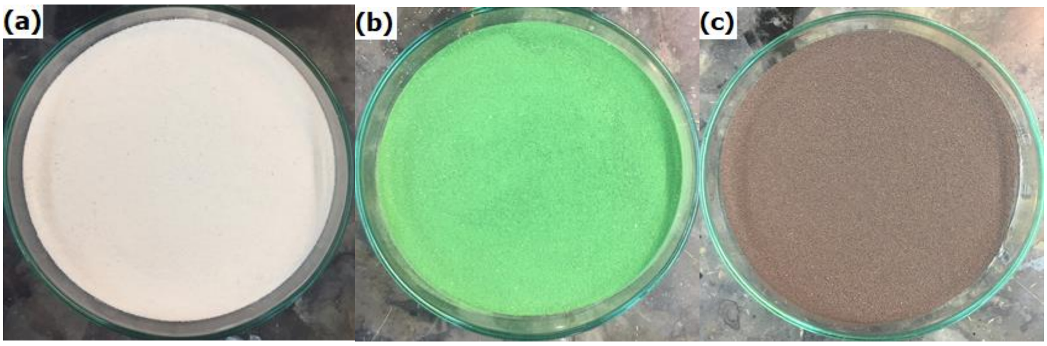


Figure 1. (**a**) Poly(hydroxamic acid) (**3**), (**b**) Cu(II)NPs@PHA (4), (c) Cu(0)NPs@PHA (5).

2.6. General Procedure of Aza-Michael Addition Reaction

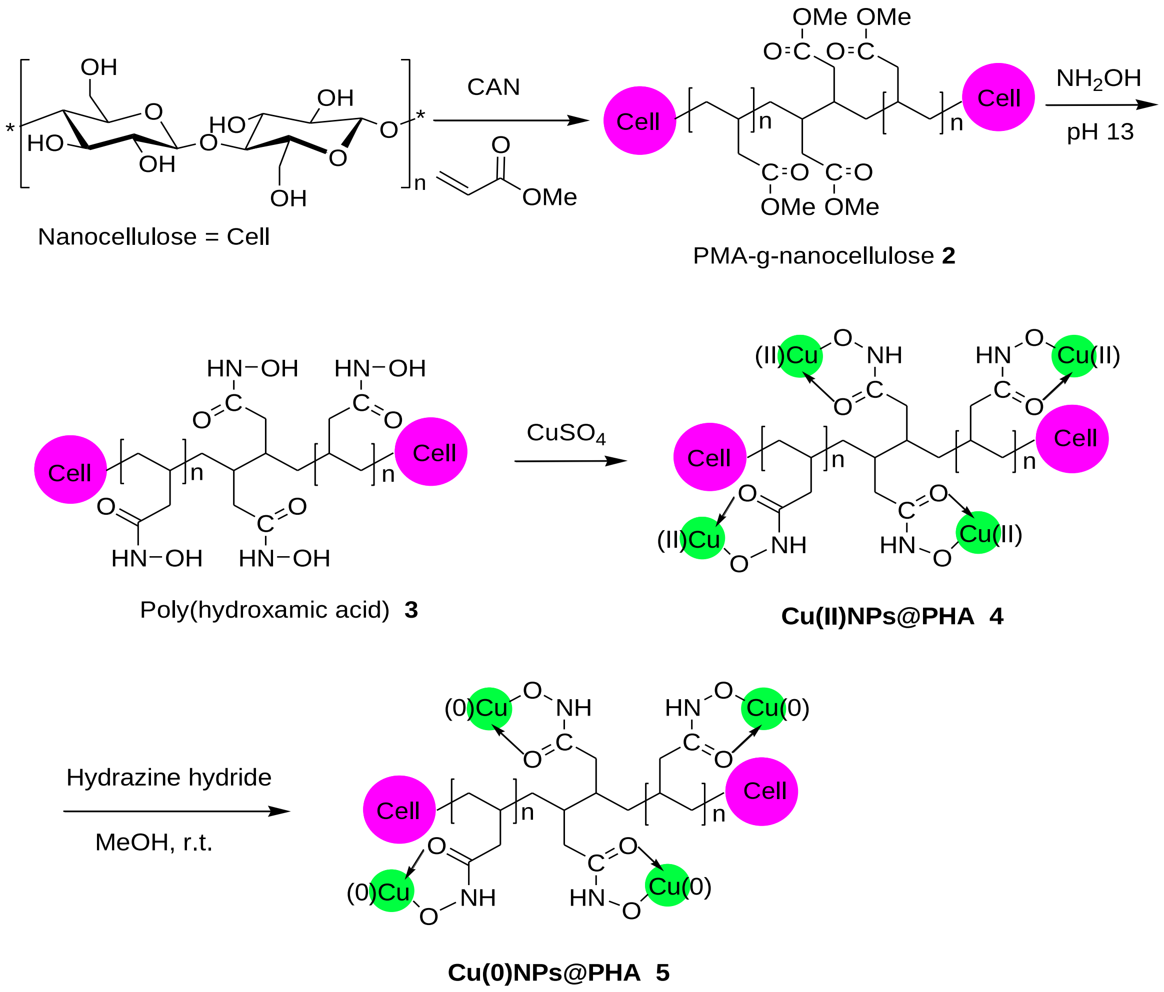
Exactly 0.5 mg of Cu(0)NPs@PHA (5) was added into a mixture of primary/secondary amine (Sigma Aldrich, St. Louis, MO, USA) (1.0 mmol), an electron deficiency alkene (1.5 mmol) at 30 ℃. TLC and GC analyses monitored the corresponding product. After the disappearing of the amine (checking by TLC/GC), the solid metal catalyst was separated by filtration. The corresponding product was extracted with dichloromethane, dried over $MgSO_4$ and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (ethyl acetate/hexane) to give the corresponding cross-coupling product [17].

