An asymmetric Salamo-based Zn complex supported on Fe$_3$O$_4$ MNPs: a novel heterogeneous nanocatalyst for the silyl protection and deprotection of alcohols under mild conditions

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In this study, a magnetic asymmetric Salamo-based Zn complex (H$_2$L$^\text{-salen}$) supported on the surface of modified Fe$_3$O$_4$ (Fe$_3$O$_4$@H$_2$L-Zn) as a new catalyst was designed and characterized via numerous analytical techniques such as FT-IR spectroscopy, XRD, EDS, ICP-AES, SEM, TEM, TGA and VSM. An efficient and sustainable synthetic protocol has been presented for the synthesis of silyl ether substructures via the silyl protection of alcohols under mild conditions. The synthetic protocol involves a two-component solvent-free reaction between various hydroxyl-bearing substrates and hexamethyldisilazane (HMDS) as an inexpensive silylating agent using Fe$_3$O$_4$@H$_2$L-Zn MNPs as a magnetically separable, recyclable and reusable heterogeneous catalyst. Fe$_3$O$_4$@H$_2$L-Zn MNPs were also applied for the removal of silyl protecting groups from hydroxyl functions using water in CH$_2$Cl$_2$ under green conditions. The catalyst demonstrated good to excellent catalytic yield efficiency for both the reactions compared to the commercial metal-based catalysts under green conditions for a wide range of substrates.

1. Introduction

In numerous preparation methods of delicate organic compounds, some specific parts of their molecules cannot survive the required reagents or chemical environments. Therefore, these parts, or groups, must be protected.$^{1-4}$ Regarding the number of protection and deprotection groups, it is highly significant to consider and reconsider the chemistry applied in unnatural structures and also in the building of nature’s architecturally beautiful and diverse molecular frameworks. Usually attached to the asymmetrically substituted carbon atom, the hydroxyl group can be regarded as the most fundamental functional group in organic chemistry.$^5$–$^{10}$ Therefore, it is evident that a wide variety of approaches have been disclosed and also the enantioselective synthesis of alcohols can be regarded as one of the most important steps in total synthesis.$^{11}$ Although there are important advances in the late-stage functionalization of complex molecules, the protection of hydroxyl groups is highly required during the succeeding steps.$^{12}$ In order to protect the alcohol group, there are several methods. In this sense, silylation can be regarded as one of the most common and easy methods in order to protect hydroxyl and thiol groups.$^{13}$ Silyl ethers are the most useful and important protecting groups for the protection of hydroxyl functional groups in organic chemistry from both synthetic and analytical point of views.$^{14}$

During the recent decades, numerous types of silyl ethers have been developed via the reaction of silyl halides with parent alcohols in the presence of a base, such as triethylamine, pyridine, and n-butyl lithium.$^{15}$–$^{17}$ To date, numerous procedures have been introduced for the silylation of alcohols using different silylation reagents in the presence of various catalysts including organo bases (e.g. N-oxides and N-halo reagents), iodine, trihalides, transition metals, Bronsted–Lowry acids as well as catalyst-free conditions.$^{5,18-20}$ These silylation methods are efficient, but unfortunately, they have serious disadvantages since they require a careful filtration or extraction process to remove the impurities derived from the reaction of by-product acids and co-bases during the silylation reaction.

