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Ultrasound-Assisted Diversion of Nitrobenzene Derivatives to their Aniline

Equivalents through Heterogeneous Magnetic Ag/Fe₃O₄-IT Nanocomposite Catalyst

Reza Taheri-Ledari¹, Jamal Rahimi¹, Ali Maleki^{1,*} and Ahmed Esmail Shalan^{2,3,*}

¹ Catalysts and Organic Synthesis Research Laboratory, Department of Chemistry, Iran University of Science and Technology (IUST), Tehran 16846-13114, Iran.

² Central Metallurgical Research and Development Institute (CMRDI), P.O. Box 87, Helwan, Cairo 11421, Egypt.

³ BCMaterials, Basque Center for Materials, Applications and Nanostructures, Martina Casiano, UPV/EHU Science Park, Barrio Sarriena s/n, Leioa 48940, Spain.

*Corresponding authors. (A. M) Tel.: +98 21 77240640-50; fax: +98 21 73021584. E-mail address: maleki@iust.ac.ir; (A. E. S.) E-mail: a.shalan133@gmail.com

Author's ORCIDs:
 Reza Taheri-Ledari: https://orcid.org/0000-0002-6511-9411
 Ali Maleki: https://orcid.org/0000-0001-5490-3350
 Ahmed Esmail Shalan: https://orcid.org/0000-0002-3424-1609

Abstract

A heterogeneous magnetic catalytic system is fabricated and suitably applied for execution of the fast and direct conversion of nitrobenzene (NB) derivatives to their aniline forms. For this purpose, different conditions and methods have been indeed checked with existence of numerous catalytic amounts of the nanocatalyst composite, which is constructed of iron oxide and silver nanoparticles, and isothiazolone organic structure. Herein, the mechanistic aspect of the catalytic function of this highly efficient nanocatalyst is highlighted and more discussed. Firstly, a convenient preparation route assisted by ultrasonication is presented for this metal and metal oxide nanocomposite. Further, a fast and direct reduction strategy for NBs is investigated using ultrasound wave irradiation (50 KHz, 200 W L⁻¹). As two great advantages for this catalyst, high magnetic property and excellent reusability could also be mentioned. However, this report well reveals that really convenient conversion of NBs to anilines could be achieved with high yield during a rapid reaction time, in presence of mild reaction conditions.

Keywords: Heterogeneity; Magnetism; Nanocatalyst; Nitrobenzene degradation; Ultrasonication

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1. Introduction

Proportional to increase the application of the nanomaterials in different industries, attentions to heterogeneous catalytic arrangements in micro and nano scales have been increased.¹ In this respect, many catalytic structures have been considered for different aims.²⁻⁵ Various catalysts with different properties, specified for a particular application, have been fabricated.⁶⁻⁸ According to the most recent reports, it was mentioned that the capability of the heterogeneous catalytic systems in facilitating the chemical reactions would be enhanced through involving other effective agents like irradiations (different lights, ultrasound, and etc.).⁹⁻¹² For instance, we have recently investigated the synergistic catalytic influence between the heterogeneous nanoscale catalytic arrangements and the ultrasound waves, and clearly disclosed that the catalytic performance of the nanoparticles are greatly enhanced via this strategy.¹³⁻¹⁵ Moreover, Zhang et al. have fabricated carbon quantum dots and investigated its photocatalytic capability for water splitting.¹⁶ Also, Shi et al. have reported a synergistic catalytic effect between iron(III) ion and iron oxide nanoparticles as a heterogeneous catalyst for reduction of the nitro derivatives.¹⁷ However, the main question is to know: *how we can improve the catalytic action of the known individual catalysts and to what extent this catalytic performance could be enhanced*?