3. Results and Discussion

3.1. Reaction and Preparation of Cu(0)NPs@PHA (5)

The free-radical reactions have been extensively used to create free radical on the starch or cellulose structure and subsequent reaction with vinyl or acrylic monomers [18,19]. One alternative process among several other methods, transition metal ions, can be the free radicals on the oxygen atom of primary -OH groups of anhydroglucose units (AGU) [20]. The free radicals bearing AGU then added with acrylic monomers and further initiated the free radicals on the cellulosic backbone for propagation reaction resulting in the grafting copolymer products. The hydrogen atom is oxidized by the reduction of the Ce^{4+} to Ce^{3+} ions. Thus, the free-radicals on the cellulose cause the double bond initiation in the monomer, subsequent propagation and termination reaction have been accomplished expected by the combination of grafting, as shown in Scheme 1 [21].

In this study, the PMA-grafted cellulose copolymer was then converted to ligands called poly(hydroxamic acid) ligand (PHA) by undergoing the Loosen rearrangement [22]. The copper metal catalyst was prepared by the adsorption process. The PHA ligand adsorbed Cu(II) ion to form Cu(II)NPs@PHA (**4**). Finally, the Cu(II)NPs@PHA was reduced to the copper(0) for the Aza-Michael addition reaction. The reduction process from Cu(II) to Cu(0) was using hydrazine hydride as the reducing agent. As expected, the green colour of Cu(II)NPs@PHA was changed into the dark brown colour **Cu(0)NPs@PHA** (**5**) (Scheme 1).



Scheme 1. The synthetic route of Cu(0)NPs@PHA (5).

3.2. Infrared Spectroscopy Analysis

IR spectrum of nanocellulose (**1**) showed an absorption peak at 3333 cm^{-1} and 1427 cm^{-1}, indicating the stretching and bending mode of -OH. The C-H stretching mode was observed at 2897 cm^{-1} (Figure 2a) which was also reported in the earlier report [23,24]. A bending mode at 1640 cm^{-1} reported that it has some water adsorb on the surface of cellulose. A small sharp peak appears at 1158 cm^{-1} is attributed to the stretching of the C-O bond in the cellulose glucose unit [23]. The vibration of hemiacetal cellulose structure (C-O-C pyranose ring skeletal) in the cellulose can be observed at 1052 cm^{-1}. A small sharp peak at 897 cm^{-1}belongs to the glycosidic C$_1$-H distortion with the bending of the O-H bond indicates the association of α-glycosidic between glucose units [23]. Based on the spectrum, the extracted nanocellulose pulp is pure form. The vibration of the symmetrical and asymmetrical structure of the C-O-C pyranose was observed clearly at 1052 cm^{-1} [25].

