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A Co-Cu bimetallic magnetic nanocatalyst with synergistic and bifunctional performance for the base-free Suzuki, Sonogashira, and C-N cross-coupling reactions in water[†]

Mohammad Ali Nasseri,* Zinat Rezazadeh, Milad Kazemnejadi, Ali Allahresani

A novel magnetically recyclable bimetallic catalyst by anchoring imidazolium moiety and PEG chains on the Fe_3O_4 NPs was prepared and named as $Fe_3O_4@PEG/Cu$ -Co. It was founded as a powerful catalyst for the Sonogashira, Suzuki, and C-N crosscoupling reactions in water as a green solvent without need to any external base. $Fe_3O_4@PEG/Cu$ -Co was well characterized with FT-IR, FE-SEM, TEM, VSM, EDX, ICP, UV-Vis, CV, and XPS analyses. Optimum range of parameters such as time, temperature, and amount of catalyst were investigated by the Design-Expert 10.0.7 software for C-C Suzuki, Sonogashira, and C-N cross-coupling reactions to find their premium conditions. The catalyst was compatible with a variety of aryl halides and *N*-arenes and give favorable coupling products with good to high yields for all of them. Hot filtration and Hg poisoning tests from the nanocatalyst revealed the stability, low metal leaching, and heterogeneous nature of the catalyst. The mechanisms were proposed by study of the UV-Vis spectra *in situ* as well as hydroquinone tests during the reaction pathway. *In situ* XPS analysis was also used to study the reaction mechanism. To prove the synergistic performance of the Co and Cu in the catalyst, its various homologues were synthesized and applied to a model reaction separately, then their catalytic activity were investigated. Finally, the catalyst could be recovered from the reaction mixture simply, and reused for several cycles with a minimum loss in catalytic activity and performance.

Introduction

Carbon-carbon and carbon-heteroatom cross-coupling reactions based on transition metal catalyst systems have revolutionized synthetic methodologies for the synthesis of simple to complex organic structures. A perspective on the development in these type reactions show their applications in the pharmaceutical¹ and agrochemical compounds,^{2,3} electronically materials,⁴ and polymers area.⁵ Transition metals include Pd, Cu, Co, Fe, Ag, Au, and Ni allow chemists to catalyze cross-coupling reactions, however, using affordable and friendly environment designed catalytic systems have more attentions among scientists, lastly.⁶⁻¹² To this end, bimetallic catalysts with their unique features such as improvement reaction conditions, cooperative interaction, increasing rate, and control of selectivity because of participating two active sites simultaneously have been taken much interest as a burgeoning catalytic area.^{13–15} Decades, to go beyond single site catalysts, have been spent introducing bimetallic systems such as [Pd/Cu], [Pd/Ag], [Pd/Rh], [Pd/Au], and [Ni/Cu] for improved cross-coupling reactions.¹⁶⁻²³ In this regard, a variety of bimetallic catalysts have been introduced for different application in organic scope, recently. Dominic et al., studied the activity of a two-metal catalytic systems based on the

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simultaneous presence of Mn and Cu on carbonylative Suzuki-Miyaura reactions.¹³ This bimetallic-catalyst served for the efficient carbonilative C-C coupling reaction via two species including aryl-copper nucleophile and metal acyl electrophile during two co-dependent cycles. Nemygina et al. studied an Au/Pd bimetallic catalytic system for Suzuki cross-coupling,²⁴ wherein, the strong synergetic effect between Pd and Au indicated higher yield for cross-coupling reactions as a ligandfree catalytic system. Next, Ahmed Ismail et al. studied the structural and electronic properties of Co/Fe bimetallic immobilized on carbon nanotube for Fischer-Tropsch reaction.²⁵ The simultaneous effect of cobalt and copper improved the interaction of the substrate with the CNT surface. Most of these cases are based on palladium as toxic, expensive and low abundance metal that cause to focuses of attention on affordable catalyst systems rather than palladium-based systems. To address of this issue, it can be referring to some bimetallic catalyzed systems for environmental, energy and chemical synthesis destinations as H₂ generation, CO oxidation, coupling reaction, hydrogenation and Fischer-Tropsch reaction.26-28

By following the pioneering metal catalysts in cross-coupling reactions, it was found that using of eco-compatible and safe metal catalysts had considerable attention for academic and industrial purposes. For example, cobalt,²⁹ copper,³⁰ nickel,³¹ and iron³² catalysts proceed coupling reactions without any significant reduction in efficiency. Copper-based catalysts as the

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^{c.} + Electronic Supplementary Information (ESI) available: Detail of ANOVA tables, FT-IR spectra, EDX analysis, and ¹H NMR & ¹³C NMR spectra

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Scheme 1. The Chemical structure of Fe₃O₄@Cu(II)IL-SB⁴³ and Fe₃O₄@PEG/Cu-Co catalysts with imidazolium moiety for cross coupling reactions

high active, inexpensive, nontoxic, and easy accessible systems have introduced for C-C and C-heteroatom cross-couplings.³³ Also, Co complexes, caused to their specific properties such as improved efficiency and reducing β -H elimination for Pd-free systems, found a special place in the catalytic purposes.⁸

In other hand, to overcome some of the challenges associated with some transition metal nanocatalyst systems in crosscoupling reactions, designing water-dispersible catalysts to removal of toxic solvents through performing medium monophasic reaction are provided a pleasant view for environmental destinations. Taking cues from these criteria, designed nanocatalysts with polyethylene glycol (PEG) chains could promote catalyst activity in aqueous media for the desired reaction in addition to facilitating catalyst separation and extractive work-up.^{34–37} Afterward, forming magnetically water-dispersible nanocatalysts cause to much better recyclability in shorter time that is a step forward for organic synthesis.

Despite the application of ionic liquids (ILs) as a green solvent with the powerful potential in various chemical reactions, immobilized ionic moieties due to enhance durability, stability, and easy utilization is the appropriate strategy for industrial purposes.^{38,39} Furthermore, these type of catalysts have valuable advantages such as i) easy catalyst recovery,⁴⁰ ii) enhanced interaction with challenging substrates such as aryl chloride, ⁴¹ and iii) and elimination of acid requirement due to the nature of the imidazolium moiety. ⁴² In our previous work, we have developed a bi-functional catalytic system based on copper with ionic tail for base/Pd free Sonogashira reaction that demonstrated in (Scheme 1).⁴³

To upgrade our previously catalytic system (Fe₃O₄@Cu(II)IL-SB),⁴³ we have extended the catalytic system with addition of water-dispersible moiety *via* PEG functional group and cooperativity between Cu/Co on the catalyst denoted as Fe₃O₄@PEG/Cu-Co. Herein, a new magnetically water dispersible/ Cu-Co bimetallic catalyst was synthesized for the efficient base/Pd free C-C and C-N cross coupling reactions in aqueous medium under mild conditions (Scheme 1).