Besides, R$_3$SiCl, MeSiN$_2$ = C(Me)OSiMe, Me$_2$SiCl, or Me$_2$SiOTf in the presence of base are the reagents applied in the traditional and conventional processes.$^{21-29}$ Moreover, hexamethyldisilazane (HMDS) is a stable, commercially available and inexpensive reagent that can be used for the protection of hydroxyl bearing compounds to trimethylsilyl ethers.$^{30-32}$ Its handling does not require special precautions, and the workup is not time-consuming because the by-product of the reaction is ammonia, which is easily removed from the reaction medium.$^{33,34}$
The use of nanostructured heterogeneous catalysts in organic transformations has recently been very exciting owing to their catalytic efficiency and selectivity. Furthermore, 2D materials have become an important platform to design numerous single-atom catalysts for diverse chemical reactions, such as N₂ reduction, CO₂ reduction, and CO oxidation. The ease of isolation and separation of the heterogeneous catalysts from the desired organic product and the recyclability and reusability further enhanced the sustainability of the catalysts. Moreover, the heterogeneous catalysts not only catalyze the reactions on their own, but also serve as an effective support for the immobilization of active catalysts and facilitate the efficient magnetic separation of the catalysts for their recovery and reusability. The functionalization and modification of iron oxide nanoparticles with numerous biocompatible and biodegradable materials in many different ways have been demonstrated with efficient and effective catalysts. Salen-based compounds can be considered as excellent candidates for the functionalization of iron oxide nanoparticles due to the presence of four coordination atoms (O, N, N, and O) in the center, which can coordinate with various metal ions to form M-Salen complexes. The structure of metal ion coordination with nitrogen and oxygen of salen complexes has attracted considerable attention in the field of catalytic methods in organic syntheses due to their important and interesting variable structures, simple synthesis route, high efficiency with high selectivity and easy recycling of the catalysts.

Zinc is an inexpensive and readily available metal (zinc is easily extracted from the minerals in high purity). Low toxicity, low cost, abundance and accessibility of zinc make it attractive for application in catalysis chemistry. In the present study, we are concerned with the high yield synthesis of silyl ether substructures via the silyl protection of alcohols and phenols, followed by their deprotection via removal of silyl protecting groups from the hydroxyl functions under mild conditions using an asymmetric Salamo-based-Zn catalytic complex-functionalized magnetically separable nanocomposite as a recyclable and reusable nanocatalyst.

2. Experimental
2.1. Materials
All the reagents and solvents were purchased from Merck and used without additional purification.

2.2. Preparation of asymmetric Salamo-based-Zn supported on the surface of Fe₃O₄ MNPs
Fe₃O₄@APTES MNPs were prepared according to a previously reported method. Then, its surface was functionalized by H₂L, which was prepared according to the procedure of Bian et al. For the synthesis of asymmetric Salamo-based ligand supported on Fe₃O₄ nanoparticles, 1 g of the as-prepared Fe₃O₄@APTES was dispersed in 50 ml of toluene via sonication for 45 min, and then H₂L (3 mmol) was added to the mixture. The reaction
mixture was stirred under nitrogen atmosphere at reflux conditions for 24 h. Then, the obtained Fe₃O₄@H₂L product was separated via magnetic decantation and washed with hot ethanol and acetone to remove the unreacted ligand and dried in an oven at 50 °C for 8 h. The obtained Fe₃O₄@H₂L (0.5 g) was dispersed in 25 ml of ethanol by sonication for 60 min and then zinc nitrate (3 mmol) was added to the reaction mixture. The reaction mixture was stirred under nitrogen atmosphere at 80 °C for 48 h. The final product (Fe₃O₄@H₂L-Zn) was separated via magnetic filtration and washed with ethanol to remove the unattached substrates. The Fe₃O₄@H₂L-Zn nanoparticulate product was dried in an oven at 60 °C for 8 h (Scheme 1).

2.3. General procedure for the trimethylsilylation of alcohols

A mixture of alcohols (1 mmol), HMDS (0.8 mmol) and Fe₃O₄@H₂L-Zn (6 mg) was stirred at room temperature under solvent-free conditions and the progress of the reaction was monitored by TLC. After the completion of the reaction, the catalyst was separated by an external magnet and the mixture was decanted. Then, the mixture was washed with EtOAc and water to destroy the extra amounts of HMDS and organic layer was dried over anhydrous Na₂SO₄. The evaporation of the solvent under a reduced pressure obtain the pure product without further purification.

2.4. General procedure for the deprotection of silyl ether derivatives

Fe₃O₄@H₂L-Zn (6 mg) was added to a mixture of TMS ethers (1 mmol) in CH₂Cl₂ (4 ml) moistened by three drops of water and then the mixture was stirred at room temperature for the specified time and the progress of the reaction was monitored via TLC. After the completion of the reaction, the catalyst was separated by an external magnet and the mixture was decanted. The solvent was evaporated under a reduced pressure to obtain corresponding alcohols.

