

Fe₃O₄@PEG core/shell nanoparticles as magnetic nanocatalyst for acetylation of amines and alcohols using ultrasound irradiations under solvent-free conditions

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Abstract

Ultrasound irradiation was used to prepare one-pot $Fe_3O_4@PEG$ core/shell nanostructure for the first time. The morphology, structure, and physicochemical properties were specified by different analytical techniques including field emission scanning electron microscopy, Fourier transform infrared spectroscopy, energydispersive X-ray spectroscopy, transmission electron microscopy, X-ray powder diffraction, and vibrating sample magnetometer. For acetylation of phenols, alcohols, and amines, the synthesized $Fe_3O_4@PEG$ core/shell nanoparticles were used as an efficient heterogeneous and green catalyst with acetic anhydride under sonication applying mild reaction conditions. Different electron-withdrawing and electrondonating substrates indicate a prominent yield of desired products with the merit of reusability of $Fe_3O_4@PEG$ nanocatalyst and magnetic separation.

Extended author information available on the last page of the article

Graphical Abstract



Keywords PEGylation · Core/shell · Magnetic · Ultrasonic · Acetylation · Amine · Alcohol

Introduction

Researchers have conducted many efforts with respect to the necessity of generating drugs through effective procedures to prepare organic compounds [1]. In recent years, ultrasound irradiation has progressively been considered as a simple, clean, and suitable method in synthesis of drugs [2]. Ultrasound irradiation is used to accelerate a number of synthetically beneficial reactions using the growth, formation, and implosive collapse of bubbles in a liquid [3]. Bubble collapse initiated by cavitation causes intense local heating, high pressures, and very short lifetimes [4, 5]. Ultrasound irradiation can activate many reactions, compared with conventional heating, which generates thermal energy in the macrosystem, through providing the activation energy in a microenvironment [6–8]. The ultrasound approach proposes many privileges, such as enhanced organic reaction rates, higher yields, milder reaction conditions, nontoxicity, environmentally friendly solvent, and waste minimization in comparison to traditional methods, and also saves money, energy, and raw materials [9, 10].

Acetylation of phenols, alcohols, and amines is a regularly used transformation in synthetic chemistry and is extensively applied as a protection agent in multi-step pharmaceutical synthesis and food or cosmetic industries [11, 12]. The acetylation of hydroxyl and amino groups has been carried out commonly by acetic anhydride or acetyl chloride through either base [13–16] or acid catalysts [17–23]. Although there are different acetylation methods, most protocols have innate shortcomings such as harsh conditions, long reaction times, tedious work-up procedures, and harmful organic solvents [24–26]. Using green and insoluble nanocatalysts or applying eco-friendly solvent-free conditions is possibly one of the solutions. These premises support the use of nanomaterials and supported nanoparticles as catalysts in different types of chemistries.

Accomplishing synthetic reactions with a heterogeneous catalyst under ultrasonic irradiation may enhance their effectiveness regarding operating cost and ecological aspects [27, 28]. Core/shell nanoparticles have received great attention due to their unique features [29, 30]. The magnetic core/shell Fe_3O_4 nanoparticles can be used as an appropriate catalyst in many reactions [31, 32]. Thus, surface modification of magnetic nanoparticles (MNPs) is an issue of increasing interest in chemical reactions in the effort to find supporting catalysts. The surface of MNPs can be simply functionalized via suitable surface modifications to make the loading of different favorable functionalities possible [33, 34]. In the current study, Fe₃O₄@polyethylene glycol (PEG) composite MNPs with a core/shell structure were provided for the first time through ultrasound irradiation. Afterwards, a new methodology was presented for the acetylation of phenols, alcohols, and amines with acetic anhydride, applying sonication energy under solvent-free conditions (Scheme 1). The synthesized Fe₃O₄@PEG nanoparticles show good catalytic activity for the reaction, with the merit of catalyst recyclability. The catalyst could be used again 10 times without losing catalytic activity. The reaction functions under solvent-free conditions at room



Scheme 1 Schematic preparation of core/shell $Fe_3O_4@PEG$ NPs and its application for acetylation of alcohols, phenols, and amines

temperature. This is a simple procedure to synthesize $Fe_3O_4@PEG$ core/shell nanoparticles, and it also can be further extended for synthesis of other metal oxides.