Experimental

Material and instruments

All substances were purchased from Sigma and Fluka suppliers and used without further treatment. The distilled and dried solvents were used for all reactions. Analytical grade was selected for all other reagents. Thin layer chromatography (TLC) was performed for monitoring reaction progress. FTIR spectra were obtained using a JASCO FT/IR 4600 spectrophotometer using KBr pellet. The ¹H NMR (250 MHz) and ¹³CNMR (62.9 MHz) spectra were recorded on a Bruker Avance DPX-250 spectrometer in the deuterated solvents (CDCl₃ and DMSO- d_6) and TMS as an internal standard. Field emission scanning electron microscopy images were achieved on a SEM FEI Quanta 200. Gas chromatography (GC) analyses were performed using a Shimadzu-14B gas chromatograph equipped with an HP-1 capillary column and N₂ as a carrier gas. Anisole was used as an internal standard. EDX analyses were performed using a FESEM, JEOL 7600F apparatus equipped with a spectrometer of energy dispersion of X-ray from Oxford instruments. TEM microscopic images were performed on a Philips EM208S microscope

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operated at 100 kV. TGA analyses of the samples were performed on a Q600 model from TA company made in U.S.A under nitrogen atmosphere with a heating rate of 10 °C /min, and in the temperature range of 25-1000 °C. VSM curve of the samples was analyzed on a Lake Shore Cryotronics 7407 at room temperature. ICP experiments were conducted using a VARIAN VISTA-PRO CCD simultaneous ICP-OES instrument. XRD patterns were obtained on a Rigaku SmartLab. UV-Vis spectra were done on a SPECORD 210 PLUS analytikjena spectrophotometer. The Design-Expert 10.0.7 software was served to find maximum response for the desired reactions. Cyclic voltammetry (CV) behavior (Electrochemical measurements) of the samples were performed on a CHI 1210A electrochemical workstation (CH Instrument, China) with a three-electrode system consisting of a standard Ag/AgCl as a reference electrode, a platinum wire electrode and a modified glassy carbon with the catalyst 8 as an auxiliary and working electrode, respectively. The experiments were performed under neutral atmosphere in the potential range from -2.0 to 2.0 V after 300 s accumulation under stirring with a scan rate of 100 mV s⁻¹. The cell temperature was prepared at 25.0 ± 0.1 °C by means of a HAAKE D8 recirculating bath.¹⁰ Elemental analyses were accomplished on а PerkinElmer-2004 instrument. photoelectron X-ray spectroscopy (XPS) investigations were conducted on a XR3E2 (VG Microtech) twin anode X-ray source with Al-K α =1486.6 eV.

Preparation of PEG-APTES (1):

Polyethylene glycol (PEG-400, 4 g) was added to a solution of NaOH 5% (3.0 mL) and (3-aminopropyl)triethoxysilane (APTES, 1.0 mmol). The mixture was stirred for 24 h at room temperature. The resulting gel-like product (**1**) was centrifuged to remove the excess NaOH and the unreacted APTES. The product was characterized by FT-IR, NMR, and EDX analyses. IR (KBr): υ (cm⁻¹) = 1105 (C-O stretching), 1254 (C-N stretching), 1354 (Si-O stretching), 2868 (CH-*sp*₃), 3103 (OH band). EDX analysis: C= 32.63 %wt, Si=24.40 %wt, N= 7.23 %wt, O=32.74 %wt. ¹H NMR (DMSO-*d*₆, 300 MHz): δ (ppm)= 2.52 (t, 2H), 3.36 (m, 2H), 3.44 (t, 2H), 3.52 (t, 2H), 3.59 (s, 1H, NH₂), 4.60 (s, 1H, OH) (†ESI, Figure S2, S3).

Preparation of PEG-APTES/Co (2):

PEG-APTES/Co complex (2) was prepared by refluxing 4.0 g of PEG-APTES and Co(OAc)₂.4H₂O (1.0 mmol) in a round-bottom flask under N₂ atmosphere for 8 h in ethanol (20.0 mL). The resulting purple powder (2) was obtained by a simple filter paper and repeatedly washing with ethanol. The product was characterized by FT-IR and EDX analyses. IR KBr u (cm⁻¹) = 470 (Co-O stretching), 1019 (C-O stretching), 1116 (Si-O stretching), 1254 (C-N stretching), 2931 (CH-*sp*₃), 3125 (OH band). EDX analysis: C= 39.74 %wt, Si=13.18 %wt, N=7.89 %wt, O= 37.26 %wt, and Co=1.93 %wt (†ESI, Figure S4).

Preparation of PEG-APTES-Schiff base/Co (3):

Chloromethylated salicylaldehyde was synthesized and purified according to our previously reported procedure.⁴³ Then, a mixture of chloromethylated salicylaldehyde (10 mmol) and the PEG-APTES/Co (0.01 g) was added to 30 mL dichloromethane

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for 4 h at room temperature. The product **3** was obtained as a yellow powder after centrifugation and drying of the sediments from the reaction mixture. The product was characterized by FT-IR and EDX analyses. IR (KBr): υ (cm⁻¹) = 464 (Co-O stretching), 699 (C-Cl stretching), 1017 (C-O stretching), 1132 (Si-O stretching), 1141 (Si-O stretching), 1410 (Ph), 1604 (Ph), 1612 (C=N stretching), 2884 (CH-*sp*₃), 2924 (CH-*sp*₂), 3309 (OH band). EDX analysis: C= 26.88 %wt, Si= 17.74 %wt, N= 5.39 %wt, O= 18.34 %wt, Cl= 29.03 %wt, and Co= 2.63 %wt (†ESI, Figure S5).

Preparation of Co complex-Schiff base-IL (4):

In a dried round bottom flask, PEG-APTES-Schiff base/Co (**3**) (2.0 mmol) and *N*-methyl imidazole was added to 5.0 mL toluene under N₂ atmosphere. The mixture was refluxed for 24 h. Then, the resulting solid was filtered by a filter paper and washed with cool EtOH (3×5 mL) to remove any unreacted materials. The product was dried into oven ($50 \, ^{\circ}$ C) for a day and the Co complex-Schiff base-IL (**4**) was isolated as a yellow powder. The product was characterized by FT-IR spectroscopy and EDX analyses. IR (KBr): u (cm⁻¹) = 460 (Co-O stretching), 1034 (C-O stretching), 1136 (Si-O stretching), 1277 (C-N stretching), 1406 (Ph), 1530 (Ph), 1632 (C=N stretching), 2865 (CH-*sp*₃), 2920 (CH-*sp*₂), 3332 (OH band). EDX analysis: C= 37.86 %wt, Si= 20.58 %wt, N= 9.18%wt, O= 9.98 %wt, Cl= 21.20 %wt, and Co= 1.20 %wt (†ESI, Figure S6).