3. Results and discussion

3.1. Synthesis and characterization of the catalyst

3.1.1. Design of catalyst. The magnetic nano catalyst was prepared based on Scheme 1. First, magnetic nanoparticles (Fe₃O₄) were synthesized according to the literature using FeCl₃·6H₂O and FeCl₂·4H₂O with the addition of NH₄OH. In order to prevent the agglomeration of the nanoparticles during the synthesis, the Fe₃O₄ MNPs were dispersed and then (3-aminopropyl)trimethoxysilane (APTES) was reacted with it until the amine functional group got attached to it. Next, an H₂L linker as the ligand was covalently bonded on the surface of Fe₃O₄@APTES groups by the intermolecular nucleophilic attack of the primary amine nucleophile to the haloalkane bond of H₂L. Finally, for the preparation of zinc-loaded materials, Fe₃O₄@H₂L-Zn particles were treated with Zn(NO₃)₂ as the Zn source (Scheme 1). The successful synthesis and physical and chemical properties of the as-prepared Fe₃O₄@H₂L-Zn was investigated via FT-IR spectroscopy, XRD, EDX, ICP-OES, SEM, TGA and VSM techniques.

3.1.2. Chemical composition of the catalyst. The FT-IR spectra of the Fe₃O₄ (a), Fe₃O₄@APTES (b), H₂L (c), Fe₃O₄@H₂L (d) and Fe₃O₄@H₂L-Zn complex (e) are shown in Fig. 1. The FT-IR patterns in figure (a) and (b) are completely consistent with the previous analyses of Fe₃O₄ MNPs and Fe₃O₄@APTES, respectively. In the FT-IR curves of H₂L and Fe₃O₄@H₂L (Fig. 1c and d), strong C=O stretching vibration band in the region of 1590–1615 cm⁻¹, C-O stretching vibration band around 1256 cm⁻¹ and C=N provide evidences for the successful immobilization of the H₂L ligand on the surface of the modified support. The shift on the C-O, C=N peaks in the Fe₃O₄@H₂L-Zn to more lower wavenumbers in comparison to the Fe₃O₄@H₂L confirm
the successful complexion of Zn ions with the oxime nitrogen atoms and phenol oxygen atoms.

The presence of Fe, O, Si, C, N, and Pd elements on the surface of the catalyst were confirmed by energy dispersive X-ray (EDX) measurements and there were no other elements showing the high purity of the sample (Fig. 2). As shown in this Figure, the presence of N was observed but Br was not observed. This indicated that the covalent adsorption of the H2L ligand successfully occurred on the catalyst surface. It is worth noting that the amount of zinc in Fe3O4@H2L-Zn was 1.17 × 10⁻³ mol g⁻¹, which was determined by the ICP analysis.

Fig. 3 depicts the XRD patterns of Fe3O4 and Fe3O4@H2L-Zn complex. In the Fe3O4 pattern, six major peaks were observed around 2θ = 30°, 35°, 43°, 53°, 57°, and 62° that corresponded to the (220), (311), (400), (422), (511), and (440) Miller indices, respectively. It can be seen in this figure that the Fe3O4@H2L-Zn pattern is in good agreement with the characteristic peaks of bare Fe3O4, which indicates the retention of the crystalline spinel ferrite core structure during the functionalization of MNPs. In the wide angle XRD pattern (Fig. 3b), the diffraction peaks corresponding to Zn ions cannot be observed for Fe3O4@H2L-Zn, which reveals high zinc dispersion. The absence of Zn diffraction peaks indicates the formation of finely dispersed zinc species on the nanocomposite that are not detectable by this technique. However, the angles of the diffraction peaks of Fe3O4@H2L-Zn decreased in comparison to those of Fe3O4 nanoparticles, which confirm the presence of zinc ions in the final complex with high dispersion.

3.1.3. Structure of the catalyst. Fig. 7 displays the FE-SEM images of Fe3O4@H2L-Zn. These images illustrated the
presence of uniform and regular spherical particles. These type of particles are good candidates for both catalysis and adsorption processes (Fig. 4).

