

FULL PAPER



Functionalization of superparamagnetic $Fe_3O_4@SiO_2$ nanoparticles with a Cu(II) binuclear Schiff base complex as an efficient and reusable nanomagnetic catalyst for *N*-arylation of α -amino acids and nitrogen-containing heterocycles with aryl halides

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Shiraz University; Iran National Science Foundation; Research Council of Shiraz University Fe₃O₄@SiO₂ nanoparticles was functionalized with a binuclear Schiff base Cu(II)-complex (Fe₃O₄@SiO₂/Schiff base-Cu(II) NPs) and used as an effective magnetic hetereogeneous nanocatalyst for the N-arylation of α -amino acids and nitrogen-containig heterocycles. The catalyst, Fe₃O₄@SiO₂/Schiff base-Cu (II) NPs, was characterized by Fourier transform infrared (FTIR) and ultraviolet-visible (UV-vis) analyses step by step. Size, morphology, and size distribution of the nanocatalyst were studied by transmission electron microscopy (TEM), scanning electron microscopy (SEM), and dynamic light scatterings (DLS) analyses, respectively. The structure of Fe₃O₄ nanoparticles was checked by X-ray diffraction (XRD) technique. Furthermore, the magnetic properties of the nanocatalyst were investigated by vibrating sample magnetometer (VSM) analysis. Loading content as well as leaching amounts of copper supported by the catalyst was measured by inductive coupled plasma (ICP) analysis. Also, thermal studies of the nanocatalyst was studied by thermal gravimetric analysis (TGA) instrument. X-ray photoelectron spectroscopy (XPS) analysis of the catalyst revealed that the copper sites are in +2 oxidation state. The Fe₃O₄@SiO₂/Schiff base-Cu(II) complex was found to be an effective catalyst for C-N cross-coupling reactions, which high to excellent yields were achieved for α -amino acids as well as *N*-hetereocyclic compounds. Easy recoverability of the catalyst by an external magnet, reusability up to eight runs without significant loss of activity, and its well stability during the reaction are among the other highlights of this catalyst.

K E Y W O R D S

magnetic heterogeneous catalyst, N-arylation, nitrogen-containing heterocycles, Schiff base copper(II) complex, α -amino acids

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1 | INTRODUCTION

In the last decades, copper complexes (Cu(0), (I), or (II)) along with various ligands have been used for the C-N cross-coupling reactions (known as amination or N-arylation) of aryl halides with different type of amines,^[1-6] because of the lower cost of copper salts and its application in the cross-coupling reactions as similar as Pd.^[7,8] The first copper catalyzed C-N bond formation was developed by Ullman and Goldberg.^[9,10] Various types of N-arylation have been reported in the literature that some examples come as follows: N-arylation of imidazoles.^[11-16] Cu(I)-catalyzed N-arylation of indoles.^[17] C–N coupling of aniline with terminal alkynes (synthesis of α -ketoamides).^[18] copper-mediated C–N coupling reaction of azido compounds and aryl halides,^[19] N-arylation of aryl halides with alkyl amine using CuBr catalyst which benefits from phosphoramidite as a ligand,^[20] Cu(I)-catalyzed N-arylation of pyrazoles,^[21] N-arylation of aryl iodide with hypervalent aryl siloxanes by Cu (OAc)₂ along with a ligand,^[22] N-arylation of α -amino acids catalyzed by Cu(I).^[23–25] cross-coupling reaction of arvl halides to aryl amines catalyzed by Cu₂O in solution of ammonia,^[26] N-alkynylation of amides catalyzed by Cu(I),^[27] Cu(I)-amidation catalyzed of aryl halides,^[28-30] Ullmann-type N-arylation of anilines,^[31] Cu-catalyzed intramolecular adjacent C-N coupling (asymmetric synthesis of atropisomeric compounds),^[32] Cu/N,N'dibenzyloxalamide-catalyzed N-arylation of heteroanilines.^[33] Cu-catalyzed N-arylation of sulfoximines.^[34] Cu-catalyzed decarboxylative N-arylation of indole-2-carboxylic acids,^[35] and Cu-catalyzed intramolecular benzylic C–H amination for the synthesis of isoindolinones.^[36]

Magnetic nanoparticles (MNs) are a class of nanoparticles which include magnetic elements (commonly Fe, Ni, or Co or their combinations),^[37,38] but they suffer from agglomeration phenomena due to large interaction between nanoparticles arising from their nano-size and high aspect ratio. So, to overcome this impediment, they are coated with silica shell, which minimizes the mentioned interactions and makes them stabilize.^[39-41] Also, this strategy provides an excellent opportunity for functionalization of the surface of silica shell and consequently immobilization of variety of organic compounds, transition metal complexes, and homogeneous catalysts on their surface.^[42,43]

In recent years, magnetic iron oxide core-shell nanocomposites prepared from Fe₃O₄ and silica shell have been highly regarded due to their widespread applications in various fields^[44] such as biomedicine^[45-58] and environmental remediation data storage,^[49] which all of these applications were not only thank to unique magnetic properties, biocompatibility and easy manipulation of

Fe₃O₄ NPs, but also they possess the both advantages of Fe₃O₄ nanoparticle core (High aspect ratio, unique catalytic, magnetic and electrical properties) and ability to preparation of shells with different structures.^[50] The Fe_3O_4 NPs, whether alone^[51] or supported,^[52] have catalytic activity in order to coupling reactions. Tang et al.^[53] supported ionic liquids on the magnetic Fe₃O₄@SiO₂ as an efficient catalyst of the C-N cross-coupling reactions along with using CuCl. Also, supporting of EDTA-Cu(II) complex on Fe₃O₄ nanoparticles was used for the *N*-arvlation of amines.^[54] *N*-arylation of chiral α -amino acids is one of the useful and applicable C-N coupling reactions which leads to core structures for a number of biologically important molecules.^[55] Cu(I)-catalyzed was a general method for the *N*-arvlation of α -amino acids with various aryl halides previously reported by Ma et al.^[55] Also, the N-arylation of α -amino acids has been reported by the assistance of microwave irradiation.^[56] Previously. Sharma et al.^[25] used Cu(I) as a catalyst and β -diketonetype ligand 2-isobutyrylcyclohexanone for coupling reactions of amino acids, amino acid esters, and peptides with aryl iodides. Han et al.^[57] reported the synthesis of PI3K inhibitor GDC-0077 via a stereocontrolled N-arylation of α -amino acids by Cu₂O. Very recently, we have developed two polyvinyl alcohol (PVA)-based resins for the Cucatalyzed N-arylation of α -amino acids using solid-phase organic synthesis (SPOS) approach.^[58] The most reported methods for the C–N coupling reactions endure from high reaction times and temperatures, which also needs stability of catalyst. Moreover, reusability of a heterogeneous catalyst is one of the significant issues in coupling reactions that was a serious problem in previously reported methods. So finding an efficient method for C-N crosscoupling reaction which covers the above-mentioned impediments is in demand. Therefore, herein, we report synthesis and full characterization of a reusable binuclear bis-salophen Cu(II) complex-functionalized superparamagnetic Fe₃O₄@SiO₂ nanoparticles which would be susceptible for efficient catalysis of N-arylation reactions and can be easily removed from the reaction media by an external magnet. Also, N-arylation of α -amino acid, which can generate new valuable α -amino acid derivatives was examined in the present study. Moreover, the yield of the products was comparable to the previously reported homogeneous systems.^[23,56-61]