Experimental

Ultrasonic-assisted preparation of Fe₃O₄@PEG core/shell nanoparticles

FeCl₃.6H₂O (10.4 g) was mixed with 4.0 g of FeCl₂·4H₂O and 1.7 mL of HCl (concentrated) in 50 mL water. The mixture was then added dropwise to 100 mL of an aqueous solution of NaOH (1.5 M) and PEG400 (1 mL) in an ultrasonic bath at 60 °C for 20 min, as shown in Scheme 1. The mixture was sonicated at 60 W of power and the drip rate was 5 mL/min. After complete addition, the reaction continued for another 20 min under ultrasonic conditions. Then, the mixture was cooled to room temperature and the Fe₃O₄@PEG MNPs as a dark solid were isolated from the solution by magnetic separation and washed several times with deionized (DI) water and ethanol.

General procedure for acylation reaction under ultrasonic conditions

A 10-mL balloon was charged with phenol/alcohol/amine (1 mmol) and acetic anhydride (3 mmol), with $Fe_3O_4@PEG$ (10 mg) as catalyst. The reaction balloon was taken in the ultrasonic bath, where the level of the reaction mixture is lower than the surface of the water. Then, the mixture was sonicated under 60 W of power of the ultrasonic bath at room temperature for the appropriate time, as shown in Table 2. After completion of the reaction (monitored by thin-layer chromatography), the reaction mixture was diluted with ethyl acetate and the catalyst was separated from reaction mixture by an external magnet. The separated catalyst was washed with DI water and absolute ethanol several times then dried in oven and reused for further reaction. The reaction mixture was washed with sat. NaHCO₃ solution (1×15 mL) and the product was extracted with ethyl acetate (3×10 mL) and dried over Na₂SO₄ and evaporated under vacuum. All the obtained products are well known in the literature and were confirmed by nuclear magnetic resonance (NMR) analysis and comparison with literature data.

Results and discussion

Characterization of nanocomposite

The core/shell $Fe_3O_4@PEG$ nanoparticles were directly provided using ultrasound irradiation (Scheme 1). When the solution with precursor [Fe(II), Fe(II), PEG400, and NaOH] is exposed through an ultrasound method, very high temperatures and pressures are generated to produce core/shell $Fe_3O_4@PEG$ nanoparticles. Field emission scanning electron microscopy (FESEM), Fourier transform infrared

(FT-IR) spectroscopy, energy-dispersive X-ray spectroscopy (EDX), transmission electron microscopy (TEM), X-ray powder diffraction (XRPD), and vibrating sample magnetometer (VSM) analyses were performed to characterize the nanoparticles. Then, core/shell $Fe_3O_4@PEG$ nanoparticles were used as a green and recyclable heterogeneous nanocatalyst to acetylate alcohols, phenols, and amines with acetic anhydride using sonication energy under solvent-free conditions (Scheme 1).

The core/shell Fe₃O₄@PEG NPs' surface chemical structure was characterized using FT-IR spectroscopy. FT-IR spectra of Fe₃O₄ (Fig. 1a) showed characteristic peaks at 569 cm⁻¹ and 1383 cm⁻¹ due to Fe–O bending and Fe–O stretch vibrations, respectively. The peak at 1624 cm⁻¹ was attributed to the bending vibration of water adsorbed on the surface of Fe₃O₄. The peak at 3424 cm⁻¹ appeared due to the OH present on the surface of Fe₃O₄ NPs [35, 36]. The FT-IR spectra of PEG400 showed its characteristic vibrations at 3405 cm⁻¹ and 1406 cm⁻¹ due to the OH stretching and bending vibration, respectively, along with at 2923 cm⁻¹



Fig. 1 FT-IR spectra of a Fe₃O₄, b PEG400, and c Fe₃O₄@PEG

(C–H stretch), 1460 cm⁻¹ (C–H bending and scissoring), 1378 cm⁻¹ (–OH bending), 1247 cm⁻¹ (C–O stretch), and 1160 cm⁻¹ (–C–O–C– stretching) and other peaks in the fingerprint region (Fig. 1b) [37, 38]. The presence of characteristic peaks of PEG in the FT-IR spectra of Fe₃O₄@PEG further confirmed the successful formation of PEGylated Fe₃O₄ MNPs (Fig. 1c).