The morphology and average size of Fe₃O₄@H₂L-Zn were determined via transmission electron microscopy and the corresponding TEM micrographs are shown in Fig. 5. The TEM images show that the as-prepared nanocatalyst has almost a spherical-like shape with monodispersity. The average size of the as-synthesized Fe₃O₄@H₂L-Zn was 22 nm, with the maximum number of particles having size in the range of 18–21 nm.

3.1.4. Physicochemical properties of the catalyst. The thermal stability of Fe₃O₄, Fe₃O₄@APTES and Fe₃O₄@H₂L-Zn nanocomposites was examined by thermogravimetric analysis (TGA) (Fig. 6). In all of the TGA curves, the first obvious weight loss was found in the temperature range of 25–200 °C, which was attributed to the release of physically adsorbed moisture and solvent from the sample. The other stage of gradual weight loss was found in the temperature range of 300–450 °C, which was caused by the decomposition of the APTES shells on the surface of the support. However, above 450 °C, catalyst decomposition started and the main weight change at 450–650 °C in the TGA curve represents the decomposition of the H₂L-Zn hybrid material. As shown, the weight loss values of Fe₃O₄ to Fe₃O₄@H₂L-Zn MNPs increased sequentially. The results show that with the increase in temperature, the organic groups of the products are gradually decomposed in the process of pyrolysis, which confirms the successful chemical adsorption of the organic complex layers via chemical bonding on the modified Fe₃O₄ MNPs.

The vibrating sample magnetometer (VSM) technique was used to examine the magnetic properties of the Fe₃O₄@H₂L-Zn and its synthons. The saturation magnetization values of Fe₃O₄, Fe₃O₄@APTES, Fe₃O₄@H₂L, Fe₃O₄@H₂L-Zn and recovered Fe₃O₄@H₂L-Zn MNPs are shown in Fig. 7. As shown in the figure, the saturation magnetization (Mₛ) value from Fe₃O₄ to Fe₃O₄@H₂L-Zn decreased sequentially. This result confirms the
successful chemical adsorption of the H$_2$L-Zn complex via chemical bonding with the modified Fe$_3$O$_4$ MNPs. As shown, the saturation magnetization value of Fe$_3$O$_4$@H$_2$L-Zn was 43 emu g$^{-1}$. Compared with that of Fe$_3$O$_4$ NPs (56 emu g$^{-1}$), this decrease can be attributed to the presence of H$_2$L-Zn and other functionalized groups on the surface of Fe$_3$O$_4$. The sequential decrease in the $M_s$ value in each step can be a sufficient reason to confirm the successful immobilization of organic functional groups at different stages.

The nitrogen physiosorption isotherm of the catalyst is shown in Fig. 8. The results of the BET analysis indicated that the highest surface area of the adsorbent was 121.92 m$^2$ g$^{-1}$. The large surface may endow the material with stronger catalytic activity. Furthermore, it can also be seen that the H$_2$L-Zn incorporation does not significantly change the BET parameters of the supports. This could indicate that the H$_2$L-Zn species are not incorporated into the framework but they are grafted on its surface.

### 3.2. Catalytic properties of the catalyst

After the successful synthesis and characterization of the Fe$_3$O$_4$@H$_2$L-Zn complex, we focused on its catalytic activity in the selective trimethylsilylation of alcohols as well as its catalytic activity in the deprotection of the as-prepared silyl ethers to parent alcohols.