Preparation of bimetallic (Cu-Co) complex (5):

The resulting complex **4** and Cu(OAc)₂.H₂O with a 1:1 molar ratio was mixed in ethanol under refluxing condition for 4 h. The resulting green powder was washed three times with ethanol and then dried in vacuum oven. IR (KBr): υ (cm⁻¹) = 469 (Co-O stretching), 626 (Cu-O stretching), 688 (Cu-N stretching), 1024 (C-O stretching), 1105 (Si-O stretching), 1129 (C-N stretching), 1455 (Ph), 1554 (Ph), 1610 (C=N stretching), 2878 (CH-*sp*₃), 2938 (CH-*sp*₂), 3420 (OH band) cm⁻¹.

Preparation of Fe₃O₄@PEG/Cu-Co (6):

The Fe₃O₄ nanoparticles were synthesized via the coprecipitation of FeCl₃.6H₂O and FeCl₂.4H₂O according to a reported procedure previously.44 To provide a nanomagnetic bimetallic catalyst, 0.1 g of bimetallic complex 5 was added to 1.0 g of Fe_3O_4 in the presence of NaOH solution (5 mL, 10% w/w) under N₂ atmosphere for 48 h. The resulting magnetic nanocatalyst was washed three times with ethanol after isolation by a permanent magnetic field. IR (KBr): υ (cm⁻¹) = 420 (Co-O stretching), 579 (Cu-O stretching), 644 (Cu-N stretching), 1003 (C-O stretching), 1030 (Si-O stretching), 1347 (C-N stretching), 1369 (Ph), 1585 (Ph), 1627 (C=N stretching), 2837 (CH-sp₃), 2923 (CH-sp₂), 3397 (OH band). EDX analysis: Fe= 53.24 %wt, O= 26.18 %wt, N= 7.61 %wt, C= 5.23 %wt, Cu= 3.38 %wt, Si=3.16 %wt, Co=1.15 %wt, Cl= 0.04 %wt. Scheme 2 shows the general synthetic route for the preparation of 1, 2, 3, 4, 5, and 6.

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Scheme 2. A general schematic for the preparation of Fe₃O₄@PEG/Cu-Co

General procedure for Suzuki-Miyaura and Sonogashira crosscoupling:

It worth noted that in all C-C and C-N cross-coupling reactions, didn't use any external base. Simply, aryl halide (1.0 mmol), phenylboronic acid (1.0 mmol), Fe₃O₄@PEG/Cu-Co (0.006 g, 0.31 mol%Cu, 0.11 mol%Co), were added to 2.0 mL of water at 80 °C. Continuously, the reaction mixture was checked by thinlayer chromatography for studding the reaction process. After filtration of the magnetic catalyst, the organic layer was separated by a mixture of CH_2Cl_2 (3 ×7 mL) and H_2O . The organic phases were dried over MgSO₄, and the solvent was removed under reduced pressure. The pure coupling product was obtained on the silica-gel column chromatography (*n*-hexane: EtOAc = 20:2).

For the Sonogashira-cross coupling reaction, phenyl acetylene was used in the presence of $Fe_3O_4@PEG/Cu$ -Co (0.007g, 0.37mol%Cu, 0.13 mol%Co). The reaction performance and product purification was as same as the Suzuki reaction. The products were purified by silica-gel column chromatography (*n*-hexane: EtOAc = 8: 5).

General procedure for C-N cross-coupling:

In a round bottom flask, a mixture of *N*-heterocycle (1.0 mmol) and aryl halide (or phenylboronic acid, 1.0 mmol) was added to 2.0 mL of water, then 0.009 g of $Fe_3O_4@PEG/Cu-Co$ (0.47 mol%Cu, 0.17 mol%Co) was added to the mixture at 90 °C. The reaction was stirred for appropriate time that was monitored by TLC. Upon reaction completion, the catalyst was magnetically separated, then the product was extracted to DCM (3×7 mL). The organic layers were combined, dried over MgSO₄ and

purified by silica-gel column chromatography (*n*-hexane: EtOAc = 10: 3).

Results and discussion Catalyst characterization

Catalyst **6** was characterized step by step by FTIR and EDX analyzes to investigate the structure and formation of the desired bonds (†ESI, Figure S1-S7).

Figure 1 shows the XRD patterns for Fe₃O₄ and Fe₃O₄@PEG/Cu-Co. Fe₃O₄ was characterized by the six main characteristic peaks at 20= 30.51°, 35.92°, 43.61°, 53.90°, 57.67°, and 63.32° related to (220), (311), (400), (422), (511), and (440) planes respectively, that completely confirmed the crystal structure of Fe₃O₄ in agreement with literature (JCPDS card no. 19-629).^{8,45} The diffraction patterns indicated obvious reduction peaks intensity after loading amorphous complex of 5 on the magnetite nanoparticles (Figure 1, b). This decrease in intensity can also be directly attributed to the coating of nanoparticles by PEG chains having an amorphous structure, which is also a confirmation of the functionality of the Fe₃O₄ nanoparticles. In addition, as shown in Figure 1, the peaks location as well as the width of peaks remained intact during the process of functionalization with complex 5, indicating the any change in structure and stability of the nanoparticles.

The magnetic properties of Fe_3O_4 and $Fe_3O_4@PEG/Cu$ -Co were investigated with the vibrating sample magnetometer (VSM) analysis at room temperature. Magnetic behavior of Fe_3O_4 and $Fe_3O_4@PEG/Cu$ -Co revealed a superparamagnetic behavior (zero coercivity) for both with saturation magnetization of 74.28

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Figure 1. XRD patterns of (a) Fe_3O_4 , (b) and $Fe_3O_4@PEG/Cu-Co$ (5)



Figure 2. VSM analyses of Fe_3O_4 and $Fe_3O_4@PEG/Cu-Co$

and 55.33 emu.g⁻¹ respectively (Figure 2). This reduction in magnetization imply the successful immobilization of Cu/Co complex on Fe_3O_4 due to simple dilution of superparamagnetic Fe_3O_4 core with the diamagnetic one.

In order to better understand the role of PEG groups in the thermal behavior of complex 6, the TGA curve of the catalyst was compared with the catalyst developed in our previous work (without PEG groups).⁴³ As shown in Figure 3, Fe₃O₄@Cu(II)IL-SB has three weight loss steps totaling 10.26%, which is consistent with the removal of adsorbed water (~120 °C) on the surface and trapped water in the crystalline structure of the catalyst (~220 °C), and the decomposition of functional organic groups immobilized on Fe₃O₄ NPs. Thermal behavior of the catalyst bearing PEG groups was quite different from that without PEG. Here, after weight loss attributable to water removal at temperatures of about 220 °C, continuous weight loss of up to 1000 °C was observed. Significantly, the weight loss is greater than before (related to water removal) in the area, which is quite consistent with the water adsorption capability of the PEG polar groups in the catalyst.