The spectrum of PMA-grafted nanocellulose (**2**) showed a new strong peak at 1727 cm^{-1} due to the carbonyl group in the methyl acrylate monomer (Figure 2b). The rest of the spectra are all found to be similar to that of the peaks for cellulose pulp (**1**) (Figure 2a) [23,24]. This result confirms that the methyl acrylate with the C=O functional group was successfully grafted onto the cellulosic material's surface and named as the poly(methyl acrylate) (**2**). Figure 1c showed that the stretching of C=O at 1727 cm^{-1} at Figure 2b was shifted toward lower wavenumber at 1677 cm^{-1}. This changed indicated the presence of acid functionality in poly(hydroxamic acid) (**3**). The new peak was also observed at 1648 cm^{-1} attributed for the N-H group's bending mode. Broad band appeared at 3119 cm^{-1} due to the O-H and N-H group's stretching. The shift of C=O to 1677 cm^{-1} and new peak at 1648 cm^{-1} (N-H group) confirmed the successful conversion of the poly(methyl acrylate) into poly(hydroxamic acid). This result is in line with previous studies [23,24]. The carbonyl group's peak was shifted in poly(hydroxamic acid) ligand from 1677 cm^{-1} to 1652 is due to the coordination of copper on the chelating functionality. Additionally, the peak at 3119 cm^{-1} for N-H starching was also affected due to the participation of complex formation with the copper metal ion (Figure 2d). This result indicates that the copper metal was successfully adsorbed onto the chelating ligand, yielding the Cu(0)NPs@PHA (**5**).

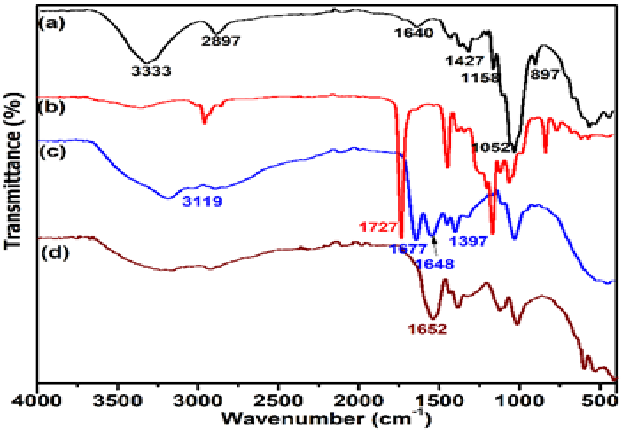


Figure 2. IR spectrum of (**a**) nanocellulose (**1**), (**b**) PMA-g-nanocellulose (**2**), (**c**) Poly(hydroxamic acid) (**3**) and (**d**) **Cu(0)NPs@PHA** (**5**).

3.3. X-ray Photoelectron Spectroscopy Analysis

X-ray photoelectron spectroscopy (XPS) used to analyzed the chemical state and surface elemental composition of Cu(0)NPs@PHA (**5**), Cu(II)NPs@PHA (**4**) and pure poly(hydroxamic acid) (**3**); XPS (PHI Quantera II) with Al 1486.6 eV mono at 25.0 W. Hydroxamic acid-functionalized ligand efficiently binds with copper due to its strong binding ability with metal ions. The XPS analysis is vital in the study the binding mechanisms of copper with hydroxamic acid ligand. The XPS spectra of pandanus nanocellulose-supported poly(hydroxamic acid) (**3**), Cu(II)NPs@PHA (**4**) and Cu(0)NPs@PHA (**5**) were shown in Figure 3a–c, respectively. For a full scan, the binding energies (BEs) peaks were found at 284.0, 399.5 and 531.0 eV, equivalent to the 1 s of carbon, nitrogen and oxygen spectra, respectively. The binding of Cu(II)NPs@PHA (**4**) is secured by the two new sharp and two small peaks with BEs of 935.5, 956.5, 125.5 and 80.5 eV for the indication of Cu2p3/2, Cu2p1/2, Cu3s and Cu3p3, respectively as shown in Figure 3b. Cu(0)NPs@PHA (**5**) also secured by the two new sharp and two small peaks with BEs of 934.5, 954.5, 125.0 and 80.0 eV for the indication of Cu2p3/2, Cu2p1/2, Cu3s and Cu3p3, respectively as shown in Figure 3c.