2 EXPERIMENTAL

2.1 | Chemicals and instrumentation

All chemicals were purchased as the reagent grade from commercial suppliers and used without further

purification. Analytical thin-layer chromatography (TLC) was performed on glass plates precoated with silica gel impregnated with a fluorescent indicator, and the plates were visualized by an exposure to ultraviolet light. NMR spectra for characterization of coupling products were recorded on a Bruker Avance DPX-250 spectrometer operating for ¹H at 250 MHz and for ¹³C at 62.9 MHz in CDCl₃. Fourier transform infrared (FTIR) spectra were run on a Shimadzu FTIR 8300 spectrometer using a KBr pellet method. GC analyses were done using a Shimadzu-14B gas chromatography equipped with HP-1 capillary column and N2 as carrier gas. Anisole was used as an internal standard. The X-ray diffraction (XRD) analysis of the powder samples was performed on a Bruker AXS D8-advance X-ray diffractometer using CuKa radiation. Transmission electron microscopy (TEM) was taken on a Philips EM208 microscope and was run at 100 kV. X-ray photoelectron spectroscopy (XPS) analysis of the nanomagnetic catalyst was performed on a XR3E2 (VG Microtech) twin anode X-ray source with AlK α = 1486.6 eV. Field emission scanning electron microscopy (FE-SEM) images were performed on a Philips XL-30ESEM. Dynamic light scatterings (DLS) were recorded on a HORIBA-LB550. Ultraviolet-visible (UV-vis) spectra were obtained on a PerkinElmer Lambda 25 UV-vis spectrometer. The elements in samples were determined by energy-dispersive X-ray (EDX) spectroscopy accessory to the Philips scanning electron microscopy (SEM). The thermal gravimetric analysis (TGA) data were obtained by a PerkinElmer device manufactured by Thermal Sciences. Vibrating sample magnetometer (VSM) measurements were performed using a BHV-55 VSM. The elemental analyses (C, H, and N) for the coupling products were obtained from a Thermo Finnigan Flash EA-1112 CHNSO rapid elemental analyzer. The loading amount of Cu was determined by inductively coupled plasma (ICP, Varian, Vista-pro). Melting points were measured in open capillaries using an Electrothermal 9100 apparatus. The products were identified by their melting points and ¹H NMR and ¹³C NMR spectra, which have been displayed in the Supporting Information, and comparison with the values were reported in literature.

2.2 | General procedure for synthesis of Fe₃O₄ nanoparticles

 Fe_3O_4 NPs were obtained by chemical coprecipitation method according to our previous research.^[59,60] Initially, 1.3 g FeCl₃.6H₂O (4.8 mmol), 0.9 g FeCl₂ (4.5 mmol), and PVA (15,000; 1.0 g) as a surfactant

were dissolved in 30-ml deionized water with mechanical stirring for 0.5 h in 80°C. Then, hexamethylenetetramine (HMTA; 1.0 M) was added dropwise with vigorous stirring to provide a black solid product when basicity of the mixture reaches pH = 10. The resultant mixture was heated on a water bath for 2 h at 60°C, and the obtained Fe₃O₄ nanoparticles were removed by an external magnet, washed with deionized water (2 × 10 ml), and dried under vacuum at 50°C for 10 h.

2.3 | Preparation of Fe₃O₄@SiO₂ NPs

In a general procedure, 0.5-g Fe₃O₄ powder was first dispersed in 5-ml deionized water. An absolute ethanol solution (50 ml) containing 5.0 ml of NaOH (10 wt%) was then added to the magnetite suspension with stirring at room temperature. Then, 0.2 ml of tetraethyl orthosilicate (TEOS) was slowly poured into the solution, and the mixture was stirred for 30 min. Finally, Fe₃O₄@SiO₂ nanospheres were magnetically removed, washed in turn with ethanol and deionized water three times, and dried at 80°C for 10 h.^[59,62]

2.4 | Preparation of Fe₃O₄@SiO₂-Cl

 $Fe_3O_4@SiO_2$ -Cl was prepared using a previously described procedure.^[63] $Fe_3O_4@SiO_2$ (1 g) was dispersed in 20 ml of ethanol through ultrasonication, followed by an addition of 3-chlorotriethoxypropylsilane (6 mmol), and the resultant mixture was stirred under reflux for 12 h. The silica-coated magnetic NPs grafted with 3-chlorotriethoxypropylsilane (Fe₃O₄@SiO₂-Cl) were separated from the reaction media using a magnet and washed several times with ethanol and deionized water to remove unreacted species and dried at $60^{\circ}C$.

2.5 | Synthesis of *p*-bis (3,4-diaminobenzophenimine) phenylenediamine (1)

PDBP was prepared according to the previously described procedure.^[64] *p*-PDBP (1 mmol, 0.11 g) was dissolved in ethanol (15 ml) at room temperature. Then 3,4-diaminobenzophenone (2 mmol, 0.43 g) was added, and the mixture was stirred for 4 h. The purple solid crude product was filtered and then recrystallized from methanol to give pure PDBP (0.46 g, yield: 92%, mp. 229°C–231°C).

2.6 | Synthesis of *p*-bis[(3,4-salicylicimino) benzophenimine] PDBP (Schiff base ligand, PSBP) (2)

PDBP (0.25 g,0.5 mmol) and salicylaldehyde (0.25 g, 2 mmol) were added to 15 ml of water as a solvent, and the mixture was stirred at room temperature for 8 h. The dark yellow solid product (**2**, PSBP) was filtered and purified by recrystallization from methanol (0.43 g, yield: 85%, mp. $195^{\circ}C-197^{\circ}C$).^[64]

2.7 | Preparation of Schiff base complex of Cu(II) 3

PSBP (0.15 g, 0.16 mmol) was solved in 10 ml of ethanol, then Cu $(OAc)_2$ (0.06 g, 0.32 mmol) was added gradually during 20 min and the mixture stirred at room temperature for 12 h. The resulting product was filtered and washed with ethanol and dried in vacuum to give the Schiff base complex of Cu(II) **3** as a green solid.