Figure 3. TGA curves of (A) $Fe_3O_4@Cu(II)IL\-SB$ and (B) $Fe_3O_4@PEG/Cu\-Co$

The total weight loss to 1000 °C is 22.62%, which have 12.36% difference by weight compared to the previous catalyst. This discrepancy can be directly attributed to the presence of PEG groups with cobalt ions coordinated by ethylene groups. Therefore, the presence of PEG groups in the catalyst with higher ability to water absorption, causes to the better dispersion of the catalyst in the water solvent and subsequently provides a suitable medium for the coupling reactions (Figure 3).^{46,47}



Figure 4. EDX analysis of Fe₃O₄@PEG/Cu-Co

Figure 4 shows the EDX spectrum of Fe₃O₄@PEG/Cu-Co. EDX analysis of Fe₃O₄@PEG/Cu-Co confirmed all the expected elements including Fe, O, C, Cu, Co, Si, Cl and N with 53.24 wt%, 26.18 wt%, 5.23 wt%, 3.38 wt%, 1.15 wt%, 3.16 wt%, 0.04 wt%, and 7.61 wt% values, respectively. The presence of chloride in the EDX spectrum proved the imidazolium moiety in the catalyst. The expected elements such as Copper and Cobalt demonstrated a bimetallic catalyst Cu-Co system.

FE-SEM and TEM images of Fe₃O₄@PEG/Cu-Co are shown in (Figure 5, a-c). All three images revealed the spherical morphology and uniformity size of the catalyst. Another interesting aspect related to TEM images is completely dispersion of the catalyst in ethanol medium, because of its hydrophilic section without any agglomeration (Figure 5, c). It is noted that the core-shell structure was confirmed obviously with the TEM images with an average size of 40 nm (Figure 5, b).⁴⁸

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The electrochemical behavior of Fe₃O₄@PEG/Cu-Co was studied in the range of -2.0 to +2.0 V (Figure 6). The results of cyclic voltammetry show the oxidation and reduction of copper and cobalt species, which exhibited a quasi-reversible behavior compared to the behavior observed for Fe₃O₄@Cu(II)IL-SB (which only contains copper centers in the structure) with two peaks appearing at $E_{pa} = -0.86$ and +1.11 V in the cathode current correspond to the Co(II) \rightarrow Co(I) and Co(III) \rightarrow Co(II) respectively. Their corresponding peaks appear in the anodic current at $E_{pc} = -0.66$ and +1.25 V respectively. The copper centers also represent the redox peak pair corresponding to the Cu(II) \rightarrow Cu(I) reduction at $E_{pc} = +0.67$ and the Cu(I) \rightarrow Cu(II) oxidation at $E_{pa} = 0.80$, confirming the certain redox-processes for the copper.⁸

XPS analysis of compound **2** was used to determine the oxidation state of cobalt species. As shown in Figure 7, compound **2** exhibited a binding energies at 777.1 eV and 793.0 eV corresponding to Co $2p_{3/2}$ and Co $2p_{1/2}$ respectively, which indicating that the cobalt centres have +2 oxidation state. ^{49,50} The electronic states of copper and cobalt species present in the catalyst was studied by high resolution XPS analysis related to Cu 2p and Co 2p binding energies. High resolution Co 2p XPS analysis revealed that Co²⁺ is the major component in the catalyst. The deconvolution of Co 2p ($2p_{3/2}$ and $2p_{1/2}$) showed Co species in a mixed-valent state of +3 (Showed as a shoulder)

and +2 (Figure 8). The binding energies appeared at 777 eV and 793.2 eV were assigned to Co $2p_{3/2}$ and 100^{2} pp D binding energies respectively, exactly matching with the Co²⁺ oxidation state.^{50,51} Moreover, the spectrum exhibited binding energies at 780 eV and 795.5 eV corresponding to the $2p_{3/2}$ and $2p_{1/2}$ levels, respectively, indicates the presence of Co(III) ions.⁵² Their satellites were appeared at 788 eV and 800 eV assigned to Co(II) and Co(III) respectively. Figure 8 also shows the Cu 2p XPS spectra of the catalyst. Two couples of peaks located at (932.0 eV, 937.0 eV) and (952.5 eV, 954.0 eV) represents the Cu $2p_{3/2}$ and Cu $2p_{1/2}$ binding energies respectively, which indicates the simultaneous presence of Cu(I) and Cu(II) sites in the catalyst.^{53,54} The spectrum indicated that the major copper existed in the form of Cu(II) oxidation state in the sample.

XPS analysis also shows an electron exchange in copper and cobalt centers. Compared with the XPS spectrum of compound **2** where cobalt species are only in +2 oxidation states, it can be seen that with the addition of Cu ions to the catalytic system, the cobalt centers have a mixture of +2 and +3 oxidation states, which can be attributed to the presence of the coordinated copper ions. On the other hand, Cu binding energies also indicate the presence of +1 and +2 concurrent species, indicating the possibility of electron exchange between copper and cobalt.



Figure 5. (a) FE-SEM and (b,c) TEM images of Fe₃O₄@PEG/Cu-Co

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Optimization of reaction parameters

An efficient technique for finding the optimum conditions in organic reactions is the statistical method response that chemists enable to study the influences of parameter effects each other in the minimum time. To study the cross-coupling reaction conditions, three operation parameters (time, temperature, and amount of catalyst) investigated in various conditions over the reaction of (i) phenylacetylene and 4iodotoluene as a Sonogashira coupling model, (ii) phenylboronic acid and 4-iodotoluene as a Suzuki coupling model, and (iii) phenylboronic acid and imidazole as a C-N coupling model). The Design-Expert 10.0.7 software was served to find maximum response for the desired reactions. Response surface plot (3D) implies the influence of three variables on the response for Sonogashira A, Suzuki B, and C-N coupling C reactions (Figure S8). To find optimum conditions, all of designed random reactions were done without any external base due to the base functionality of the imidazolium moiety. The imidazolium moiety played the role of a base in the cross-coupling reactions. Selected optimization range achieved for Sonogashira crosscoupling reaction including 4-5 hours during time of reaction, 0.007-0.009 g amount of catalyst, and 85-95 °C by the Design-Expert software (Figure S8, A). As shown in Figure S8, B, experimental Suzuki reaction shows three variable ranges for the optimal ranges such as 3-4 hours during time of reaction, (a)

View Article Online 0.006-0.007 g amount of catalyst, and 704800 C D the other drift reaction, C-N cross coupling reaction, founded three optimum range including 6-7 hours during time of reaction, 0.009-0.010 g amount of catalyst, and 90-110 °C (Figure S8, C). Therefore, optimum points were chosen for all three reactions due to investigated other substituted scopes of reactants.