The particle size and morphology of the synthesized nanocomposite were examined by recording FESEM, indicating $Fe_3O_4@PEG$ particle formation with diameters in the range of nanometers (Fig. 2).

The EDX spectrum of the nanostructure is displayed in Fig. 3. Signals relating oxygen, carbon, and iron were detected. Metallic Fe nanocrystals commonly indicate typical optical absorption peaks about 1.0 and 7.0 keV because of surface plasmon resonance. The strong signals of iron, carbon, and oxygen regions approved the formation of the nanocomposite under study.

TEM presents more insight into the nanostructures' morphology, shape, and size. The synthesized NPs' TEM image showed that NPs with almost spherical core/shell morphology are generated with relatively decent dispersity. The sizes of particles are 8–12 nm (Fig. 4). The TEM image depicts that a clear PEG coat (about 3 nm in thickness) is immobilized on the Fe_3O_4 nanoparticles' surface, showing the core/shell structure of Fe_3O_4 @PEG.

Adequate magnetic properties are crucial for practical usages of magnetic materials in aqueous solution. The saturation magnetization value of Fe_3O_4 @PEG NPs is 59.1 emu g⁻¹ (Fig. 5) and could be strong enough to provide an easy and effective way to separate the catalyst from the reaction system.

The Fe₃O₄@PEG NPs' high-angle XRD patterns are presented in Fig. 6. The strong characteristic diffraction peaks at 2 h of 30.1° , 35.5° , 43.1° , 53.4° , 56.9° , and 62.6° can be attributed to the diffraction of (220), (311), (400), (422), (511), and (440) of the Fe₃O₄ as core, revealing successful synthesis of the core/shell Fe₃O₄@ PEG NPs without spoiling the Fe₃O₄ core's crystal structure.



Fig. 2 FESEM image of core/ shell Fe₃O₄@PEG NPs



Fig. 3 EDX spectrum of core/shell Fe₃O₄@PEG NPs

Fig. 4 TEM image of core/shell Fe₃O₄@PEG NPs



Thermogravimetric analysis (TG) of core/shell Fe₃O₄@PEG NPs was applied to prove the existence of different groups on the NPs' surface (Fig. 7). The initial weight loss from the catalyst was below 200 °C, and attributed to the loss of physically adsorbed solvent or bound water. The weight loss at 220–500 °C in the TG curve of core/shell Fe₃O₄@PEG NPs is mainly assigned to the decomposition of PEG groups linked to the Fe₃O₄ surface.



Fig. 5 VSM image of core/shell Fe₃O₄@PEG NPs



Fig. 6 XRD pattern of core/shell Fe₃O₄@PEG NPs



Fig. 7 TG curve of core/shell $Fe_3O_4@PEG NPs$

Catalytic application of core/shell Fe₃O₄@PEG NPs in the acetylation of Nitrogen/ Oxygen (*N*/O)

In continuation of our works in developing heterogeneous magnetic nanocatalysts [39–49], the catalytic activity of the prepared core/shell Fe₃O₄@PEG NPs was investigated as a novel heterogeneous magnetic nanocatalyst for acetylation of alcohols, phenols, and amines with acetic anhydride using sonication energy at room temperature under solvent-free conditions (Scheme 1). The sonication energy has many merits including high efficiency, low waste, and less energy requirement; also, it generates cavitation bubbles which enhance the interaction between reactant and catalyst; it accelerates the reaction speed, and it produces better mass and heat transfer efficiency in comparison to conventional heating; it is also economical with easy operation [50, 51].