Reportedly, among all of the various species of the nanoscale heterogeneous catalysts, silver (Ag) and iron oxide nanoparticles (Fe₃O₄ NPs) have been extensively used for catalyzing the different types of the chemical reactions.¹⁸⁻²⁴ In addition, other distinguished features such as nontoxicity, convenient separation, surface functionalization capability, and well composition capability with other materials, led Fe₃O₄ NPs to be widely applied for various applications such as drug delivery and catalytic applications.^{25,26} Recently, we have reported a composition of Ag and Fe₃O₄ NPs, functionalized with isothiazolone (IT) organic compound, and used that for facilitating the peptide coupling reactions.²⁷ In fact, the activation of the carboxyl groups of amino acids was done without any need to the conventional peptide coupling reagents such as TBTU and HBTU. There, we referred that the Heck reaction approach was implemented for surface functionalization of the vinyl-coated Fe₃O₄ NPs, further, Ag NPs were composited with them.

Here, we try to produce IT-functionalized silver/iron oxide (Ag/Fe₃O₄-IT) NPs via a novel *in situ* process assisted by ultrasonication pathway. From physical aspect, wide surface area is provided by NPs due to their nano scales.²⁸ So, only a small amount of NPs would be enough to obtain the desirable result. From chemical aspect, execution of the reactions under mild conditions leads to obtain stable structures with lower decompositions. In this study, this is well revealed that this novel fabrication process yields in the NPs with excellent morphology and composition form, and high catalytic performance is achieved in follows. We intend to suitably apply the produced Ag/Fe₃O₄-IT nanocatalyst for fast and direct reduction of nitrobenzene (NB) derivatives, which are considered as hazardous agents for human health.²⁹ From industrial aspect, this is so important issue to introduce a convenient, fast, economic, and environmentally benign strategy for catalyzing the chemical reaction, through which hazardous agents are converted to their useful analogues.

2. Experimental

2.1. Materials and equipment

All the used reagents and solvents, and also the employed equipment in this project have been recorded in Table S1 (supporting information).

2.2. Procedural pathways

2.2.1. Sonochemical synthesis of Ag/Fe₃O₄-APS NPs

In a glass tube (the brand shown in Table S1), AgNO₃ (5.0 mmol, 0.85 g) was dissolved in DI water (5.0 mL) through ultrasonication pathway. All steps of the preparation route were carried out in an ultrasound bath (50 KHz, 200 W L⁻¹). Furthermore, the reaction environment was then basic using NH₃ aqueous solution (25%) and pH was controlled with pH meter paper to be around 12. Next, 5.0 mL of a mixture of hydrated iron chloride salts (Fe²⁺ and Fe³⁺) in DI water was prepared (1 M per Fe²⁺ and 2 M per Fe³⁺), and dropwise added into the tube during ultrasonication at 60 °C. After completion of the addition,

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ultrasonication was continued at the same conditions for 30 min. At that moment, a solution of APTES in EtOH (40% v/v, 4.0 mL) was added drop by drop during ultrasonication (at 60 °C), and after completion of the addition the produced Ag/Fe₃O₄-APS NPs were magnetically separated, washed with DI water and EtOH, and dried at 60 °C.

2.2.2. Sonochemical synthesis of IT-functionalized Ag/Fe₃O₄ nanocatalyst

In the same glass tube, Ag/Fe₃O₄-APS NPs (0.1 g) were isolated in DI water/EtOH (1:1, 5.0 mL) and K₂CO₃ (0.5 mmol, 0.069 g) 5-chloro-2-methyl-4-isothiazolin-3-one (2.0 mL, 1 M in EtOH) was added. Then, the mixture was ultrasonicated for 1 h, at 60 °C. Ultimately, the magnetic NPs were collected, washed for several times with EtOH and acetone, and dried at 60 °C.

2.2.3. General procedure for ultrasound-assisted reduction of NB derivatives, catalyzed by ITfunctionalized Ag/Fe_3O_4 nanocatalyst

Generally, in a glass tube, NB compound (1.0 mmol), N₂H₄.H₂O (5.0 mol%), and IT-functionalized Ag/Fe₃O₄ NPs (0.01 g) were well mixed in EtOH (3.0 mL), and ultrasonicated for 15 min at room temperature. After accomplishment of the desired reaction, the NPs were magnetically disconnected and 5.0 mL of DMF was added to the reaction mixture. Finally, desired aniline compound was decontaminated via flash-column chromatography. Additionally, the NMR spectra data of all of the synthesized aniline derivatives are founded in Figures S5-S12, in the supporting information (SI).