2.8 | Immobilization of Schiff base complex of Cu(II) on Fe₃O₄@SiO₂ NPs

The Fe₃O₄@SiO₂-Cl NPs **4** (1.5 g) produced from the previous step were ultrasonically dispersed in a solution containing K₂CO₃ (0.53 g, 4 mmol), catalytic amount of tetrabutylammonium bromide (TBAB, 0.02 g, 0.06 mmol), the Schiff base complex of Cu(II) **3** (1.0 mmol), and MeCN (15 ml). Then, the mixture was refluxed under constant stirring for 12 h. Finally, the Fe₃O₄@SiO₂/Schiff base-Cu(II) complex NPs **5** were separated with a magnet and washed with ethanol and water for three times to remove unreacted reagents and dried at 60°C overnight.

2.9 | General procedure for the *N*-arylation of nitrogen-containing heterocycles with aryl halides

In a 10-ml round-bottom flask, a mixture of aryl halide (1 mmol), nitrogen-containing heterocycles (1.2 mmol), Cs_2CO_3 (2 mmol), $Fe_3O_4@SiO_2/Schiff$ base-Cu(II) NPs (0.012 g, 0.6 mol%), and DMF (3 ml) was stirred under nitrogen atmosphere at 110°C, whereas the completion of reaction was monitored by TLC. The catalyst was removed from the reaction mixture by an external magnet. Then, the reaction mixture was diluted with 20 ml of water, and the product was extracted with 20-ml ethyl acetate three times. The organic phases were combined and dried over anhydrous Na₂SO₄ (5 g), then the solvent

was removed under reduced pressure to get the coupling product. The resulting crude product was purified by flash chromatography to give the desired products.

2.10 | General procedure for the *N*-arylation of α -amino acids with aryl halides

N-Arylation of α -amino acids catalyzed by Fe₃O₄@SiO₂/ Schiff base-Cu(II) (5) was taken place as follows: A mixture of α -amino acid (1 mmol), aryl halide (1 mmol), K₂CO₃ (2.0 mmol), and catalyst (0.015 g, 0.75 mol%) was dissolved in DMF (3 ml) in a 10-ml round-bottom flask. This mixture was stirred at 80°C. Termination of the reaction was detected by TLC. At the end of the reaction, the catalyst was separated from the reaction mixture by an external magnetic field. The residual solution was cooled to room temperature and diluted with water and ethyl acetate (1:1, 20 ml). Then, the mixture was acidified (pH = 2-3) by HCl (37%), and the two phases were separated. The aqueous layer was extracted with ethyl acetate $(3 \times 20 \text{ ml})$, and the combined organic layers was dried over Na₂SO₄ and then filtered. Ethyl acetate was evaporated with rotary evaporator, and the coupling product was isolated as a solid powder. Recrystallization in ethanol was utilized for further purification.

3 | **RESULTS AND DISCUSSION**

The nanocatalyst was initially produced through the complexation of Cu(II) with a bis-salophen ligand followed by immobilization on Fe₃O₄@SiO₂ nanoparticles (Schemes 1 and 2) and then characterized by various analytical methods.

FTIR spectra of the samples have been shown in Figure 1a-f. Stretching vibration related to Fe-O bond at Fe_3O_4 was found at 572 cm⁻¹. Moreover, two peaks at 3,407 and 1,622 cm^{-1} show the vibration of the adsorbed water on Fe₃O₄ nanoparticles framework.^[65] The presence of the three main peaks in the spectrum of Fe₃O₄@SiO₂ at regions of 575 (Fe-O stretching vibration), 1,090 (Si-O-Si asymmetric stretching), and 3,407 cm⁻¹ (-OH stretching vibration) confirm the successful coating of the Fe₃O₄ surface nanoparticles by SiO₂ shell (Figure 1b). Figure 1c shows the vibration of C-H (stretching), -CH₂- (bending), and C-Cl (stretching) at 2,955, 1,443, and 702 cm^{-1} , respectively for 4, which formed through the treatment of Fe₃O₄@SiO₂ with 3-chloromethoxypropylsilane. Stretching vibration of imine bond (C=N) at 1,651 cm⁻¹ is an evidence for the synthesis of PSBP (2) (Figure 1d). The chelation of



SCHEME 2 Preparation process of Schiff base complex of $Cu(\Pi)$ supported on superparamagnetic Fe₃O₄@SiO₂ nanoparticles (5)

copper to PSBP causes a red shift of imine bond vibration from 1,651 to 1,635 cm⁻¹ as shown in Figure 1e, which is an evidence for the complex formation of copper by the Schiff base ligand. The presence of peaks of Cu(II) binuclear Schiff base complex and Fe₃O₄@SiO₂ core-shell in FTIR spectrum of **5** confirms well immobilization of **3** on the surface of Fe₃O₄@SiO₂ nanoparticles (Figure 1f). Moreover, the evidence for ligands bridging between nanoparticles provide with comparing FTIR spectrum of the Cu-Schiff base complex **3** with Fe₃O₄@SiO₂ NPs. The elimination of C–Cl stretching vibrations at 702 cm⁻¹ in FTIR of **5** in addition to the presence of vibrations allocated to the bis-salophen copper complex (**3**) is enough evidence for immobilization of the copper complex (**5**) on Fe₃O₄@SiO₂ nanoparticles (Figure 1f). More importantly, advent of the new strong absorption at 1,126 cm⁻¹ that was assigned to C–O–C stretching bond (bridging bond) strongly confirms the formation of ether bond between the nanoparticles and the ligand. Given that there is no other place in the Cu-Schiff base complex to bridging to nanoparticles, therefore, the structure drawn for the catalyst in Scheme 2



FIGURE 1 FTIR spectra of (a) Fe₃O₄, (b) Fe₃O₄@SiO₂, (c) Fe₃O₄@SiO₂-Cl, (d) PSBP, (e) Cu(II) binuclear Schiff base complex, and (f) Fe₃O₄@SiO₂/Schiff base-Cu(II)

appears to be the most likely structure, and it is suggested that the connection between the ligand and the nanoparticles is carried out through oxygen groups.