As can be seen in Figure S8, the amount of catalyst, during time reaction, and temperature are three vital variables in crosscoupling reactions. According to Figure S8, there was a direct relationship between maximum response (yield) and amount of the catalyst that could be justified by higher available active sites. The yield was increased with increase of temperature, as shown in Figure S8. Due to thermal stability of the catalyst (from TGA curve, Figure 3), the catalyst could operate in high temperatures without notable loss of activity. As shown in Figure S8, the yield was raised up with increase of reaction time. Decreasing yield is observed after the mentioned time that could be illustrated by poisoning effect of oxygen on the catalyst. Strong chemisorption of O_2 on active sites cause to block sites for catalytic purpose.^{55,56}



Figure 6. Cyclic voltammogram of (a) catalyst **6** and (b) $Fe_3O_4@Cu(II)IL-SB^{43}$ in 0.1 mol L⁻¹ Britton–Robinson (BR) buffer solution (pH 7.0) with a scan rate of 100 mV s⁻¹ at room temperature



Figure 7. High resolution normalized (energy corrected) Co 2p XPS spectrum of compound 2

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Figure 8. High resolution (normalized-energy corrected) Co/Cu 2p XPS spectrum of the catalyst Fe₃O₄@PEG/Cu-Co (6)

Preliminary results illustrated the maximum yields in water as a green solvent for all three reactions due to the high dispersion of catalyst and strong interaction of active sites with the reactants in this medium (Figure 9). H₂O/EtOH (1:1, v/v) gave good yield but the reaction completion needed to longer time (up to 10 h). Mixture of H₂O/DMSO and solvent-free conditions was shown moderate to good yield, which need to higher temperatures (up to 110 °C).⁵⁷

In accordance with the obtained reaction conditions in the preceding step, the catalytic activity of **6** was studied in the Suzuki, Sonogashira, and C-N coupling reactions. C-N cross-coupling reactions were conducted on a variety of alkyl halides as well as phenylboronic acids with *N*-heterocycles compounds by $Fe_3O_4@PEG/Cu-Co (0.47 mol\% Cu, 0.17 mol\% Co) at 90 °C in water (Table 1,$ **9a-9k**). It was founded that phenylboronic acid has a dramatic influence in the desired output product compared with aryl halide derivatives (Table 1, entry**9a-9g**).



Figure 9. Effect of solvent in Sonogashira, Suzuki, and C-N coupling reaction. Reaction conditions: Sonogashira: 4-iodotoluene (1.0 mmol), phenylacetylene (1.2 mmol), Cat. (0.007 g, 0.37 mol% **Cu**, 0.13 mol% **Co**), H_2O (2 mL), 80 °C. Suzuki: 4-iodotoluene (1.0 mmol), phenylboronic acid (1.2 mmol), Cat. (0.006 g, 0.31 mol% **Cu**, 0.11 mol% **Co**), H_2O (2 mL), 80 °C. C-N coupling: phenylboronic acid (1.2 mmol), Imidazole (1.0 mmol), Cat. (0.009 g, 0.47 mol% **Cu**, 0.17 mol% **Co**), H_2O (2 mL), 90 °C.

Para substituted aryl halides give satisfactory yields than their corresponding *ortho* substituted, that may be attributed to the steric hindrance effect (Table 1, entry **9i** and **9j**).^{58,59}

It is also important to note that aryl halides with iodine and bromine leaving groups have an insignificant efficiency drop, which can be attributed to the effect of imidazolium groups on the catalyst (Table 1, entry **9h-9k**).^{43,60} However, the slight decrease in efficiency for aryl bromide can be attributed to a mechanism involving oxidative-addition and reductive-elimination stages (Table 1, entry **9h-9k**).

In following, the catalytic activity of 6 was evaluated toward Sonogashira cross-coupling reaction using Fe₃O₄@PEG/Cu-Co (0.37 mol% Cu, 0.13 mol% Co). Various substituted aryl halides with phenyl acetylene were coupled in high to excellent yields in water at 80 °C (Table 2). It should be noted that the electronwithdrawing groups on aryl halides (Table 2, entry 11g-11k) reduced the efficiency compared to electron-donating groups (Table 2, entry 11b-11f).61,62 Moreover, I, Br, and Cl leaving groups in aryl halides delivered little difference yields, which increasing output was as order of I> Br> Cl. This effective reaction efficiency between Chloride, Bromide, and iodide leaving groups on aryl halides was another influence of imidazolium moiety in the catalyst according to the proposed mechanism (refer to Schemes 6,7). Another important point for the Sonogashira catalyzed by Fe₃O₄@PEG/Cu-Co was its high selectivity, so that no homo-coupling (typical Glaser reaction) or any other side-coupling product was observed.

Finally, the catalytic activity of Fe₃O₄@PEG/Cu-Co (0.31 mol% Cu, 0.11 mol% Co) on the Suzuki coupling reaction was also evaluated. Again, a variety of aryl halides were served in order to coupling with phenylboronic acid under optimum conditions. A same result was found for the effect of leaving groups and electron withdrawing groups on efficiency of the coupling products (Table 3).⁶³ The electron-withdrawing groups on aryl halides (Table 3, entry **12g-12k**) demonstrated more satisfactory yields than the corresponding aryl halides bearing electron-donating groups (Table 3, entry **12b-12f**). Iodine as a good leaving group showed a successfully C-C transformation compared with bromine and chloride (Table 3).

To show the advantage and synergistic effects of various parts of the catalyst, including imidazolium moiety, PEG tail, and bimetallic section, some analogues were prepared and then Journal Name

applied in the Sonogashira model reaction under premium conditions (Table 4). Compounds **13**, **14**, **15**, and **16** were separately prepared and characterized and used as a catalyst for the reaction (†ESI, Fig. S9).

Copper and cobalt salts did not give any detectable products in water for the Sonogashira model reaction (Table 4, entries 1,2). It is important to note, however, that in all model reactions no base is used. Fe₃O₄ nanoparticles did not exhibit any catalytic effect as the core and magnetic substrate (Table 4, entry 3). The remarkable result was the high catalytic activity of compound **2** over **3** (Table 4, entries 4,5). Due to their structural difference, this efficiency can be attributed to the effect of the amino

groups in compound **2**, that plays the role of a base Compound **4** with 83% efficiency fully supports this (Table 4, entry 6). These results are consistent with the previous reports, wherein a imidazoilum moiety plays the role of a base in the coupling reactions.^{8,43} In addition, the catalytic effect of the copper and cobalt metal centers was evaluated. For this purpose, analog **13** (of the catalyst **6**) was prepared without metal centers and used as a catalyst in the model reaction (Scheme 3). As shown in Table 4, entry 8, no significant efficiency was observed. In the next step, the synergistic effect of the two encoded metals was investigated.