3. Results and discussion

3.1. Synthesis of IT-functionalized Ag/Fe₃O₄ nanocatalyst

Scheme 1 briefly presents a simple preparation route for Ag/Fe_3O_4 -IT NPs. As can be seen, in this method, an alkaline solution of silver nitrate was prepared and then a mixture of iron(II) and iron(III) in deionized (DI) water was dropwise added during ultrasonication process. For this purpose, a cleaner ultrasound bath

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with 50 KHz frequency and 200 W L⁻¹ has been used. Afterward, ultrasonication at 60 °C was continued and a solution of 3-aminopropyl triethoxysilane (APTES) was added and well mixed. Then, the magnetic NPs were collected, and well dispersed again via ultrasonication. Next, a solution of 5-chloro-2-methyl-4isothiazolin-3-one in ethanol was added. The presented preparation route is more discussed in mechanistic study section in more details.



Scheme 1. Preparation route of IT-functionalized Ag/Fe₃O₄ nanocatalyst.

3.2. Characterization of IT-functionalized Ag/Fe₃O₄ nanocatalyst

From microscopic images for the prepared materials, it is well revealed that spherical-shaped nanocomposite has been fabricated via the presented technique. As perceived in Figure 1, high uniformity for the NPs has been resulted with average size of about 48 nm diameter. In comparison with reflux method and Heck approach (reported in our previous article),²⁷ monodispersed spheres have been formed of Fe_3O_4

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and Ag NPs via this ultrasound-assisted method. From scanning-electron microscopy (SEM) image (Figure 1a), it is figured out that the particles are accumulated in the solid state that is most likely due to their high magnetic property. In contrast, in the suspension state, formed by ultrasonication, the uniform particles are well dispersed. This claim was well proven by transmission-electron microscopy (TEM) (Figure 1b, c). This new composition form of Ag and Fe₃O₄ NPs has shown excellent catalytic performance, magnetic behavior, and stability in recovering process. All of these featured features are further discussed with more details, in continue. However, to highlight the uniformity of the NPs (as a great feature), dynamic light scattering (DLS) analysis has also been investigated. For this purpose, an ultrasound probe was used for dispersion of the NPs. It is mentioned in the DLS spectrum (Figure 1b, inset) that a single peak with polydispersity index (PDI) of 0.62 was observed around 48 nm, which confirms the extracted information from the microscopic images. Besides, HRTEM of the produced Ag/Fe₃O₄-IT nanocomposite were illustrated in Figure 1d, e. the obtained results confirm the prepared materials are in fine and homogenous structure and the Ag domain can confirmed as founded in the inset of Figure 1d. Moreover, to gain more information related to the structure proposed in Scheme 1 of the produced Ag/Fe₃O₄-IT nanocomposite, the mapping measurements of the different elements including in the prepared nanocomposite was checked as founded in Figure 1f.

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Figure 1. (a) SEM image for Ag/Fe₃O₄-IT nanocomposite in solid state (powder), (b, c) TEM images of Ag/Fe₃O₄-IT nanocomposite (suspension and sampling on lam), and (inset) intensity-based DLS spectrum of the produced Ag/Fe₃O₄-IT nanocomposite, (d, e) HRTEM images of Ag/Fe₃O₄-IT nanocomposite, (f) The mapping of the different elements including in the produced Ag/Fe₃O₄-IT nanocomposite.