The reaction of phenol with acetic anhydride as acetylating agent was selected as a model reaction and conducted in the presence of Fe₃O₄@PEG NPs under solvent-free conditions at room temperature to determine the best conditions using a sonication bath (60 W of power). The reaction occurred in the absence of the catalyst at the beginning to examine the influence of sonication on reaction. Formation of 15% yield of acylation product was observed (Table 1, entry 1). Afterwards, the reaction was replicated in the presence of Fe₃O₄ NPs and provided 45% yield of favored product (Table 1, entry 2). Then, the catalyst loading was screened via the model reaction catalyzed by Fe_3O_4 @PEG NPs (Table 1, entries 3-7). Catalyst at 5 mol% provided great yield (96%) of the favored product (Table 1, entry 6). A pronounced increase in the product yield did not occur through increasing the catalyst concentration (Table 1, entry 7). The reaction was carried out in the absence of sonication at room temperature with Fe₃O₄@PEG NPs, but the reaction did not work. The possibility of homogeneous catalysis of the acylation with PEG are investigated (Table 1, entries 8, 9), but it did not provide a good result. The increased catalytic activity of the PEG-coated Fe₃O₄

Entry	Catalyst	Catalyst (mol%)	Time (h)	Yield (%)
1	No catalyst	0.0	4	15
2	Fe ₃ O ₄	1.0	2	45
3	Fe ₃ O ₄ @PEG	1.0	2	60
4	Fe ₃ O ₄ @PEG	2.0	2	70
5	Fe ₃ O ₄ @PEG	3.0	1	85
6	Fe ₃ O ₄ @PEG	5.0	0.5	96
7	Fe ₃ O ₄ @PEG	10	0.5	96
8	PEG	5.0	2	60
9	PEG	10	2	70

Reaction conditions: phenol (1 mmol), acetic anhydride (2 mmol), room temperature, and sonication (60 W of power) under solventfree conditions at room temperature

The reactions were conducted in duplicate

Table 1	Investigation of best
conditio	ns in the acetylation
of phene	ol in the presence of
the Fe ₃ C	O ₄ @PEG NPs and
sonicati	on energy

nanoparticles can be a result of the higher specific surface area of the prepared $Fe_3O_4@PEG NPs$.

Assuming the optimized conditions for the acetylation of alcohols (Table 1, entry 6), a wide range of various alcohols, such as benzylic, primary, secondary, and tertiary alcohols were screened. All the alcohols tested were converted, under the optimized conditions, to the corresponding acetates in excellent yields (Table 2). Benzylic alcohols with electron-donating groups were the most reactive of all substrates examined and were converted, in the shortest reaction times, to the corresponding acetates. Moreover, the reaction progressed at a slower rate for aromatic substrates with an electron-withdrawing group (Table 2, entries 2–4). The tertiary alcohol 1-adamantanol was also acetylated successfully in high yield to provide the corresponding acetylated material (Table 2, entry 12). In addition, cinnamyl alcohol, an allyllic alcohol, was converted selectively to the corresponding acetate, in which the carbon double bond was intact in the process of acetylation reaction (Table 2, entry 7).

To study this catalytic system's potential, the acetylation of a variety of phenols and amines was studied assuming solvent-free conditions (Table 2). The

Entry	Substrate	Time (min)	Yield (%) ^a	References
1	Benzyl alcohol	10	96	[52]
2	4-Bromo-benzyl alcohol	10	96	[52]
3	4-Chloro-benzyl alcohol	10	96	[53]
4	2,4-Dichloro-benzyl alcohol	10	90	[52]
5	Phenol	30	96	[25]
6	4-Chlorophenol	40	90	[52]
7	Cinnamyl alcohol	60	85	[52]
8	2-Phenylethanol	25	85	[52]
9	Diphenylmethanol	10	96	[52]
10	Cyclohexanol	30	90	[52]
11	2-Adamantanol	45	90	[52]
12	1-Adamantanol	60	70	[52]
13	Benzyl amine	10	96	[39]
14	4-Methyl-benzyl amine	10	96	[39]
15	4-Methoxy-benzyl amine	15	90	[52]
16	Aniline	20	96	[24]
17	4-Methyl-aniline	30	88	[52]
18	Dibenzylamine	10	96	[52]
19	Piperazine	10	96	[52]
20	Ethane-1,2-diamine	10	96	[52]