Table 1. C-N cross-coupling reaction of on aryl halides or phenylboronic acid with *N*-heterocycles catalyzed by Fe₃O₄@PEG/Cu-Co^{a,b}



^a Reaction conditions: aryl halide or phenylboronic acid (1.2 mmol), *N*-heterocyclic compound (1.0 mmol), Cat. (0.009 g, 0.47 mol% **Cu**, 0.17 mol% **Co**), H₂O (2 mL), 90 °C. ^b Isolated yields were reported.

Table 2. Sonogashira cross-coupling reaction of aryl halide with phenylacetylene catalyzed by $Fe_3O_4@PEG/Cu-Co^{a,b}$



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^a Reaction conditions: aryl halide (1.0 mmol), phenylacetylene (1.2 mmol), Cat. (0.007 g, 0.37 mol% Cu, 0.13 mol% Co), H₂O (2 mL), 80 °C. ^b Isolated yields were reported.





^a Reaction conditions: aryl halide (1.0 mmol), phenylboronic acid (1.2 mmol), Cat. (0.006 g, 0.31 mol% Cu, 0.11 mol% Co), H₂O (2 mL), 80 °C. ^b Isolated yields were reported.

Homolog **14** of catalyst **6** lacking cobalt centers (presence of copper centers only) yielded 70% of the coupling product (Scheme 3 and Table 4, entry 9).

On the other hand, homolog **15**, which only had copper centers coordinated by the salen ligand, produced higher yields than **14** under identical conditions (Table 4, entry 10, 75%).

By comparing with compound **4** that only uses copper metal centers (83% conversion, entry 6), one can draw the following conclusions: (1) The iminium ligand performs better than polyethylene glycol and produces a more dominant catalyst effect,⁶⁴ (2) cobalt centers alongside copper have a plausible

synergistic effect towards the coupling reactions, (3) the imidazolium group acts as an effective base on the coupling reactions.

Finally, to illustrate the effect of PEG groups on the model reaction, the reaction was performed in the presence of both copper and cobalt salts (simultaneously) in the PEG solvent (Table 4, entry 11). As expected, no detectable product was found. The experiment showed that not only can no catalytic activity be assumed for the copper and cobalt salts in the PEG solvent, but the reaction is strongly dependent on the presence of the base. In addition, the presence of PEG chains on the silicate compound gives a remarkable ligand effect to the

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compound, which can load 0.11 mol% of cobalt metal (Suzuki reaction).

Since Fe_3O_4 nanoparticles did not exhibit any catalytic activity, therefore, the observed efficiency difference between compounds **5** and **6** can be attributed to the effect of increasing the surface area induced by the nano substrate and subsequently increasing its catalytic property.



Scheme 3. Chemical structure of 13, 14, and 15 as three analogues of the main catalyst 6

In order to investigate the effect of the ligand, the metal centers of cobalt and copper were replaced by each other. For this purpose, as shown in Scheme 4, the catalyst **16** was made in such a way that the copper ions were first coordinated by ethylene glycol groups and subsequently cobalt ions were coordinated between the four-dentate Schiff base ligands. The results showed that catalyst **16** provide 80 % yield over 4 h for the model sonogashira reaction under optimum conditions. Results demonstrated a low drop of yield which is related to some reasons: (i) cobalt is coordinated by a strong four dentate Schiff base ligands, while copper centers are coordinated by ether bonds; (ii) Accordingly, and according to the mechanism proposed below, copper (I) species responsible for the coupling

Table 4. Designed control experiments for Sonogashira cross-coupling^a

Entry	Catalyst	Yield (%)
1 ^b	Cu(OAc) ₂ .H ₂ O	0
2 ^c	Co(OAc) ₂ .4H ₂ O	0
3	Fe ₃ O ₄ NPs	0
4 ^c	Compound 2	30
5°	Compound 3	Trace
6 ^c	Compound 4	83
7 ^d	Compound 5	88
8	Compound 13 (Metal-free analogue of 6)	Trace
9°	Compound 14	70
10 ^b	Compound 15	75
11 ^e	$Cu(OAc)_2.4H_2O + Co(OAc)_2.H_2O$	Trace
12	Cobalt acetate /PEG	Trace

^a Reaction conditions: aryl halide (1.0 mmol), phenylacetylene (1.2 mmol), Cat. (except noted, 0.006 g), H₂O (2 mL), 80 °C, 4 h. ^b 0.37 mol%Cu. ^c 0.13 mol%Co. ^d 0.31 mol%Cu, 0.11 mol%Co. ^eThe reaction was performed in the presence of Co(OAc)₂.4H₂O (0.13 mol%) and Cu(OAc)₂.H₂O (0.37 mol%) in PEG-400 as a solvent.



Scheme 4. Chemical structure of 16 as an analogue of the main catalyst 6

reaction is generated by electron transfer from cobalt (II) and oxidation to cobalt (III), while in the opposite case (catalyst **16**), formation of the copper (III) species at first seems unlikely; (iii) with the presence of PEG groups, the catalytically active centers are placed distance and separated from the surface of the magnetic nanoparticles, which increases the contact with the reactants and subsequently promotes the catalytic properties. In addition to all these results, it is important to note that the synergistic effect between cobalt and copper is quite evident by comparing the present results of compounds **14** and **15** with 70 and 75% efficiency, respectively.

Mechanism study

The simultaneous presence of copper and cobalt centers enables the electron transfer between the centers and subsequent the redox oxidation processes. According to the results obtained in control reactions, the simultaneous presence of metal centers which results in a synergistic effect and a significant increase in efficiency can also be attributed to this effect.¹³ In order to probe the presence of radical species in the Sonogashira reaction, two separate tests under oxygen and nitrogen atmosphere were studied (under completely identical conditions for 4 hours; the reaction progress was monitored continuously by GC). The results were obtained with no change to the normal state (air atmosphere), reflects the lack of influence of oxygen and radical species in the reaction medium. In addition, the effect of hydroquinone as a potent radical scavenger on the reaction of the Sonogashira model reaction was investigated. This test was studied on three separate reactions in the presence of compounds 5, 15, and 16 as a catalyst (Scheme 5). The results showed that hydroquinone causes a significant decrease in the efficiency of the catalytic coupling product by 5 and 16 (the reaction is not completely stopped), while remaining constant for the efficiency of 16. The lack of effect of hydroquinone on compound 15 (containing only copper centers) can be interpreted as causing hydroquinone to interfere with the electronic transfer between cobalt and copper and subsequently reduce their synergistic effect. As shown in Scheme 5, the results for these reactions show only a ~40 percentage drop for 5 or 16. Thus, the results do not indicate that the reaction passes through radical mechanism and that hydroquinone may have an adverse effect on the catalytically active sites. Accordingly, a mechanism could be proposed, in agreement with the literature,65 on the basis of oxidative-addition and reductive-elimination stages.



* Conditions: Phenyl acetylene (1.0 mmol), 4-iodotolune (1.0 mmol), H2O (2 mL) 80 °C, 4h.