The crystalline structures of Fe₃O₄, Fe₃O₄@SiO₂, and Fe₃O₄@SiO₂/Schiff base-Cu(II) NPs were studied by XRD measurement (Figure 2a). The characteristic peaks at $2\Theta = 30.1^{\circ}$, 35.4° , 43.1° , 53.4° , 57.0° , and 62.6° , which are marked respectively by their indices (220), (311), (400), (422), (511), and (440), have a good matching with Fe₃O₄ nanoparticles cubic spinel crystal structure (reference JCPDS card no. 19–629).^[66,67] These patterns are also observed for Fe₃O₄@SiO₂ and Fe₃O₄@SiO₂/Schiff

base-Cu(II) NPs, which confirm the successful functionalization of Fe₃O₄ NPs. It was found that the diffraction peaks of the functionalized MNs (Figure 2a(B,C)) decreased in intensity in comparison with those of bare magnetic particles, probably due to the amorphous silica and Schiff base complex coating. This result indicates that the core-shell nanoparticles have been successfully synthesized without damaging the crystal structure of Fe₃O₄ core during the silica coating and surface functionalization. Besides the peaks related to iron oxide, the XRD patterns of Fe₃O₄@SiO₂ and Fe₃O₄@SiO₂/Schiff base-Cu(II) NPs present a broad XRD peak at low diffraction angle ($2\theta = 5-25^{\circ}$), which is allocated to the amorphous state SiO₂ and Schiff base complex shells (Figure 2a(B,C)). For Fe₃O₄@SiO₂/Schiff base-Cu (II) nanoparticles, this broad peak is shifted to the lower angles because of the synergetic effect of amorphous silica and Cu(II) binuclear Schiff base complex.^[67,68] Moreover, using XRD analysis, the size of the nanoparticles was calculated using the Scherrer's equation: $D = K\lambda/\beta$ $\cos\theta$, where K is a constant (K = 0.9 for Cu–K α), D is the average diameter in A° , β is the broadening of the diffraction line measured at half of its maximum intensity in radians, λ is the wavelength of the X-rays, and θ is the Bragg diffraction angle. The sizes measured by this method were 11, 20, and 29 nm that correspond to Fe_3O_4 , base-Cu(II), Fe₃O₄@SiO₂, and Fe₃O₄@SiO₂/Schiff respectively.

The oxidation state of the copper species present in the catalyst was studied by 2p-high resolution (energy corrected) XPS analysis. As shown in Figure 2b, the two peaks appearing in 934.5 and 954.2 eV are related to the bonding energies $2p_{3/2}$ and $2p_{1/2}$, respectively. The peak positions appearing in the spectrum are in agreement with the oxidation state of Cu^{2+} .^[69,70] The absence of other peaks in this area also indicates that only Cu^{+2} species are present in the catalyst.

FE-SEM, TEM, and DLS analyses of the synthesized nanoparticles have been shown in Figure 3. The synthesized Fe₃O₄ nanoparticles have a well-size distribution; however, in some areas, bigger structures with nonspherical morphology are also could be seen (Figure 3a). The Fe₃O₄ particles have an average diameter of 10 nm (Figure 3d). The FE-SEM and TEM images of the Fe_3O_4 ($OSiO_2$ NPs are shown in Figure 3b,e. It is apparent that the synthesized Fe₃O₄@SiO₂ nanoparticles are well dispersed, are nearly spherical in shape (Figure 3b), and have an average diameter of 20 nm (Figure 3e). From the TEM results, the thickness of silica shell in sphericalmagnetite composites is inferred to be around 5 nm (Figure 3e). Figure 3c depicts typical FE-SEM image of the core-shell structured Fe₃O₄@SiO₂/Schiff base-Cu(II) nanoparticles with near-spherical morphology. More

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(a)



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FIGURE 2 (a) XRD patterns of (A) Fe₃O₄ and (B) Fe₃O₄@SiO₂ and Fe₃O₄@SiO₂/Schiff base-Cu(II) NPs. (b) High resolution (energy corrected) XPS spectrum of Fe3O4@SiO2/Schiff base-Cu(II) NPs

detailed information is obtained from the TEM image. After successive coating with the Schiff base complex, these composites still maintain their spherical shape with an average diameter of approximate 30 nm (Figure 3f). To investigate the size distribution of these nanoparticles, particle size histograms were prepared by DLS analysis (Figure 3g-i). This size distribution is centered at a value of 12, 20, and 33 nm for Fe₃O₄, Fe₃O₄@SiO₂, and Fe₃O₄@SiO₂/Schiff base-Cu(II) nanoparticles, respectively (Figure 3g-i). The results were completely in agreement with the results from FE-SEM and TEM images as well as XRD analysis.

The components of the composite particles were confirmed by EDX analysis given in Figure 4a,b. The EDX results of Fe₃O₄@SiO₂/Schiff base-Cu(II) demonstrated that Cu(II) binuclear Schiff base complex has been immobilized onto the Fe₃O₄@-SiO₂ NPs. The weight percentage of the elements was shown as an inset table in Figure 4a,b. The results showed that 3.3%wt copper was present in the catalyst. The absence of Cl element in the catalyst indicates the covalent bonding of the Cu(II) complex 3 to the substrate via its hydroxyl groups (completely in agreement with the FTIR spectrum), as illustrated in Scheme 2.

Electronic spectra for Cu (OAc)₂, Fe₃O₄@SiO₂, Schiff base-Cu(II) complex 3, and Fe₃O₄@SiO₂/Schiff base-Cu (II) complex 5 were scrolled at region of 250-750 nm, which are shown in Figure 4c. Fe₃O₄@SiO₂ nanoparticles

show only one peak around at 285 nm, which is masked after immobilization of Schiff base copper complex by $\pi \to \pi^*$ absorptions. UV-vis spectrum of Schiff base-Cu (II) shows that the copper valence state is +2 in the complex, in accordance with Cu (OAc)₂ adsorption at 307 nm and in agreement with the XPS results. Also, $n \rightarrow \pi^*$ transition for C=N bonds in the Schiff base complex appears at 360 nm. The electronic spectrum of the catalyst shows two characteristic peaks at 300 and 363 nm related to the transitions for benzene rings and imine bonds respectively. Also, in comparison with Cu (OAc)₂ UV-vis spectrum, it could be concluded that the valence of copper has not changed and remains +2 after immobilization on the Fe₃O₄@SiO₂ NPs.^[71]