The binding energies of Cu(II)NPs@PHA **4** and Cu(0)NPs@PHA **5** were increased for N1s and O1s due to the nitrogen atom in a hydroxamic acid functional group possessing lone pair electrons that allows for donation to a metal atom of the copper [26]. Thus, the lone pair electrons present on the nitrogen atom are donated to the copper metal, resulting in a decrease in electron density on the nitrogen atom, giving rise to sharp BE peaks [27]. Same event was happened on the O1s due to coordination bond formed between copper and ligand atoms.

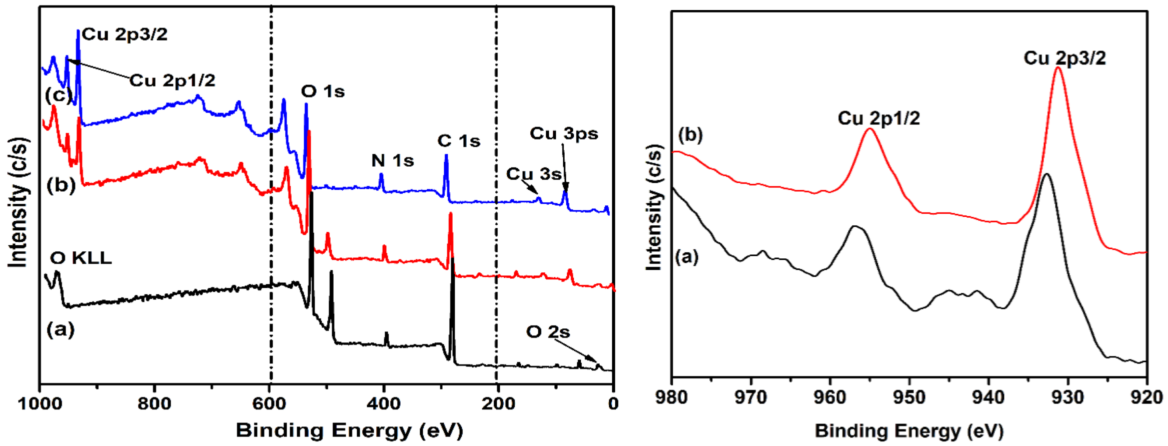


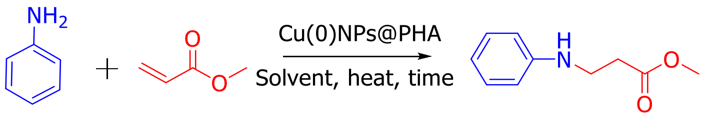
Figure 3. The XPS spectra of left (**a**) poly(hydroxamic acid) (**3**), (**b**) **Cu(II)NPs@PHA** (**4**), (**c**) **Cu(0)NPs@PHA** (**5**) and right a narrow scan of (**a**) **Cu(II)NPs@PHA** (**4**), (**b**) **Cu(0)NPs@PHA** (**5**).

3.4. Cu(0)NPs@PHA Catalyzed Aza-Michael Addition

The functionality of the pandanus cellulose-supported **Cu(0)NPs@PHA** (**5**) was investigated in the Aza-Michael addition of Michael acceptor (activated alkene) and various type of amine. The initial reaction was performed using aniline (1.2 mmol) and methyl acrylate (2 mmol) in the presence of 0.030 mol% (15.0 mg) of Cu(0)NPs@PHA in DMF at 80 ℃ for 24 h.

It was observed that **Cu(0)NPs@PHA** (**5**) forwarded the reaction smoothly to afford the corresponding product **6a** with 70% yield (Table 1, Entry 1). Interestingly, the quantitative yield was obtained (90%) when the reaction was carried out in the presence of aqueous ethanol (1:1) (Entry 2). However, the yield was not improved when acetonitrile and tetrahydrofuran (THF) were used as solvents (Entries 3–4). The reaction yield was tremendously decreases (30–50%). We then accomplished the reaction by changing the catalyst dose (Entries 5–8). It is note that the reaction can move efficiency even using 0.01 mol% (5 mg) of **Cu(0)NPs@PHA** (**5**) (Entry 6). At time same time, we also observe that the reaction would not proceed efficiency when no catalyst; <5% yield (Entry 8). Lastly, we forwarded the reaction by changing the time (Entries 9–12) and temperature (Entries 13–14). Eventually found that 5.0 mg (0.01 mol%) of **Cu(0)NPs@PHA** (**5**), 4 h of reactions time, aqueous ethanol (1:1) as a solvent and the reaction conduct at 30 ℃ shall be sufficient to bring forward the reaction efficiently (Table 1; Entry 14).