Scheme 5. Effect of hydroquinone as a radical scavenger over the model Sonogashira reaction using 5, 15, and 16 compounds as a catalyst

It is not possible to determine which metal conducts the reaction through oxidative-addition and reductive-elimination. However, the proposed mechanism is based on previous observations and reports in Scheme 6, in which the copper center is proposed to conduct the reaction *via* oxidative addition and reductive-elimination route. By transferring an electron, Cu^{2+} is reduced to Cu^+ . Next, a π -complex is formed between the metal centers in the catalyst and the acetylene groups. The imidazolium group forms an intermediate of copper-acetylide (intermediate B) by removing the proton.



Scheme 6. A plausible reaction mechanism for (A) Sonogashira (B) Suzuki cross-coupling reaction catalyzed by $Fe_3O_4@PEG/Cu-Co$

The presence of polyethylene glycol groups promotes the hydrophilicity of the catalyst and causes it to provide a Suitable medium for aryl halide to close to the intermediate B (Scheme 6). By an oxidative addition, aryl halide is added to copper and the metal capacity is increased to +3. At the end of the product the desired coupling is produced by a subtraction removal and the catalyst returns to the cycle. In the end, the desired coupling product is produced by a reductive elimination reaction and the catalyst returns to the cycle (Scheme 6). A similar mechanism was proposed for the C-N coupling catalyzed by Fe₃O₄@PEG/Cu-Co (Scheme 7). In this mechanism, also formed active Cu(I) species are attacked by the nucleophilic group by the amine group. Next, the Cl⁻ counter ion of the imidazolium moiety remove the proton from the amine and forms an intermediate c. In the next step, aryl halide is close to the intermediate c and the oxidative-addition causes the intermediate e as well as the oxidation of the active centers of Cu(I) to Cu(III). Finally, by the reductive-elimination, the C-N coupling product is prepared and the catalyst returns to the cycle.

To investigate the oxidation state of metal centers in the catalyst, the electron transfer in the catalyst in the reaction of the model was studied using UV-Vis *in situ* continuously. Figure 10b shows the electron transitions of the Cu²⁺, Cu⁺¹ and Co²⁺ ions in the Cu(OAc)₂.H₂O, Co(OAc)₂.4H₂O, and CuI salts. The presence of electron transitions involving Cu²⁺ and Cu⁺ in the reaction mixture confirms the electron transitions. As shown in Figure 10a, the concentrations of Cu²⁺ ions gradually decrease to +1.

In addition, in order to investigate the mechanism more precisely and also to investigate the effect of electron transfer on the catalyst (between Cu and Co), XPS analysis was performed *in situ* for the Sonogashira reaction (Figure 11). XPS



Scheme 7. A plausible reaction mechanism for C-N cross-coupling reaction catalyzed by $Fe_3O_4@PEG/Cu-Co$

analysis confirmed the proposed mechanism. As shown in Figure 11, at the beginning of the reaction the peak intensities

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for Cu (II) species are low, and in contrast, the peak intensities for Cu (I) and Co (III) increase. The presence of two peaks at the binding energies of 780 eV and 795 eV confirms the presence of Co(III) species, which increases with the reaction progress due to the exchange of electrons with copper. At the same time, the concentration of Cu(I) species increased at the binding energies of 932 eV and 952 eV and it appears that an increase in oxidation occurs with these species (Scheme 6A, a-c). According to the proposed mechanism, copper-acetylide formation is carried out by copper (I) species, whereby it is oxidized to copper (II) species. At the end of conversion, too, the elements return to almost their initial oxidation state.

Accordingly, the proposed mechanism for the Suzuki reaction was expanded. The Scheme 6B, shows a proposed mechanism for the Suzuki reaction that first, by electron transfer between Cu and Co (confirmed by XPS analysis in the preceding step), creates active Cu(I) species for the oxidative-addition reaction in the presence of aryl halide and copper is oxidized to +3. The imidazolium moiety of the catalyst plays a base role and, in the presence of phenylboronic acid, leads to vitherticlective intermediate of Ar-Cu(III)-Ph. Eventually,¹⁰ the/Peductive elimination step results in the desired coupling product and the catalyst returns to the cycle again. The presence of polyethylene glycol chains increases the hydrophilicity of the catalyst and consequently causes to high solubility of the catalyst in the aqueous medium, which facilitates the separation. Figure 12a,b illustrates how the catalyst is dispersed in aqueous phase in the mixture of H₂O/DCM and H₂O/EtOAC.

As shown in the images, the catalyst selectively enters the aqueous phase with no distribution in the organic phase. Figure 12 illustrates the effect of PEG groups on the dispersibility of aqueous media compared to the similar catalyst with lacking PEG groups ($Fe_3O_4@Cu(II)IL-SB$).⁴³ As shown in Figure 12, the two-phase separation did not work well. Figure 12d, also shows an easy workup involving the separation of the catalyst and the product from the reaction environment involving the coupling of phenylacetylene with 4-iodotoluene.



Figure 10. (a) Taken UV-Vis spectra *in situ* every 15 min from the reaction mixture of phenyl acetylene, 4-iodotoluene and catalyst (the model reaction) under mild conditions. (b) UV-Vis spectra of Cu(OAc)₂.H₂O, Co(OAc)₂.4H₂O, and Cul in water



Figure 11. High resolution normalized *in situ* XPS (energy-corrected) survey of the mixture of phenylacetylene, iodobenzene, and $Fe_3O_4@PEG/Cu-Co$ in water at 80 °C at (a) the beginning, and after (b) 1 h, (c) 2 h, (d) at the end of the reaction (recovered catalyst)

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Recyclability studies

In the heterogeneous catalysts field, recovering and recycling are the important matters for environmental and practical destinations. In this way, the recyclability of the catalyst was studied over the model Sonogashira cross-coupling reaction (between 4-iodotoluene and phenylacetylene) at 80 °C in water. As shown in Figure 13a, the catalyst could be recovered and reused for at least seven consecutive times without any notable reduction in catalytic activity (Figure 13a). Figure 13 shows that every recovery yields a very low efficiency drop, so that after the seventh cycle the efficiency reached to 90% (only 5% decrease) which is insignificant. In addition, the residual solution after each cycle was studied by ICP analysis to measure metal(s) leaching. For both copper and cobalt metals, the leaching was very low, so that after the seventh recovery for copper and cobalt, the leaching amount was 1.8% and 2% respectively, that was negligible. The presence of imidazolium moiety and PEG tail in the catalyst backbone prevented metal leaching in aqueous media which remains catalytic activity for practical goals due to its water stability.⁴⁸ It is noted that the hydrophilic section provided new separation method without

using an external magnet because of the complete dispersion of catalyst in the aqueous phase regardless of organic solvent. The heterogeneous nature of the catalyst was studied by Hg(0)poisoning and hot filtration tests on the model Sonogashira reaction under optimized conditions. In the filtration test, the catalyst was magnetically recovered after two hours of reaction. As shown in Figure 13b, the efficiency reached to 57% after 4 hours, indicating the heterogeneous performance of the catalyst in the reaction medium, which no leaching occur due to the coordinated metals (Cu or Co) in the reaction mixture (Completely consistent with the results of the leaching studies). In addition, in the Hg(0)-poisoning test, mercury was added both initially, and in a separate test, after 2 hours of reaction time (Yield%= 55%, GC analysis). If the catalyst is heterogeneous, the mercury deactivates its activity by poisoning the catalyst (blokes the active sites) and subsequently the reaction stops. Mercury has no effect on homogeneous catalysts.10