For the optimization of reaction conditions, we studied the reaction of HMDS as a green silylation agent using benzyl alcohol in different conditions, and the effective reaction parameters including amount of the catalyst, type of solvent and temperature were optimized. The results show that the reaction promotion is highly affected by the catalyst loading and the solvent type. The effects of the catalyst amount in the reaction were examined by varying the catalyst loadings (2, 3, 4, 5, 6 and 7 mg) in the model reaction. It was observed that the yield of the trimethylsilyl ethers product enhanced with the increase in the amount of Fe$_3$O$_4$@H$_2$L-Zn from 2 to 6 mg (Table 1).

| Entry | Catalyst | Catalyst (mg) | Solvent | Temperature | Time | Yield (%) |
|-------|----------|---------------|---------|-------------|------|-----------|
| 1     | —        | —             | Solvent free | RT          | 12 h | NR        |
| 2     | Fe$_3$O$_4$ | 6             | Solvent free | RT          | 2 h  | Trace     |
| 3     | Fe$_3$O$_4$@APTES | 6         | Solvent free | RT          | 2 h  | 33        |
| 4     | Fe$_3$O$_4$@H$_2$L  | 6             | Solvent free | RT          | 2 h  | Trace     |
| 5     | Fe$_3$O$_4$@H$_2$L-Zn | 2          | Solvent free | RT          | 10 h | 51        |
| 6     | Fe$_3$O$_4$@H$_2$L-Zn | 3          | Solvent free | RT          | 10 h | 83        |
| 7     | Fe$_3$O$_4$@H$_2$L-Zn | 4          | Solvent free | RT          | 10 h | 89        |
| 8     | Fe$_3$O$_4$@H$_2$L-Zn | 5          | Solvent free | RT          | 10 h | 96        |
| 9     | Fe$_3$O$_4$@H$_2$L-Zn | 6          | Solvent free | RT          | 10 h | 100       |
| 10    | Fe$_3$O$_4$@H$_2$L-Zn | 7          | Solvent free | RT          | 10 h | 100       |
| 11    | Fe$_3$O$_4$@H$_2$L-Zn | 6          | Acetonitrile | RT          | 15 h | 94        |
| 12    | Fe$_3$O$_4$@H$_2$L-Zn | 6          | EtOAc      | RT          | 20 h | 95        |
| 13    | Fe$_3$O$_4$@H$_2$L-Zn | 6          | n-Hexane   | RT          | 15 h | 92        |
| 14    | Fe$_3$O$_4$@H$_2$L-Zn | 6          | THF        | RT          | 10 h | 97        |
| 15    | Fe$_3$O$_4$@H$_2$L-Zn | 6          | CH$_2$Cl$_2$ | RT          | 60 h | NR        |
| 16    | Fe$_3$O$_4$@H$_2$L-Zn | 6          | Solvent free | 45 h       | 7 h  | 100       |
| 17    | Fe$_3$O$_4$@H$_2$L-Zn | 6          | Solvent free | 60 h       | 5 h  | 100       |
| 18    | Fe$_3$O$_4$@H$_2$L-Zn | 6          | Solvent free | 90 h       | 5 h  | 100       |

Fig. 8 Nitrogen adsorption/desorption isotherm of Fe$_3$O$_4$@H$_2$L-Zn MNPs.
Table 2  Catalytic trimethylsilylation of various alcohols with HMDS in the presence of 6 mg of Fe₃O₄@H₂L-Zn

| Entry | Substrate | Product | Time (min) | Yieldᵢ,ᵢ (%) |
|-------|-----------|---------|------------|--------------|
| 1     |           |         | 10         | 100          |
| 2     |           |         | 10         | 99           |
| 3     |           |         | 12         | 97           |
| 4     |           |         | 17         | 96           |
| 5     |           |         | 13         | 91           |
| 6     |           |         | 8          | 100          |
| 7     |           |         | 12         | 100          |
| 8     |           |         | 12         | 94           |
| 9     |           |         | 17         | 98           |
| 10    |           |         | 15         | 95           |
| 11    |           |         | 55         | 92           |
The best result in an appropriate time was obtained using 6 mg of the catalyst (Table 1, entry 9). It is worth mentioning that in the presence of 7 mg of Fe$_3$O$_4$@H$_2$L-Zn almost the same result as that in the presence of 6 mg was observed (Table 1, entry 10). Moreover, in the catalyst free conditions, the reaction did not proceed at all even after 12 h.