Table 1. Screening of Aza-Michael Addition reaction.



6a

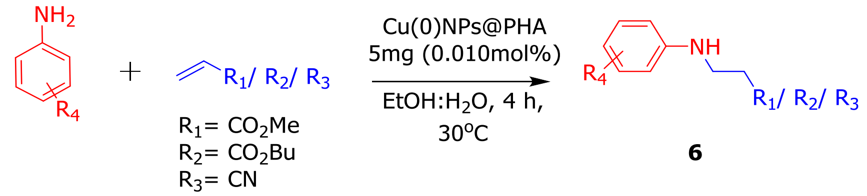
Type	Entry	Solvent	Base	Catalyst (mg)	Temperature (°C)	Time (h)	Yield (%)
Solvent	1	DMF	K_2CO_3	10	80	24	70
	2	EtOH:H_2O	K_2CO_3	10	80	24	90
	3	Acetonitrile	K_2CO_3	10	80	24	66
	4	THF	K_2CO_3	10	60	24	54
Amount of catalyst	5	EtOH:H_2O	K_2CO_3	8	80	24	88
	6	EtOH:H_2O	K_2CO_3	5	80	24	90
	7	EtOH:H_2O	K_2CO_3	2.5	80	24	80
	8	EtOH:H_2O	K_2CO_3	0	80	24	5
Time	9	EtOH:H_2O	K_2CO_3	5	80	12	91

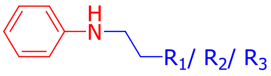
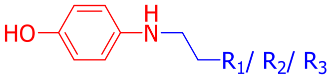
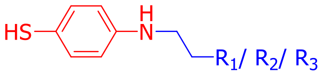
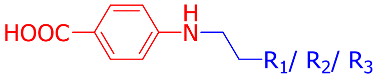
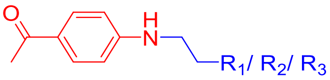
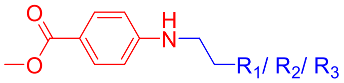
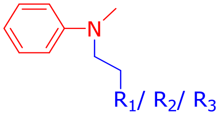
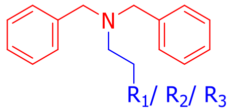
	10	EtOH:H_2O	K_2CO_3	5	80	8	90
	11	EtOH:H_2O	K_2CO_3	5	80	6	89
	12	EtOH:H_2O	K_2CO_3	5	80	4	91
Temperature	14	EtOH:H_2O	K_2CO_3	5	60	4	90
	14	EtOH:H_2O	K_2CO_3	5	30	4	89

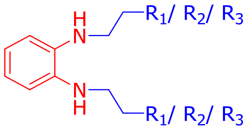
Conditions: Aniline (1.2 mmol), methyl acrylate (2 mmol), a catalytic amount of copper (0) in 5 mL of aqueous ethanol (1:1). Yield of product was determined by GC.

Having the optimized conditions in hand, we investigated the extensive applicability of Cu(0)NPs@PHA (5) in the Aza-Michael Addition reaction with plenty of structurally diverse of amine compound and several Michael acceptor compound. All the results were summarized in Tables 2–4. As illustrated in Table 2, the Cu(0)NPs@PHA (5) could efficiently drive these reactions toward the desired product in good to satisfying yield. The electron-withdrawing acid e.g., 4-aminobenzoic acid smoothly forwarded the Aza-Michael addition reaction with methyl acrylate in presence of 0.01 mol% of Cu(0)NPs@PHA (5) to afford the respective 6j with 85% yield. Amine derivatives with both electron-donating and electron-withdrawing groups preceded smoothly with very good efficiency to form the desired products 6a–6y in high yields (50–95%), Table 2. It should be noted that, there was no tress amount of *S*-alkylated and *O*-alkylated product was observed in the NMR and MS spectra. Therefore, it was confirmed that Cu(0)NPs@PHA (5) was selectively catalyzed only the N-alkylated reaction. The sterically hindered dibenzyl amine and benzene 1,2 diamine underwent Michael addition reaction with methyl acrylate, butyl acrylate, and acrylonitrile in the present of 0.010 mol% of Cu(0)NPs@PHA (5) at 30 ℃ in aqueous ethanol to afford *N*-alkylated product **6t** to **6y** in 52–95%.