Thermogravimetric analysis of Fe₃O₄@SiO₂/Schiff base-Cu(II) along with its precursors was performed, and their spectra were exhibited in Figure 5a. Fe₃O₄@SiO₂ shows good thermal stability, and only $\sim 12\%$ weight loss is occurred until 800°C. The same phenomenon is taken place in the thermal analysis of Fe₃O₄@SiO₂-Cl NPs. Small weight loss in the beginning of thermal analysis of Fe₃O₄@SiO₂-Cl (50-200°C) shows scape of humidity and solvent from the structure of core-shell. A weight loss at higher temperatures around 390°C supports the effective functionalization of Fe_3O_4 ($in SiO_2$ NPs with 3-chlorotrimethoxypropylsilane. Thermal behavior of Fe₃O₄@SiO₂/Schiff base-Cu(II) complex is occurred in one step corresponded to 37.8% weight loss that shows the decomposition of Schiff base



FIGURE 3 FE-SEM images of (a) Fe_3O_4 (b) Fe_3O_4 (c) Fe_3O_4 (

complex moiety as well as immobilized organic compounds on Fe₃O₄@SiO₂ in the temperature span 200–680°C. This main degradation strongly confirms the immobilization of Schiff base complex on the Fe₃O₄@SiO₂ core shell, which is not observed in the thermal behavior of Fe₃O₄@SiO₂ or Fe₃O₄@SiO₂-Cl NPs.

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The magnetic properties of Fe_3O_4 , Fe_3O_4 @SiO₂, and Fe_3O_4 @SiO₂/Schiff base-Cu(II) NPs were examined by VSM analysis at room temperature (Figure 5b). This figure shows almost zero coercivity and remanence, which proves the superparamagnetic properties of the synthesized MNs. Although these superparamagnetic

particles do not have permanent magnetic moments in the absence of an external field but can respond to an external magnetic field. The saturation magnetization for Fe₃O₄, Fe₃O₄@SiO₂, and Fe₃O₄@SiO₂/Schiff base-Cu (II) NPs was found to be 64.8, 40.3, and 29.1 emu/g, respectively. Although the saturation magnetization decreases after coating of the surface of the Fe₃O₄ core,^[72] the complete magnetic separation of Fe₃O₄@SiO₂/Schiff base-Cu(II) complex samples is achieved in 0.5 min by placing a magnet near the vessels containing the aqueous dispersion of the nanoparticles (Figure 4d).



FIGURE 4 EDX spectra of (a) Fe₃O₄@SiO₂ and (b) Fe₃O₄@SiO₂/Schiff base-Cu(II); (c) UV-vis spectra of Cu (OAc)₂, Fe₃O₄@SiO₂, Schiff base-Cu(II), and Fe₃O₄@SiO₂/Schiff base-Cu(II); (d) photo images of magnetic field-responsive of Fe₃O₄@SiO₂/Schiff base-Cu (II) nanoparticles before magnetic field and under magnetic field



FIGURE 5 (a) Thermogravimetric analysis of (A) Fe₃O₄@SiO₂, (B) Fe₃O₄@SiO₂-Cl, and (C) Fe₃O₄@SiO₂/Schiff base-Cu(II); (b) magnetization curves for (A) Fe₃O₄ and (B) Fe₃O₄@SiO₂ and Fe₃O₄@SiO₂/Schiff base-Cu(II) NPs

The amount of copper content of the Schiff base complex copper immobilized on the surface of $Fe_3O_4@SiO_2$ NPs was determined by ICP analysis. The obtained results revealed the presence of 0.52 mmol of copper per 1 g of $Fe_3O_4@SiO_2/Schiff$ base copper complex.

To show the merit of application of this magnetic nanocatalyst in organic synthesis, we planned to employ it as the catalyst in the N-arylation of nitrogen-containing heterocycles and α -amino acids (Scheme 3). Therefore, in order to determine optimum conditions, the reaction of imidazole with iodobenzene was picked up as a model reaction, and the effect of the involved parameters such as solvent, catalyst amount, base, and temperature was investigated on the its efficiency. The obtained data are tabulated in Table 1. There is no progress for the model reaction in absence of the catalyst, which indicates vital role of the catalyst in this reaction (Table 1, entry 1). Also, bare Fe_3O_4 did not show any catalytic activity (Table 1, entry 2). Moreover, the efficiency of the reaction depends on the amount of the catalyst. So that 0.6 mol% of the catalyst is sufficient for completion of the model reaction and production of the desired product in 93% yield (Table 1, entry 6) and using higher and lower amounts than 0.6 mol% of the catalyst are led to reduction in the reaction efficiency (Table 1, entries 3-5 and 7). Among the used bases, Cs_2CO_3 shows the best performance for the coupling reaction. The other bases do not provide suitable vields except t-BuONa, which give the related product with 81% yield in DMF at 110°C after 12 h (Table 1, entry 17). The efficiency of the catalyst was also checked in various solvents, and according to the results, high efficiencies are observed in DMF and DMSO

with 93% and 90% yields, respectively (Table 1, entries 6 and 11), and water and ethanol provide the lowest yields (Table 1, entries 8 and 9). Another effective parameter is temperature which was explored (Table 1, entries 6 and 19–22). This study discloses the highest catalyst efficiency at 110°C (Table 1, entry 6) and raising the reaction temperature to higher than 110°C does not show any increasing in its efficiency (Table 1, entry 22). Moreover, the reaction does not show any progress at room temperature (Table 1, entry 19). Finally, on the basis of the data summarized in Table 1, it is clarified that the model reaction gives the highest yield of the desired product when 0.6 mol% catalyst is used along with Cs_2CO_3 (2 mmol) as a base in DMF (3 ml) at 110°C for 3.5 h (Table 1, entry 6).

The above-mentioned optimum conditions were served for a wide variety of N-arylation of nitrogencontaining heterocycles, and their data are registered in Table 2. As shown in Table 2, high to excellent yields were obtained for all substrates with different electronic type of substitution, electron-rich, or electron-deficient. The existence of electron withdrawing substitutions on aryl halides leads to higher efficiency than electron donating groups. The highest efficiencies were achieved in the coupling of 4-nitroiodobenzene with imidazole and 2-iodopyridine with indole with 95% and 94% yields respectively (Table 2, entries 3 and 6). Aryl bromides undergo the N-arylation reaction efficiently but in lower yield than iodide counterpart even after longer reaction time (Table 2, entries 13-20). Piperazine as an aliphatic amino substrate carries out the reaction and results in high yield of 1,4-diphenylpipirazine when it reacts with