Moreover, to provide more evidences for the formation of the IT-functionalized Ag/Fe₃O₄ nanocatalyst, energy-dispersive X-ray (EDX), X-ray photoelectron spectroscopy (XPS), and Fourier-transform infrared (FT-IR) spectroscopic methods were employed (Figure 2). As shown in the EDX spectra (Figure 2a,b), all the necessary elements are exist in the final structures. Furthermore, this is observed that the peaks intensity related to carbon atom has been increased after functionalization process of IT. In addition, the appearance of the sulfur atom around 2.6 keV, proves successfully functionalization of the Ag/Fe₃O₄ NPs with IT organic compound (Figure 2b). To obtain more confirmation on the preparation process, XPS spectrum of the IT-functionalized Ag/Fe₃O₄ nanocatalyst was detected. As exhibited, the existence of all the essential

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elements was well confirmed (Figure 2c). Besides, the high-resolution XPS spectra of the different elements including Ag and Fe elements are founded in Figure 2d, e. the high-resolution XPS spectra detected to further valid the presence of constituent of Ag/Fe₃O₄-IT nanocomposite and help to analyze the valence state of the different elements. Figure 2d shows the XPS spectra of Ag 3d state at 373.13 and 368.13 eV, which can be fitted with two spin-orbit splitting doublets of Ag to $3d_{5/2}$ and $3d_{3/2}$, while Figure 2e shows the XPS spectra of Fe 2p state at 712.52 and 725.12 eV, which can be fitted with two spin-orbit splitting doublets of Fe to $2p_{3/2}$ and $2p_{1/2}$. The results are reliable with the reported values of both Ag and Fe₃O₄.^{30,} ³¹Finally, the FT-IR spectra was needed to investigate the functional groups of the products. As can be seen in Figure 2f, a sharp peak has been appeared in both spectra around 3450 cm⁻¹ that is related to Ag NPs.³² In spectrum (I), which belongs to Ag/Fe₃O₄-APS NPs, the existence of N-H, C-H (sp3), Si-O, SiO-H, and Fe-O bonds have been confirmed by the appeared peaks at 3350, 2920, 950, 870, and 590 cm⁻¹, respectively.³³ In spectrum (II), it is plainly seen that the peak intensity of the C–H (sp3) band has been increased. Most likely, this is because of the addition of a methyl group through functionalization with IT organic compound. Also, the peak related to the N-H band has been almost disappeared. It could be due to well attachment of the amine group to the IT. Obviously, there is a strong resonance between the amine group and the IT organic compound. That is maybe the reason beyond why the related peak to N-H band is almost disappeared. However, the main criterion of the IT-functionalization is a peak performed at ~ 1730 cm⁻¹ that approaching from C=O group of the loaded IT onto the surfaces. Furthermore, to reveal the crystal structure of the produced Ag/Fe₃O₄-IT nanocomposite catalyst, XRD measurements were noticed (Figure 3). The obtained patterns indicate the presence of Ag as well as F_3O_4 nanoparticles. The as-prepared Ag- Fe_3O_4 were approved using XRD data and composed of identical crystalline particles that corresponded to JCPDS cards of silver (#04–0783) and magnetite (#16–0629), respectively.^{34, 35} For Ag nanoparticles, different planes including (111), (200) and (220) that crossponding to XRD peaks at 20 of 38.18°, 44.25° and 64.72°, respectively were founded and indicated that the structure of Ag-NPs crystals is face-centered cubic,^{36, 37} while different diffraction peaks that crossponding to the planes including (220), (311), (400),

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(422) and (440) were detected for Fe₃O₄ with inverse spinel structure (JCPDS No. 19-0629, a = 8.396 Å).³⁸ Besides, new peak were founded at around 52°, which may refer to the IT crystalline network, which has been formed onto the surfaces. Besides, there are other new peaks too, which have not been referred due to their low intensity such as around 36°, 44°, 58°, and 62°. All of these new peaks can be attributed to the formed layer by the IT compound onto the nanoparticles surfaces.

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Figure 2. EDX spectra of (a) Ag/Fe₃O₄-APS, and (b) Ag/Fe₃O₄-IT nanocomposite, (c) XPS spectrum of the produced Ag/Fe₃O₄-IT nanocomposite, (d,e) high-resolution XPS spectrum of Ag and Fe elements, and (f) FT-IR spectra of Ag/Fe₃O₄-APS (I) and Ag/Fe₃O₄-IT nanocomposite (II).