Table 2. Aza-Michael Addition of subsituited-arylamine and Michael acceptor.



 R_1, 6a = 90% R_2, 6b = 73% R_3, 6c = 80%	 R_1, 6d = 75% R_2, 6e = 70% R_3, 6f = 73%
 R_1, 6g = 95% R_2, 6h = 85% R_3, 6i = 80%	 R_1, 6j = 85%
 R_1, 6k = 90% R_2, 6l = 78% R_3, 6m = 60%	 R_1, 6n = 88% R_2, 6o = 70% R_3, 6p = 90%
 R_1, 6q = 80% R_2, 6r = 65% R_3, 6s = 75%	 R_1, 6t = 90% R_2, 6u = 85% R_3, 6v = 95%

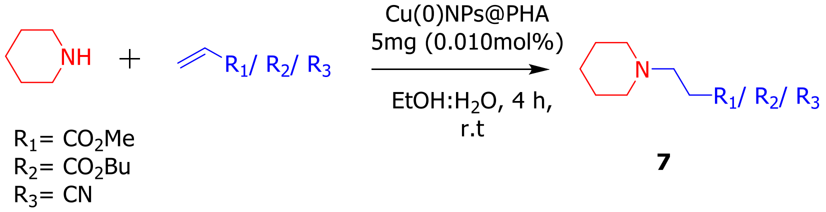


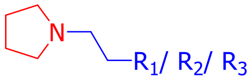
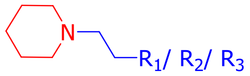
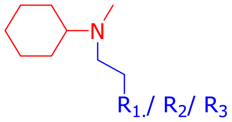
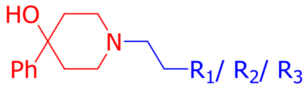
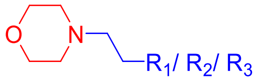
R1, 6w = 52%
R2, 6x = 30%
R3, 6y = 55%

Conditions: Arylamine (1.2 mmol), Michael acceptor (2 mmol), ±5.0 mg (0.005 mol%) of Cu(0)NPs@PHA in 5 mL of aqueous ethanol (1:1). Yield was determined by GC.

Begin inspired by the successful application of Cu(0)NPs@PHA (5) in Aza-Michael addition, the substituted-heterocyclic amine and aliphatic amine compound was considered to find the catalytic versatility of the prepared pandanus cellulose-supported Cu(0)NPs@PHA (5). The addition reaction of substituted-heterocyclic amine and aliphatic amine compound with several Michael acceptor also efficiency forward to corresponded product in up to 96% yield (Tables 3 and 4). Interestingly, the substituted-heterocyclic amine and aliphatic amine compound with several Michael acceptor compound only need only conduct in room temperature to forward the reaction efficiency. Recently, Goswami [28] and Ros [29] reported that cellulose-supported copper nanoparticles catalyzed Aza-Michael reaction of primary and secondary amines compound. In their study, they used 0.036 mol% of copper nanoparticles for both study and obtained almost similar result. Whereas, we only needed 0.010 mol% of Cu(0)NPs@PHA (5) which is 3 times lower catalytic loading compare to their report. Thus, it is observed that pandanus nanocellulose-supported Cu(0)NPs@PHA effectively explored Michael addition reaction with both aromatic, aliphatic and heterocyclic amine compound.

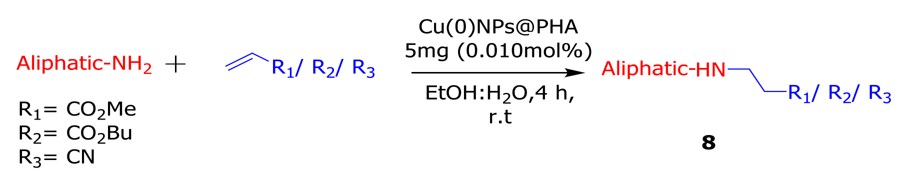
Table 3. Aza-Michael Addition of substituted-heterocyclic amine and Michael acceptor.