Entry	Catalyst amount (mol%)	Base	Solvent	Temp (°C)	Time (h)	Yield (%) ^b
1	None	Cs ₂ CO ₃	DMF	140	12	0
2	Bare Fe ₃ O ₄	Cs ₂ CO ₃	DMF	110	3.5	Trace
3	0.2	Cs ₂ CO ₃	DMF	110	12	41
4	0.3	Cs ₂ CO ₃	DMF	110	8	53
5	0.4	Cs ₂ CO ₃	DMF	110	5	75
6	0.6	Cs ₂ CO ₃	DMF	110	3.5	93
7	0.7	Cs_2CO_3	DMF	110	3.5	89
8	0.6	Cs ₂ CO ₃	H ₂ O	Reflux	12	7
9	0.6	Cs_2CO_3	EtOH	Reflux	10	17
10	0.6	Cs ₂ CO ₃	CH ₃ CN	Reflux	10	46
11	0.6	Cs ₂ CO ₃	DMSO	110	4	90
12	0.6	Cs ₂ CO ₃	Toluene	110	12	78
13	0.6	NaOH	DMF	110	12	54
14	0.6	Et ₃ N	DMF	110	12	21
15	0.6	NaOAc	DMF	110	12	28
16	0.6	K ₂ CO ₃	DMF	110	12	73
17	0.6	t-BuONa	DMF	110	12	81
18	0.6	K ₃ PO ₄	DMF	110	12	63
19	0.6	Cs ₂ CO ₃	DMF	r.t	12	Trace
20	0.6	Cs ₂ CO ₃	DMF	80	12	51
21	0.6	Cs ₂ CO ₃	DMF	100	5	87
22	0.6	Cs_2CO_3	DMF	120	4	92

TABLE 1 Influence of the reaction parameters in the catalyzed N-arylation of imidazole by Fe₃O₄@SiO₂/Schiff base-Cu(II) NPs

^aReaction conditions: Iodobenzene (1 mmol), imidazole (1.2 mmol), base (2 mmol), Fe₃O₄@SiO₂/Schiff base-Cu(II) catalyst, and solvent (3 ml).

^bIsolated yield.

two equivalent of iodobenzene (Table 2, entry 11). Also, *N*-phenylpiperazin gives 1-phenyl-4-(pyridine-2-yl) piperazine in excellent yield (Table 2, entry 20).

Due to the ability of Fe₃O₄@SiO₂/Schiff base-Cu(II) complex as an efficient catalyst in arylation of amines and nitrogen-containing heterocycles, it was decided to apply this catalyst for N-arylation of α -amino acids (Scheme 3). First of all, the reaction of L-leucine with iodobenzene was chosen as a model reaction for optimization of effective parameters in N-arylation of α-amino acids. The effect of solvent, temperature, and catalyst amount was examined, which the corresponding collected data have been presented in Table 3. These results show that all of the parameters are effective on the efficiency of the reaction. Among the solvents employed, DMSO and DMF show the highest performance with 90% and 95% yields, respectively (Table 3, entries 4 and 10). The reaction in protic solvents such as H₂O and EtOH does not happen (Table 3, entries 5 and 6). The reaction was also temperature dependence and yields 27% and 95% of the desired product at ambient temperature and 80°C, respectively (Table 3, entries 7 and 10). No more efficiency is achieved at higher temperature than 80°C (Table 3, entry 11). The experiments show 0.75 mol% of the catalyst is sufficient in order to get the highest efficiency (Table 3, entry 10). Using higher amount of the catalyst does not create impressive change in efficiency of the reaction (Table 3, entry 12). To evaluate the base effect, the model reaction was also tested toward the N-arylation reaction in the presence of various kinds of bases and 0.75 mol% catalyst in DMF at 80°C (Table 3, entries 10, 13-18). The results indicated using the bases such as K₃PO₄, NaOAc, Et₃N, and NaOH result in low to moderate yield of the N-arylated product (Table 3, entries 14-17) and although the reaction shows good reactivity in the presence of t-BuONa (Table 3, entry 13) but excellent results are obtained when K₂CO₃ and Cs₂CO₃ are applied (Table 3, entries 10 and 18). Due to accessibility and lower price of K₂CO₃ relative to Cs₂CO₃, we choose K₂CO₃ for the rest of study. The control experiments, that 12 of 20 WILEY Applied Organometallic.

TABLE 2	Catalyzed N-arylation of nitrogen-containing heterocycles by Fe ₃ O ₄ @SiO ₂ /Schiff base-Cu(II) NPs ^a
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Entry	Aryl halide	N(H)-heterocycle	Product	Time (h)	Yield (%) ^c
1	C ₆ H ₅ I	Imidazole		3.5	93
2	4-Me–C ₆ H ₄ I	Imidazole	Me	7	89
3	4-NO ₂ -C ₆ H ₄ I	Imidazole	O ₂ N	3	95
4	C ₆ H ₅ I	Indole		5	94
5	4-Me-C ₆ H ₄ I	Indole	Me	5.5	90
6	2-Iodopyridine	Indole		4	94
7	C ₆ H ₅ I	2-Me-Indole	Me	6	83
8	C ₆ H ₅ I	Benzimidazole		4	92
9	4-MeO-C ₆ H ₄ I	Benzimidazole	MeO	6	86

(Continues)

TABLE 2 (Continued)

Entry	Aryl halide	N(H)-heterocycle	Product	Time (h)	Yield (%) ^c
10	C ₆ H ₅ I	Pyrrole		4	91
11 ^b	C ₆ H ₅ I	Piperazine		6	84
12	C ₆ H ₅ I	1-Phenylpiperazine		5	87
13	C ₆ H ₅ Br	Imidazole		9	89
14	4-Me–C ₆ H ₄ Br	Imidazole	Me	10	7
15	4-NO ₂ -C ₆ H ₄ Br	Imidazole	O ₂ N-NN	5	92
16	2-Bromopyridine	Imidazole		6	93
17	C ₆ H ₅ Br	Indole		10	86
18	2-Bromopyridine	Indole		7	93
19	2-Bromopyridine	Benzimidazole		7	86

(Continues)

TABLE 2 (Continued)

Entry	Aryl halide	N(H)-heterocycle	Product	Time (h)	Yield (%) ^c
20	2-Bromopyridine	Phenylpiperazine		6	91

^aReaction conditions: Aryl halide (1 mmol), amine (1.2 mmol), Cs₂CO₃ (2 mmol), Fe₃O₄@SiO₂/Schiff base-Cu(II) catalyst (0.6 mol%), DMF (3 mL), 110°C.

^bReaction conditions: Aryl halide (2 mmol), amine (1.2 mmol), Cs₂CO₃ (4 mmol), Fe₃O₄@SiO₂/Schiff base-Cu(II) catalyst (1 mol%), DMF (5 mL), 110°C.

°Isolated yield.

is, the model reaction in the absence of the catalyst or in the presence of bare Fe_3O_4 (Table 3, entries 24 and 25), did not proceed at all, which reveals the vital role of the catalyst in the reaction. The premium amount for DMF as a solvent was found to be 3.0 ml (Table 3, entries 19–23).