Figure 12. How dispersion of $Fe_3O_4@PEG/Cu$ -Co in (a) H_2O/CH_2Cl_2 , (b) $H_2O/Ethyl$ acetate. How dispersion of $Fe_3O_4@Cu(II)IL$ -SB in (c) $H_2O/\frac{Ethyl}{acetate}$ biphasic medium, and (d) product separation via H_2O/CH_2Cl_2 biphasic medium.



Figure 13. (a) Recycling studies of $Fe_3O_4@PEG/Cu$ -Co and (b) the results of Hg poisoning and Hot filtration tests in the Sonogashira reaction of 4-iodo toluene with phenylacetylene

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Figure 14. FT-IR spectroscopy (a) and TEM image (b) of 7^{th} reused ${\rm Fe_3O_4@PEG/Cu-Co}$ catalyst

Table 5.	Comparison	of the Fe ₂ O ₄ @PFC	G/Cu-Co catal	vst activity wi	th other ren	orted in literature
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Entry	Reaction	Catalyst ref	Base	Solvent	T (°C)	Time (h)	Yield (%)	Ref.
1	Suzuki ^a	Fe ₃ O ₄ @PEG/Cu-Co	-	water	80	3	91	This work
2 ^b		TiO ₂ -Pd/Au-Al ₂ O ₃	NaOH	CH₃CN	r.t	1	71	65
3°		GO/Au-Pd	K ₂ CO ₃	EtOH/H ₂ O	r.t	2	87	66
4	Sonogashira ^d	Fe ₃ O ₄ @PEG/Cu-Co	-	water	80	3.5	95	This work
5 ^e		CuO/TiO ₂	K ₂ CO ₃	EtOH	r.t	15	54	67
6 ^f		Pd₃Cu₁/SiC	Cs ₂ CO ₃	DMF	60	8	99	68
7 ^g		PdCu@GQD@Fe ₃ O ₄	DABCO	Toluene	60	24	99	69
8	C-N coupling ^h	Fe ₃ O ₄ @PEG/Cu-Co	-	water	90	7	75	This work
9		CuNps/TiO₂	Cs ₂ CO ₃	DMF	120	16	99	70
10 ⁱ		[Fe]/[Cu]	Cs ₂ CO ₃	DMSO/H ₂ O	150	0.5	39	71

^a Suzuki reaction of iodobenzene and phenylboronic acid

^b Visible light irradiation

^c GO=Graphene oxide

^d Sonogashira reaction of iodobenzene and phenylacetylene

^e ≥350 nm light intensity

^f 400-800nm light intensity

^g GQD=Graphene Quantum Dot

¹ Microwave, Reaction of 4-iodobenzonitrile and imidazole

The results show that the addition of mercury (0) to the reaction medium immediately suspends the reaction, indicating that the catalyst is fully heterogeneous in the reaction medium. The reaction kinetics for both the filtration and mercury poisoning tests are shown in Figure 13b. When the catalyst was added from the beginning, a very low efficiency is observed (4% for 160 minutes, Figure 13b). Based on the previous results, it can be concluded that the catalyst is somewhat resistant to mercury poisoning that could be seen for some transition metal.⁵⁵ To investigate the stability and structure of the recovered catalyst (after 7th run), it was characterized with FTIR as well as TEM analyses. The FTIR analysis of the recovered catalyst was quite similar to that of the fresh one (Figure 14), indicating that the catalyst retained its structure after repeated recovery and reuse, remaining intact, thus demonstrating its stability. In addition, the TEM image of the recovered catalyst also shows the homogeneous and spherical morphology of the

nanoparticles as the fresh one. More importantly, no significant agglomeration was seen in the images, reflecting the high dispersibility of the nanoparticles.

Table 5 shows the comparison of our uniqueness water dispersible bimetallic catalyst with other literature for C-C and C-N coupling reactions. Fe₃O₄@PEG/Cu-Co as a magnetic, recoverable, cheap, and available bimetallic system can handle Suzuki, Sonogashira, and C-N coupling in the water medium without any external base under mild conditions.

Conclusion

In summary, we described an environmentally, economically, and magnetically recyclable bimetallic nanocatalyst with an imidazolium moiety bearing polyethylene glycol chains on Fe_3O_4 nanoparticle for the base/Pd-free C-C and C-N cross-coupling reactions in aqueous medium. The presence of PEG chains

^h C-N coupling reaction 1-iodo-4-nitrobenzene and morpholine

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causes the nanoparticles to be water-dispersible and subsequently to increase the efficiency for the coupling reactions in water. Fe₃O₄@PEG/Cu-Co catalyst was characterized using different techniques such as FT-IR, TEM, FE-SEM, VSM, UV-Vis, EDX, ICP, CV, and XPS analyses. All the mentioned analyses emphasized the proposed structure, spherical morphology, being nano-scale, magnetic nature, oxidation states, expected elements, and metals loading. Imidazolium moiety, PEG chains, and bimetallic features of the catalyst cause high catalytic performance due to the reduction of metal leaching, facile separation, removal need to any base and toxic solvent, which proved by various control experiments. Moreover, data of Hg-poisoning and hot filtration experiments demonstrated that the catalyst acts heterogeneously in the reactions and didn't occur any significant metal leaching to the mixture. Designed Cu-Co catalyst via transferring an electron from Co(II) to Cu(II) aimed formation of active copper species Cu(I), which the copper center is proposed to conduct the reaction via an oxidative-addition/ reductive-elimination route. Furthermore, the result of the hydroquinone test was in agreement with the proposed mechanism. Studies over the recycled nanocatalyst after 7^{th} run such as FT-IR and TEM revealed the stability of the catalyst and confirmed the proposed structure, morphology, and size distribution as same as the fresh one.

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Immobilization of a bi-ligand framework including polyethylene glycol as well as salen ligand containing imidazolium ionic moieties on the magnetic γ -Fe₂O₃ NPs afforded a novel and efficient bi-metallic catalytic system based on Cu/ Co that used as an efficient, eco-friendly, and recyclable catalyst for base-, Pd-free Sonogashira, Suzuki and C-N cross-coupling reaction in mild reaction conditions with an obvious synergistic effect.