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Figure 3. XRD patterns of Ag/Fe₃O₄-IT nanocomposite

3.4. Application of Ag/Fe₃O₄-IT nanocatalyst in direct reduction of NB derivatives

3.4.1. Optimization

Obviously, the first step for performing the catalytic process is to check and determine the optimal conditions. For this purpose, a model reaction was chosen and different conditions were applied for that purpose. Table 1 briefly reports the applied conditions including various catalytic amounts of Ag/Fe_3O_4 -IT nanocomposite, different frequencies of the ultrasound bath, temperature, and etc. that intended for the reduction process of nitrobenzene (NB). In this way, thin-layer chromatography was used for controlling the reaction progress, and melting point measurement, FT-IR and NMR spectroscopy were applied to detect the final aniline products. Applying several catalysis systems with different amount of Ag/Fe_3O_4 -IT nanocomposite catalysts at different ultrasound-assisted reduction reaction conditions were yield different quantities of NB derivatives. For instance, the lowest amount of yield for NB derivatives was obtained at temperature of 50° C and time of 15 min. Accordingly, the optimal parameters for the ultrasound-assisted reduction of the NBs was obtained when only 0.01 g of Ag/Fe₃O₄-IT nanocomposite was used, during 15

min of ultrasonication with 50 KHz frequency as well as 200 W L⁻¹ power density, at room temperature. As discussed in the introduction section, the efficiency of the nanoscale catalytic systems is substantially enhanced through applying various effective agents. Today, different irradiations are being used for this aim. For instance, gold NPs are converted to hot spots in the body's internal environment, through applying near-IR irradiation and surface plasmon resonance (SPR) effect for cancer therapy.³⁹ Here, the main driving force for catalyzing the reduction reactions of NB derivatives, is provided through irradiation of the ultrasound waves (with particular frequency besides the power density) to Ag NPs. In fact, it seems that the ultrasound waves enhance the surface resonance of the Ag NPs (due to electron excitation), and the prepared hot surfaces provide the required driving force for chemical reactions.^{40,41} On the other hand, the ultrasound irradiation causes NPs to be well dispersed and accordingly an extreme surface area is delivered in the suspension state. Moreover, it should be noted that the required driving force is only provided at the main and essential sites of chemical structure and other area remain unstimulated. In other words, the desired chemical reaction is generally carried out under mild conditions via this method (Figure 4).

According as our previous experiences^{42,43} and also the new experimented reaction (Table 1, entry 14), a catalytic saturation is occurred in a specified and known ratio. In this work, it has been observed that increasing the amount of the catalyst from 0.01 g to 0.03 g has no significant effect on the obtained yield (Table 1, entries 5 and 7). While, decreasing that to ~0.005 g has dramatically affected the reaction yield (entry 14). Accordingly, it can be supposed that a catalytic saturation is occurred around 0.01 g.

Table 1. Different reaction conditions optimized for ultrasound-assisted reduction of the NB derivatives, catalyzed

via Ag/Fe₃O₄-IT nanocomposite.

Entry	Cat. system	Cat. (g)	Conditions	Temp.	Time	Yield ^a
				(°C)	(min)	(%)
1	-	-	Stirring	25	15	Trace
2	-	-	Stirring	50	15	Trace
3	Ag/Fe ₃ O ₄ -IT	0.01	Stirring	50	15	55
4	-	-	Ultrasonication (F: 50, P: 200) ^b	25	15	31
5	Ag/Fe ₃ O ₄ -IT	0.01	Ultrasonication (F: 50, P: 200)	25	15	97*
6	Ag/Fe ₃ O ₄ -IT	0.01	Ultrasonication (F: 50, P: 200)	50	15	97
7	Ag/Fe ₃ O ₄ -IT	0.03	Ultrasonication (F: 50, P: 200)	25	15	97
8	Ag/Fe ₃ O ₄ -IT	0.01	Ultrasonication (F: 50, P: 200)	25	30	97
9	Ag/Fe ₃ O ₄ -IT	0.01	Ultrasonication (F: 50, P: 100)	25	15	94
10	Ag/Fe ₃ O ₄ -IT	0.01	Ultrasonication (F: 50, P: 150)	25	15	96
11	Ag NPs	0.01	Ultrasonication (F: 50, P: 200)	25	15	38
12	Fe ₃ O ₄ NPs	0.01	Ultrasonication (F: 50, P: 200)	25	15	36
13	Fe ₃ O ₄ -IT	0.01	Ultrasonication (F: 50, P: 200)	25	15	50
14	Ag/Fe ₃ O ₄ -IT	0.005	Ultrasonication (F: 50, P: 200)	25	15	69