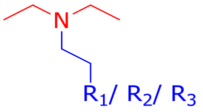


 R1, 7a = 93% R2, 7b = 85% R3, 7c = 96%	 R1, 7d = 75% R2, 7e = 66% R3, 7f = 90%
 R1, 7g = 88% R2, 7h = 90% R3, 7i = 97%	 R1, 7j = 45% R2, 7k = 50% R3, 7l = 60%
 R1, 7m = 95% R2, 7n = 96% R3, 7o = 95%	

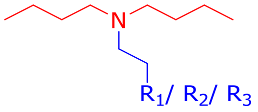
Conditions: Heterocyclic amine (1.2 mmol), Michael acceptor (2 mmol), ±5.0 mg (0.010 mol%) of Cu(0)NPs@PHA in 5 mL of aqueous ethanol (1:1). Yield of product was determined by GC.

Table 4. Aza-Michael Addition of Aliphatic amine and Michael acceptor.

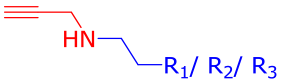




R_1, 8a = 78%
R_2, 8b = 85%
R_3, 8c = 96%



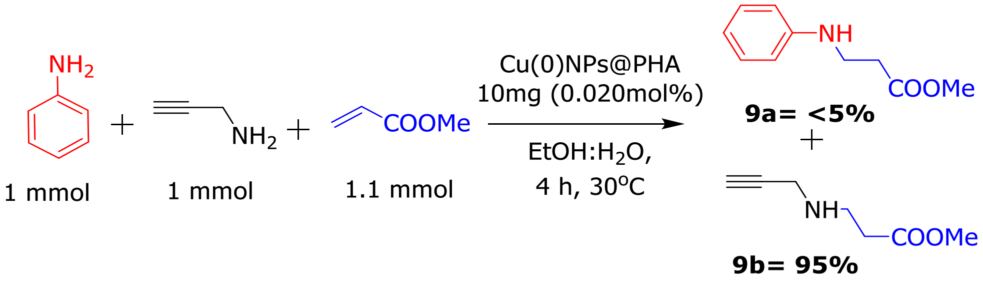
R_1, 8d = 88%
R_2, 8e = 95%
R_3, 8f = 97%



R_1, 8g = 92%
R_2, 8h = 88%
R_3, 8i = 95%

Conditions: Aliphatic amine (1.2 mmol), Michael acceptor (2 mmol), ±5.0 mg (0.005 mol%) of Cu(0)NPs@PHA in 5 mL of aqueous ethanol (1:1). Yield of product was determined by GC.

Chemoselectivity is a vital issue in organic synthesis. Hence, we turn our attention to investigate the chemoselectivity of **Cu(0)NPs@PHA** (**5**) in the Aza-Michael addition reaction. The chemoselectivity study was carried out using a mixture of aniline (1 mmol), propagylamine (1 mmol) and methyl acrylate (1.1 mmol) in a present of 10 mg (0.020 mol%) of Cu(0)NPs@PHA in aqueous ethanol at 40 °C. It was fascinating that only a trace amount of methyl 3-(phenylamino)propanoate form **9a** (<5% yield) rather than methyl 3-(prop-2-yn-1-ylamino)propanoate **9b** (95% yield) was obtained exclusively (Scheme 2). It indicated that chemoselectivity of **Cu(0)NPs@PHA** (**5**) in Aza-Michael addition reaction toward aliphatic amine versus aromatic amine. Therefore, these could be utilized to differentiate between two types of amine in the organic synthesis applications.



Scheme 2. Chemoselectivity of Aza-Michael addition reaction.