When these optimized conditions (i.e., aryl halide [1 mmol], α -amino acid [1 mmol], K₂CO₃ [2.0 mmol],

TABLE 3 Summary of optimization results in N-arylation of L-leucine^a

Entry	Catalyst amount (mol% Cu)	Base	Solvent	Temp (°C)	Time (h)	Yield (%) ^b
1	0.75	K ₂ CO ₃	THF	80	8	75
2	0.75	K ₂ CO ₃	Toluene	80	8	55
3	0.75	K ₂ CO ₃	CH ₃ CN	80	5	88
4	0.75	K_2CO_3	DMSO	80	5	90
5	0.75	K_2CO_3	H ₂ O	80	8	N. R.
6	0.75	K_2CO_3	EtOH	80	8	10
7	0.75	K_2CO_3	DMF	RT	5	27
8	0.75	K_2CO_3	DMF	50	5	55
9	0.5	K_2CO_3	DMF	80	3	77
10	0.75	K_2CO_3	DMF	80	2	95
11	0.75	K_2CO_3	DMF	90	2	93
12	0.90	K_2CO_3	DMF	80	2	92
13	0.75	t-BuONa	DMF	80	8	88
14	0.75	K ₃ PO ₄	DMF	80	8	68
15	0.75	NaOAc	DMF	80	8	35
16	0.75	Et ₃ N	DMF	80	8	22
17	0.75	NaOH	DMF	80	8	18
18	0.75	Cs_2CO_3	DMF	80	2	94
19	0.75	K ₂ CO ₃	DMF (1.0 ml)	80	2	90
20	0.75	K_2CO_3	DMF (2.0 ml)	80	2	92
21	0.75	K ₂ CO ₃	DMF (3.0 ml)	80	2	95
22	0.75	K ₂ CO ₃	DMF (4.0 ml)	80	2	95
23	0.75	K ₂ CO ₃	DMF (6.0 ml)	80	2	92
24	-	K ₂ CO ₃	DMF	80	2	Trace
25	Bare Fe ₃ O ₄	K ₂ CO ₃	DMF	80	2	Trace

^aReaction conditions: Iodobenzene (1 mmol), L-leucine (1 mmol), base (2.0 mmol), $Fe_3O_4@SiO_2/Schiff base-Cu(II)$, solvent (except entries 20–24, 3 ml), temperature.

^bIsolated yield.

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TABLE 4Catalyzed N-arylation of α -amino acids with various aryl halidesby Fe₃O₄@SiO₂/Schiff base-Cu(II) NPs^a

	X + R + R OH <u>C</u>	atalyst (0.7 K ₂ CO ₃ , E	75 mol% Cu) DMF, 80 °C)
	α-Amino acid	Aryl h	alide		
Entry	(R)	X	Y	Time (h)	Yield (%) ^b
1	L-leucine (-CH ₂ CH(CH ₃) ₂)	4-Cl	CH_3	14	78
2		4-Br	$\rm CO_2 H$	9	98
3		Ι	2-Br	8	88
4		Ι	Н	7	95
5		Cl	Н	14	67
6		Br	Н	12	87
7	L-cysteine (-CH ₂ SH)	4-Cl	CH_3	14	75
8		4-Br	$\rm CO_2 H$	8	98
9		Ι	2-Br	6	87
10		Ι	Н	6	96
11		Br	Н	10	80
12		Cl	Н	11	65
13		Br	Н	10	80

^aReaction conditions: Aryl halide (1 mmol), α -amino acid (1 mmol), K₂CO₃ (2.0 mmol), Fe₃O₄@SiO₂/Schiff base-Cu(II) (0.75 mol%), DMF (3 ml), 80°C. ^bIsolated yield.

Fe₃O₄@SiO₂/Schiff base-Cu(II) complex as catalyst [0.75 mol%], DMF [3 ml], and 80°C) were utilized toward *N*-arylation of α -amino acids with a variety of aryl halides, it is found that aryl halides with electron-releasing and electron-withdrawing substitutions undergo this reaction (Table 4). Lower efficiency was belonged to chlorobenzene toward both of the α -amino

acids of L-leucine and L-cysteine (Table 4, entries 5 and 11). Furthermore, iodobenzene shows higher efficiency than bromobenzene and chlorobenzene (Table 4, entries 4–6 and 10–12), which is in agreement with the C–N coupling reactions reported in literature.^[66] This finding will be felt better when 1-bromo-2-iodobenzene is applied in the reaction (Table 4, entries 3 and 9). Also, L-cysteine,



FIGURE 6 The results obtained from (a) recoverability and (b) leaching experiments of the catalyst for several runs. Reaction conditions: iodobenzene (1 mmol), L-leucine (1 mmol), K_2CO_3 (2.0 mmol), $Fe_3O_4@SiO_2/Schiff base-Cu(II)$ (0.75 mol%), DMF (5 ml), 80°C. Reaction conditions: iodobenzene (1 mmol), imidazole (1.2 mmol), Cs_2CO_3 (2 mmol), $Fe_3O_4@SiO_2/Schiff base-Cu(II)$ (0.6 mol%), DMF (3 ml), 110°C



FIGURE 7 (a) FTIR spectra of (A) the fresh and (B) recovered catalyst after eighth run. (b) FE-SEM, (c) VSM, and (d) TEM of the recovered catalyst after eighth run

which bears -SH in addition to -NH₂ functional group, undergoes the high selective N-arylation when it is treated with iodobenzenes and bromobenzenes (Table 4, entries 8-11).

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Recoverability and reusability of the catalyst, which aspects important in the two green are chemistry,^[40,41,73,74] were checked in N-arylation of nitrogen-containing heterocycles as well as a-amino acids. For this goal, the reaction of iodobenzene with imidazole and L-leucine was chosen respectively, as the model reactions. The nanocatalyst was successfully retrieved from two reaction mixtures by an external magnet and reused for six and eight runs in N-arylation of imidazole and L-leucine respectively, as shown in

Figure 6a, without any considerable change in reactivity. Copper leaching from the surface of catalyst was measured by ICP analyzer, which the related data can be seen in Figure 6b. These analyses showed that 4.68% and 4.10% copper leaching after six and eight runs in N-arylation of imidazole and L-leucine with iodobenzene, respectively. These findings were confirmed when the chemical structure, morphology, size, and magnetic behavior of the recovered catalyst, after eighth run the N-arylation of L-leucine, were examined by FTIR, VSM, FE-SEM, and TEM analyses (Figure 7). The FTIR spectrum of the recovered catalyst does not show any significant change in comparing to the fresh catalyst, which is an evidence for remaining of the chemical structure of