^{*a*} Isolated yield for reduction reaction of nitrobenzene using 1.0 mmol of nitrobenzene, 5.0 mol% of N_2H_4 . H_2O , 3.0 mL of ethanol; ^{*b*} F: frequency, P: power density (ultrasonication was supported in an ultrasound cleaner bath); *optimal conditions.

New Journal of Chemistry Accepted Mar

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Figure 4. Schematic of the catalytic process of ultrasound-assisted conversion of the NB derivatives to their aniline analogues by metallic NPs.

3.4.2. Reduced NB derivatives

To monitor the catalytic activity of the presented IT-functionalized Ag/Fe₃O₄ nanocatalyst in the presence of the ultrasound waves, different derivatives of NB were used. All the reactions have been supported with the optimized parameters (Table 1). Furthermore, Table 2 presents the structure and reaction yields of the resulted aniline products. Different NB derivatives were obtained via the ultrasound-assisted reduction reaction, catalyzed by IT-functionalized Ag/Fe₃O₄ nanocatalyst. The obtained NB derivatives display isolated yield of 97, 96, 96, 97, 96, 94, 96, 95, 94 and 97% for Nitrobenzene, 1,4-Dinitrobenzene, 1,3-Dinitrobenzene, 3-

Nitrobenzaldehyde, 4-Nitrobenzoic acid, 4-Nitrophenol, 4-Nitrobenzaldehyde, 1-(4-Nitrophenyl)ethan-1-

one, 3,4-Dinitrobenzoic acid and 1-Chloro-4-nitrobenzene, respectively.

Table 2. Different nitrobenzene derivatives reduced to their aniline analogues via the ultrasound-assisted reductionreaction, catalyzed by IT-functionalized Ag/Fe $_3O_4$ nanocatalyst.

Entry	NB derivative	Yield ^a (%)	Melting point (°C)		Ref.
			Found	Reported	
1	Nitrobenzene	97	-	-	[44]
2	1,4-Dinitrobenzene	96	144	145	[45]
3	1,3-Dinitrobenzene	96	65	65	[46]
4	3-Nitrobenzaldehyde	97	31	30	[44]
5	4-Nitrobenzoic acid	96	188	187	[44]
6	4-Nitrophenol	94	187	186	[47]
7	4-Nitrobenzaldehyde	96	79	78	[47]
8	1-(4-Nitrophenyl)ethan-1-one	95	105	105	[44]
9	3,4-Dinitrobenzoic acid	94	209	208	[48]
10	1-Chloro-4-nitrobenzene	97	71	70	[45]

^a Isolated yield.

3.4.3. Recyclability

One of the most important properties of each heterogeneous catalytic system is related to its capability to be used for several times deprived of significant decay in the catalytic activity. Here, we have fabricated a magnetic system that is conveniently collected by using a magnet, then washed, dried, and reused again. Magnetic behavior of the produced IT-functionalized Ag/Fe_3O_4 nanocatalyst has been considered through vibrating-sample magnetometer (VSM) technique (Figure S1, in supporting information section). Accordingly, our catalytic system was magnetically separated from the reaction mixture (reduction reaction of nitrobenzene), and reused for additional 10 times. As can be seen in Figure 5, the catalytic activity of the fabricated IT-functionalized Ag/Fe_3O_4 nanocatalyst has been almost maintained after 10 times recycling.

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Moreover, the structure of the catalyst was checked after the recycling process by FT-IR, EDX, and SEM analyses (Figures S2-S4, in supporting information section). From these analyses, it was clearly disclosed that the structure of the IT-functionalized Ag/Fe_3O_4 nanocatalyst is stable under the reduction reaction conditions.