Table 2 (Contd.)

| Entry | Substrate | Product | Time (min) | Yield$^{a,b}$ (%) |
|-------|-----------|---------|------------|-------------------|
| 12    | ![Substrate Image] | ![Product Image] | 18         | 97                |
| 13    | ![Substrate Image] | ![Product Image] | 15         | 95                |
| 14    | ![Substrate Image] | ![Product Image] | 13         | 97                |
| 15    | ![Substrate Image] | ![Product Image] | 35         | 92                |
| 16    | ![Substrate Image] | ![Product Image] | 15         | 100               |
| 17    | ![Substrate Image] | ![Product Image] | 25         | 89                |
| 18    | ![Substrate Image] | ![Product Image] | 27         | 95                |
| 19    | ![Substrate Image] | ![Product Image] | 25         | 97                |
| 20    | ![Substrate Image] | ![Product Image] | 60         | 98                |
| 21    | ![Substrate Image] | ![Product Image] | 50         | 100               |
| 22    | ![Substrate Image] | ![Product Image] | 23         | 100               |

$^a$ Isolated yield. $^b$ Reaction conditions: alcohol (1 mmol), HMDS (0.8 mmol) and Fe$_3$O$_4$@H$_2$L-Zn (6 mg) at room temperature under solvent-free conditions.
(Table 1, entry 1). The efficiency of the catalyst was also considerably affected by the solvent (Table 1). Among the applied solvents such as acetonitrile, ethyl acetate, \( n \)-hexane, tetrahydrofuran, dichloromethane and solvent-free conditions, the best result was obtained in excellent yield after 10 min under solvent-free conditions as the reaction media (Table 1, entries 9 and 11–15). However, acetonitrile, ethyl acetate, \( n \)-hexane, tetrahydrofuran show good yields, but dichloromethane delivered a low yield of the corresponding product. By increasing the reaction temperature from 25 to 90 °C, the reaction time was reduced but room temperature was selected purely on the basis of green chemistry principle and high yield of the reaction in this condition. Finally, the best conditions for this coupling reaction are the following: \( \text{Fe}_3\text{O}_4@\text{H}_2\text{L-Zn} \) (6 mg), at room temperature under solvent-free conditions (Table 1, entry 9).

After the optimization of reaction conditions, the direct silylation of hydroxyl bearing compounds for the preparation of their corresponding trimethylsilyl ethers was studied under the obtained optimized reaction conditions. The results are presented in Table 2. As shown in Table 2, the \( \text{Fe}_3\text{O}_4@\text{H}_2\text{L-Zn} \) catalytic complex exhibited high efficiency in the solvent-free trimethylsilylation of numerous alcohols including several functional groups in excellent yields using hexamethyldisilazane under mild conditions at room temperature (25 °C). In this method, 24 different examples of benzylic and aliphatic alcohols including primary, bulky secondary, tertiary hydroxyl functional groups reacted with the HMDS (0.6 mmol) reagent and transformed to the corresponding trimethylsilyl ethers in good to excellent yields (89–100%) in short reaction time (8–60 min).

As silyl ether can be further converted to the parent alcohols under acidic conditions, the silylation of alcohols can be regarded as an alternative method for hydroxyl protection under ambient reaction conditions. Merging the silyl protection/deprotection of alcohols with modern methodologies, such as green chemistry and nanoscience, has added additional value to these temporary components of synthetic intermediates. Furthermore, in the final part of our studies, we report the use of the resulted nanocomposite \( \text{Fe}_3\text{O}_4@\text{H}_2\text{L-Zn} \) as a highly efficient catalyst for the chemoselective deprotection of some of the obtained trimethylsilyl ethers to their parent hydroxyl groups in wet dichloromethane moistened by 3 drops of water at room temperature. The results of this study are summarized in Table 3. As presented in Table 3, this catalytic system worked very well and the selected trimethylsilyl ethers gave the parent hydroxyl compounds in good to excellent yields in the presence of catalytic amount of \( \text{Fe}_3\text{O}_4@\text{H}_2\text{L-Zn} \) at room temperature.