 $\label{eq:comparison} \textbf{TABLE 5} \quad \text{Comparison among efficiency of $Fe_3O_4@SiO_2/Schiff base-Cu(II)$ with the reported catalysts for preparation of 1-phenyl-1$ H-imidazole from iodobenzene with imidazole from iodobenze$

Entry	Catalyst	Conditions	Time (h)	Yield (%)	Reference
1	Cu ₂ O (10 mol%)	DMSO, KOH, 110°C	24	99	[79]
2	Metformin (10 mol %)/Cu(I) (5 mol %)	DMF, Cs ₂ CO ₃ , 110°C	10	98	[80]
3	Nano-CuO (2.5 mol%)	DMSO, KOH, 110°C	24	91	[81]
4 ^a	Cu (OAc) ₂ .H ₂ O (15 mol%)/8-HQ	DMF, K ₂ CO ₃ , 130°C, Ar Atm.	24	99	[82]
5	Cu(I)/MNP-3 (10 mol%)	DMF, Cs ₂ CO ₃ , 110°C	24	98	[83]
6	Cu-Y zeolite (10.8 mol%)	DMF, K ₂ CO ₃ , 120°C	24	99	[84]
7 ^b	Fe ₃ O ₄ @TiO ₂ /Cu ₂ O composite (0.01 g)	DMSO, KOH, 100°C	9	87	[85]
8	CuFe ₂ O ₄	K ₃ PO ₄ , PEG-400, 100°C	12	85	[86]
9 ^c	CoFe ₂ O ₄ @SiO ₂ -NH ₂ -Furfural-Cu (5 Wt%)	CH ₃ OH, R.T.	5	92	[5]
	Cu ₂ O (0.05 mol%)/Ligand ^c (20 mol%)	EtOH/H ₂ O, TBAB, NaOH, 120°C	12	78	[87]
	Fe ₃ O ₄ @SiO ₂ -PVA_Cu(II) catalyst (0.6 mol%)	DMF/t-BuONa/100°C	5	94	[59]
10	Fe ₃ O ₄ @SiO ₂ /Schiff base-Cu(II) (0.6 mol%)	DMF, Cs ₂ CO ₃ , 110°C	3.5	93	Present work

Abbreviation: HQ, hydroxylquinoline.

^aAryl halide is bromobenzene.

^bPhenylboronic acid is used instead aryl halide.

°1-(2-Me-hydrazine-1-carbonyl)-isoquinoline 2-oxide.

fresh catalyst during eight runs reaction (Figure 7a) and VSM analysis reveals its supermagnetization behavior with saturation magnetization of \sim 30 emu.g⁻¹ (Figure 7c). and

The FE-SEM and TEM images of the recovered catalyst appear the spherical shape nanoparticles with slightly bigger size in compare to the fresh catalyst (Figure 7b,d). In order to determine the responsible active copper species in catalyzing the coupling reaction and the extent of Cu leaching into the reaction mixture, we have utilized the hot filtration test.^[75] This test was performed over the model reaction, that is, iodobenzene (1 mmol), imidazole (1.2 mmol), Cs_2CO_3 (2 mmol), catalyst (0.6 mol%), and DMF (3 ml), 110°C. The heterogeneous nanomagnetic copper complex catalyst was removed magnetically from the reaction mixture after 40% conversion (GC analysis) and was allowed to the residual reaction mixture to be stirred at 110°C for 4 h. The GC analysis of the mixture showed only 3% raising in conversion. This result disclosed the heterogeneous nature of responsible catalyst and also negligible leaching of copper into the reaction mixture.

3.1.1 | Mechanism study

According to the mechanism described by Kong et al.,^[76] Kianmehr et al.,^[77] and Mostafalu et al.,^[54] for Cucatalyzed N-arylation of nitrogen-containing heterocycles, we proposed a plausible mechanism based on our observations that were in agreement with the literature (Scheme 4). The proposed mechanism involves a nucleophilic coordination between Cu^{II} in the catalyst I, and the amine group in α -amino acid in the first stage which is resulted in the reduction of Cu^{II} to Cu^{II[78]]} metal carbonate (M₂CO₃, M=K, or Cs) as a base abstract hydrogen atom from the intermediate II to make III. Then electrophilic coordination through the amino group at α -amino acid forms the intermediate IV which undergoes the oxidative addition with any iodide to produce the Cu(III) species V. The reductive elimination on V is led to the desired N-arylated α -amino acid and regeneration of the catalyst (Cu^{II}L₂) through the oxidation of Cu^IL₂(VI) with air oxygen. As a support for proofing of the vital role of oxygen, the model reaction was run under an inert atmosphere (N2 or Ar) but no indication of the expected product production was observed after 4 h.

In order to demonstrate the superiority of the present method over previous ones, the present catalytic system was compared with some other catalysts in the literature for *N*-arylation of imidazole (Table 5). As shown in Table 5, $Fe_3O_4@SiO_2/Schiff$ base-Cu(II) as a magnetic nanocatalyst has some advantages such as excellent yield, short reaction time, and simple separation from the reaction mixture. The catalyst produced the desired product in much lower amount of copper. Also, the structure of the catalyst remained intact during eight consecutive runs, demonstrating its stability that leads to saving energy and money.

4 | CONCLUSIONS

Herein, we have introduced a novel approach to functionalization of superparamagnetic Fe₃O₄@SiO₂ coreshell nanoparticles with a binuclear Cu(II) Schiff base complex to synthesize a novel, efficient heterogeneous, and magnetic catalyst which is able to catalysis efficiently the N-arylation of aliphatic amines, nitrogencontaining heterocycles, and α -amino acids. The catalyst was thoroughly characterized with FTIR, XRD, FE-SEM, TEM, DLS, UV-vis, TGA, VSM, EDX, XPS, and ICP analyses. The special features of the present catalyst are (a) heterogeneity, (b) easy recoverability by an external magnet, (c) reusability, (d) stability against heating and moisture, (e) easy handling, and (f) production N-arylated products in high to excellent yields. Consequently, we have provided suitable opportunity for highly efficient, cost-effective, and relatively benign route for N-arylation of aliphatic amines, N-heterocycles, and α -amino acids.

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AUTHOR CONTRIBUTIONS

Ali sardarian: Conceptualization; funding acquisition; methodology; supervision. **Milad Kazemnejadi:** Data curation; formal analysis. **mohsen esmaeilpour:** Data curation; formal analysis.

DATA AVAILABILITY STATEMENT

The data that support findings of this study are available in the Supplementary Information.

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