Figure 5. Recycling diagram of IT-functionalized Ag/Fe_3O_4 nanocatalyst applied in ultrasound-assisted reduction reaction of nitrobenzene.

3.5. Mechanistic study

To prepare the catalyst, from the mechanistic aspect, chlorine is in a suitable situation for leaving the structure of 5-chloro-2-methyl-4-isothiazolin-3-one after amine attack. For this purpose, basic conditions activates the amine group, present in the structure of aminopropyl silane (APS) for attack. The electronic

New Journal of Chemistry

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resonance in the structure of 5-chloro-2-methyl-4-isothiazolin-3-one provides an appropriate substrate (carbocation) to be attacked by activated amine group. Here, one of the advantages for enhancing this mechanism is Ag NPs that assist this electronic resonance through effective electronic interactions with oxygen atom of carbonyl (Scheme 2a). These electronic interactions are positively enhanced by ultrasound waves and heating the surfaces. In reduction process of the NB derivatives, again, Ag NPs create positive electronic interactions with oxygen atoms of NBs.⁴⁹ At this stage; ultrasonication provides well dispersed NPs with hot surfaces, created through the enhanced SPR. Another oxygen atom is grafted by sulfur atom present in the structure of the leaded IT onto the Fe₃O₄ NPs. Finally, reduction is occurred by hydrazine hydrate during some successive stages (Scheme 2b).

New Journal of Chemistry

Page 18 of 25

New Journal of Chemistry Accepted Manus

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Scheme 2. Plausible mechanism for: (a) functionalization of the Ag/Fe₃O₄ NPs with IT organic compound, and (b) reduction of the NB derivatives.

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4. Conclusions

In this report, we introduced an innovative process for expedient preparation of isothiazolone-functionalized silver/iron oxide nanocomposite assisted by ultrasound wave irradiation. Then, it has been shown that a fast and direct reduction of nitrobenzene derivatives is performed through synergistic effect between the fabricated heterogeneous organic-functionalized Ag/Fe₃O₄ nanocomposite and ultrasound waves. Here, we have easily converted the nitrobenzene derivatives to their aniline analogues with high yield (97%) in 15 min ultrasonication, under mild reaction conditions (25 °C). However, from microscopic images it was revealed that a special morphology has been obtained via the presented preparation method. In the microscopic images, it has been observed that highly uniform nanoparticles with spherical morphology, which are formed by silver and iron oxide nanoparticles, are obtained. Also, surface functionalization of the particles with isothiazolone organic compound has been investigated by various analytical methods. Moreover, a mechanistic study for the synthesis of the catalytic structure and the reduction process of the nitrobenzene derivatives has been suggested and discussed in the current paper. For all of the practical stages, an ultrasound cleaner bath with 50 KHz frequency and 200 W L⁻¹ power density has been used. Overall, the presented strategy for direct conversion of the nitrobenzene derivatives to their useful aniline analogues is strongly suggested for industrial applications due to its high convenience, great reusability of the catalytic system, low cost, excellent time saving and etc.

Abbreviations

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NB: Nitrobenzene NPs: Nanoparticles IT: Isothiazolone APS: Aminopropyl silane APTES: 3-aminopropyl triethoxysilane DI: Deionized DMF: Dimethyl formamide TBTU: N,N,N',N'-Tetramethyl-O-(benzotriazol-1-yl)uronium tetrafluoroborate HBTU: N,N,N',N'-Tetramethyl-O-(1H-benzotriazol-1-yl)uronium hexafluorophosphate

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Conflict of Interest

The authors affirm no conflict of interest.

Supporting Information

The SI section includes NMR spectra (and spectral data) of the produced aniline derivatives, VSM analysis of nanocatalyst, FT-IR, EDX, and SEM analyses of recovered nanocatalyst, and Table related to the applied materials and equipment.

Page 21 of 25

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New Journal of Chemistry

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Abstract (graphical)