Table 2 $O_{,N}$ acetylation with Ac₂O under solvent-free conditions in the presence of Fe₃O₄@PEG NPs

Reaction conditions: substrate (1 mmol), catalyst (5 mol %), acetic anhydride (2 mmol), sonication (60 W of power) for desired time at room temperature under solvent-free conditions

^aIsolated yields

acetylation of phenols proceeded slowly in comparison to amines. Acetylation of benzylic amines and aliphatic amines was indicated to be more rapid compared with anilines and needed lower reaction times.

A possible mechanism for the reaction applying $Fe_3O_4@PEG$ nanoparticle is depicted in Scheme 2, showing the activation of the carbonyl group of acetic anhydride via coordinating to PEG groups. Then, the activated carbonyl reacts with the substrates to provide the corresponding acetates.

The heterogeneous catalysts' reusability is crucial, particularly for commercial uses. To examine the reusability and recyclability of the catalyst, the acetylation of aniline with acetic anhydride was investigated assuming identical reaction conditions. The catalyst could be separated by an external magnet and similarly used again for the next experiments after completion of the reaction (nine times). The product yield and reaction time remained the same, approving the reusability and recyclability of the catalyst without loss of its activity (Fig. 8).

The reaction of benzyl alcohol with acetic anhydride was done to compare the effectiveness of the synthesized $Fe_3O_4@PEG$ nanoparticle with the previous catalyst for acetylation reaction (Table 3). The previously reported catalyst had one or more disadvantages such as non-reusability, low yield of products, toxicity, and longer reaction time.



Scheme 2 Proposed mechanism for acetylation of alcohols, phenols, and anilines





Table 3 Comparison efficiency of ${\rm Fe_3O_4@PEG}$ NPs with some reported catalysts for the acetylation reactions of benzyl alcohol

Entry	Reaction conditions	Time	Yield%	References
1	Fe ₃ O ₄ @PEG NPs, sonication, r.t., solvent-free	10 min	96	This work
2	ZnCl ₂ , r.t., solvent-free	3 h	63	[53]
3	Borated zirconia, 110 °C, toluene	14 h	25	[24]
4	SiO ₂ –ZnCl ₂ , 80 °C, CH ₃ CN	3 h	90	[52]
5	Silica sulfamic acid, r.t., solvent-free	15 min	93	[54]
6	Yttria-zirconia, 110 °C, solvent-free	6 h	94	[26]
7	Copper zirconium phosphate NPs, 60 °C, solvent-free	30 min	91	[55]
8	Nano γ -Fe ₂ O ₃ , sonication, r.t., solvent-free	1 h	64	[56]
9	CuO–ZnO, r.t., CH ₂ Cl ₂	15 min	92	[57]

Conclusion

In this research, a simple and efficient procedure is developed for ultrasonic-assisted one-pot synthesis of $Fe_3O_4@PEG$ core/shell nanostructure as a green magnetic catalyst under ultrasonic irradiation for the acetylation of various alcohols, phenols, and amines at room temperature under solvent-free conditions. The catalyst generates excellent yields of acetate products and is recyclable. The significant merits of this method are its easy work-up, one-pot preparation of core/shell Fe₃O₄@PEG NPs, recycling of the catalyst, short reaction times, and using ultrasonic irradiation as an efficient technology.

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References

- 1. C. Hulme, V. Gore, Curr. Med. Chem. 10, 51 (2003)
- 2. N.C. Eddingsaas, K.S. Suslick, Nature 444, 163 (2006)
- 3. K.S. Suslick, Science **247**, 1439 (1990)
- 4. K.S. Suslick, Sci. Am. 260, 80 (1989)
- 5. J.H. Bang, K.S. Suslick, Adv. Mater. 22, 1039 (2010)
- 6. H. Xu, K.S. Suslick, J. Am. Chem. Soc. 133, 9148 (2011)
- 7. S. Allahyari, M. Haghighi, A. Ebadi, S. Hosseinzadeh, Ultrason. Sonochem. 21, 663 (2014)
- M. Mirza-Aghayan, N. Ganjbakhsh, M. Molaee Tavana, R. Boukherroub, Ultrason. Sonochem. 32, 37 (2016)