| Entry | Substrate | Product | Time (min) | Yield\(^a, b\) (%) |
|-------|-----------|---------|------------|-------------------|
| 1     | ![Image](image1.png) | ![Image](image2.png) | 15          | 100               |
| 2     | ![Image](image3.png) | ![Image](image4.png) | 23          | 100               |
| 3     | ![Image](image5.png) | ![Image](image6.png) | 85          | 98                |
| 4     | ![Image](image7.png) | ![Image](image8.png) | 37          | 96                |
| 5     | ![Image](image9.png) | ![Image](image10.png) | 47          | 100               |
| 6     | ![Image](image11.png) | ![Image](image12.png) | 29          | 100               |

\(^a\) Isolated yield. \(^b\) Reaction conditions: TMS ethers (1 mmol), HMDS (0.8 mmol) and \( \text{Fe}_3\text{O}_4@\text{H}_2\text{L-Zn} \) (6 mg) at room temperature in \( \text{CH}_2\text{Cl}_2 \) (4 ml) moistened by three drops of water.

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Table 3  Deprotection of trimethylsilyl ethers (1 mmol) in the presence of the \( \text{Fe}_3\text{O}_4@\text{H}_2\text{L-Zn} \) catalyst in \( \text{CH}_2\text{Cl}_2 \) (4 ml) moistened by 3 drops of water at room temperature.
3.3. Scale-up production

Developing a strategy for scaling up of the protection and deprotection of alcohols is a challenge for numerous drug and pharmaceutical manufacturers. Attempting larger-scale chemical fabrication with reactions previously optimized at the laboratory scale is a big challenge. To clearly demonstrate the potential of this method for the scaled up protection of benzyl alcohol and deprotection of its corresponding trimethylsilyl ether to its parent hydroxyl compound, the reactions were investigated using 20.0 mmol of substrates under optimized conditions. Desired protected and deprotected products were obtained in 97 and 95% yields, respectively.

4. Recycling ability, hot filtration and leaching tests of the catalyst

Recyclability is one of the most important properties of heterogeneous catalysts. The recyclability of the catalyst Fe$_3$O$_4$@H$_2$L-Zn was studied in a typical trimethylsilylation reaction with benzyl alcohol and HMDS under the optimized reaction conditions. Briefly, after the finalization of each run of the trimethylsilylation reaction, which was monitored by TLC, the heterogeneous catalyst was separated using an external magnet, washed with acetone and water and dried overnight under vacuum at 60 °C to use in the next run. Fig. 9 shows that the Fe$_3$O$_4$@H$_2$L-Zn complex can be reused 10 times and the catalytic activity was not significantly reduced and it was indicated that the catalyst has good recyclability. It was also proved by the hot filtration test that the Fe$_3$O$_4$@H$_2$L-Zn complex played a catalytic role in the reaction rather than the free Zn in the solution. Furthermore, difference in the Zn content for the fresh and reused catalyst, after eight run, was only 0.5%, proving a low rate of leaching.

5. Comparison

In order to investigate the efficiency of this new procedure compared to the reported procedures in the literature, the results for the trimethylsilylation of benzyl alcohol as the representative example was compared to the best of the well-known data from the literature, as outlined in Table 4. The comparison results show that the present catalytic system modified the Heck reaction time, yields and conditions.

6. Conclusion

In summary, a novel catalyst H$_2$L-Zn complex was successfully prepared on the Fe$_3$O$_4$ surface and was characterized by a progressive mode for the preparation. The Fe$_3$O$_4$@H$_2$L-Zn catalysts have an efficient catalytic activity for the silyl protection and deprotection of alcohols by the selective trimethylsilylation of primary, secondary and tertiary aromatic and aliphatic alcohols in high yields in green media at 25 °C in low reaction times. More importantly, Fe$_3$O$_4$@H$_2$L-Zn has several advantages such as simple to synthesize, wide range of carriers, ligand-free protocol and easy to separate the use of commercially available, eco-friendly, inexpensive and chemically stable reagents with operational simplicity, practicability and good to high yields. The separation of products and recycling of catalysts are easier and simpler with the assistance of an external magnet. The catalyst can be reused 10 times with little loss of activity.

7. Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

There are no conflicts to declare.

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