3.5. Recycling of Cu(0)NPs@PHA (5) in Aza-Michael Addition

Considering the stability and reusability are the critical component of a real heterogeneous catalyst, we recycling our **Cu(0)NPs@PHA** (**5**) in the reaction (Figure 4). After the first run of the organic reaction, the reaction mixture was filtered out, and the **Cu(0)NPs@PHA** (**5**) was washed with CH_2Cl_2 followed by acetone. The **Cu(0)NPs@PHA** (**5**) catalysts were dried at 65 °C under vacuum and then used it in the next run of reaction without changing the reaction condition. The **Cu(0)NPs@PHA** (**5**) were observed to work efficiently up to five times without significant loss of its catalytic ability. The only small and negligible loss of catalytic performance was found compared to the initial run. While the reduction of product yield was noticed after the fifth cycles owing to the loss of **Cu(0)NPs@PHA** (**5**) during the filtration and washing process and some of the copper (0) oxidize back to copper (II). The absence of any significant leaching of copper metal was also confirmed by ICP analysis. According to ICP result, it was ascertained that only a trace amount of copper (<0.05 mol ppm of copper) was leached into the reaction mixture after several consecutive runs. Therefore, it can be rationally believed that continually utilized our prepared catalyst can be recycled as well as reused in industrial-scale production with no significant loss of its catalytic performance.

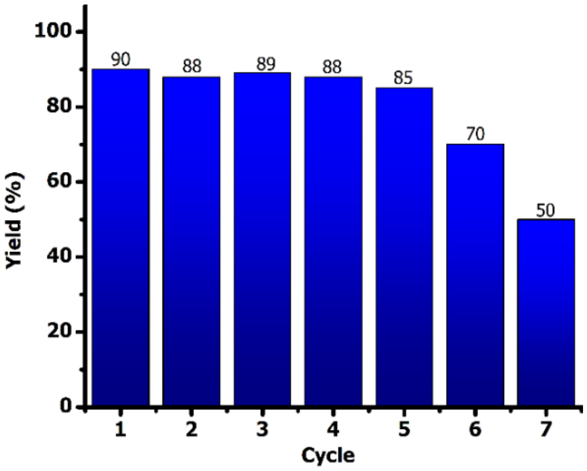


Figure 4. Reusability of Cu(0)NPs@PHA (5).

3.6. Comparison with Other Work

In order to investigate the efficiency of this new procedure in comparison to the reported procedures in the literature, the results for the C–N coupling of Aza-Michael addition reaction as the representative example were compared to the best of the well-known data from the literature as outlined in Table 5. So, this protocol based on cellulose-supported copper catalyst enjoys the advantages of easy separation and reusability and takes advantage of a cost-effective, open-air operating and ligand-free catalytic system.

Table 5. Comparison of pandanus cellulose-supported Cu(0)NPs@PHA for the Aza-Michael addition reaction with the previously reported procedure.

Entry	Type of Supported Catalyst	Catalyst Loading	Conditions	Yield (%)	Ref.
1	Nanocellulose	0.036 mol%	MeOH, r.t, 5.5 h	10–99	[30]
2	Cellulose	-	Toluene, reflux, 0.3–3 h	90–98	[31]
3	silica	0.2 g	Solv. free, r.t, 1–20 h	Up to 90	[32]
4	SBA-15	1 mmol	THF, r.t, 1–4 h	77–95	[33]
5	Polystyrene	8.5 mol%	DMF, 75°C, 4 h	77–90	[34]
6	Polyaniline	2.5 mol%	MeOH, 60°C, 0.5–8 h	88–95	[35]
7	MOF-199	5 mol%	MeOH, r.t, 2 h	Up to 80	[36]
8	Cellulose	500 mol ppm	MeOH, r.t, 5.5 h	80–90	[37]
9	Cellulose-PHA	0.010 mol%	This study	Up to 97	-

4. Conclusions

In summary, we have synthesized the cellulose-supported **Cu(0)NPs@PHA** (**5**) and it was successfully applied in the Aza-Michael addition cross-coupling reaction with different substituted compounds. Only a small quantity (±5.0 mg/0.010 mol%) of the synthesized catalyst is needed to promote the Aza-Michael addition cross-coupling reaction to produce corresponding products with satisfying yields (up to 97%). Besides, the synthesized catalysts can be reused for up to five cycles without losing its catalytic reactivity. Moreover, it is also very stable in the reaction and safe to be utilized because it does not leach out the copper after the reaction is done. Hence, it is a promising reusable environment-friendly catalyst for practical applications.

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