- 9. H. Xu, B.W. Zeiger, K.S. Suslick, Chem. Soc. Rev. 42, 2555 (2013)
- 10. G. Cravotto, P. Cintas, Chem. Soc. Rev. 35, 180 (2006)
- 11. T.W. Green, P.C.M. Wuts, Protective Groups in Organic Synthesis, 3rd edn. (Wiley, New York, 1999)
- 12. J. Otera, Esterification: Methods, Reactions and Applications, 1st edn. (Wiley, New York, 2003)
- 13. W. Steglich, G. Hofle, Angew. Chem. Int. Ed. 8, 981 (1969)
- 14. E. Vedejs, T.S. Diver, J. Am. Chem. Soc. **115**, 3358 (1993)
- 15. E.F.V. Scriven, Chem. Soc. Rev. 12, 129 (1983)
- 16. S. Tomohumi, O. Kousaburo, O. Takashi, Synthesis 12, 1141 (1991)
- 17. A. Orita, C. Tanahashi, A. Kakuda, J. Otera, Angew. Chem. Int. Ed. 39, 2877 (2000)
- 18. R. Alleti, M. Perambuduru, S. Samanha, V.P. Reddy, J. Mol. Catal. A Chem. 226, 57 (2005)
- 19. B. Karimi, J. Maleki, J. Org. Chem. 68, 4951 (2003)
- 20. N. Ghaffari Khaligh, J. Mol. Catal. A Chem. 363-364, 90 (2012)
- 21. F. Rajabi, Tetrahedron Lett. 50, 395 (2009)
- 22. L. Osiglio, A.G. Sathicq, G.P. Romanelli, M.N. Blanco, J. Mol. Catal. A Chem. 359, 97 (2012)
- 23. I. López, J.L. Bravo, M. Caraballo, J.L. Barneto, G. Silvero, Tetrahedron Lett. 52, 3339 (2011)
- 24. F. Tamaddon, M.A. Amrollahi, L. Sharafat, Tetrahedron Lett. 46, 7841 (2005)
- 25. R. Gupta, V. Kumar, M. Gupta, S. Paul, R. Gupta, Indian J. Chem. Sect. B 47, 1739 (2008)
- P. Kumar, R.K. Pandey, M.S. Bodas, S.P. Dagade, M.K. Dongare, A.V. Ramaswamy, J. Mol. Catal. A Chem. 181, 207 (2002)
- 27. P.G. Mandhane, R.S. Joshi, D.R. Nagargoje, C.H. Gill, Tetrahedron Lett. 51, 3138 (2010)
- 28. E. Mosaddegh, Ultrason. Sonochem. 20, 1436 (2013)
- 29. F. Wang, R. Deng, J. Wang, Q. Wang, Y. Han, H. Zhu, X. Chen, X. Liu, Nat. Mater. 10, 968 (2011)
- 30. S.H. Joo, J.Y. Park, C.K. Tsung, Y. Yamada, P. Yang, G.A. Somorjai, Nat. Mater. 8, 126 (2009)
- 31. Z. Xu, Y. Hou, S. Sun, J. Am. Chem. Soc. 129, 8698 (2007)
- 32. R. Liu, Y. Guo, G. Odusote, F. Qu, R.D. Priestley, A.C.S. Appl, Mater. Interfaces. 5(18), 9167 (2013)
- 33. J. Safaei-Ghomi, R. Masoomi, M. Hamadanian, S. Naseh, New J. Chem. 40, 3289 (2016)
- 34. F. Mi, X. Chen, Y. Ma, S. Yin, F. Yuan, H. Zhang, Chem. Commun. 47, 12804 (2011)
- 35. Z. Zarnegar, J. Safari, New J. Chem. 38, 4555 (2014)
- 36. Y. Ahn, E.J. Choi, E.H. Kim, Rev. Adv. Mater. Sci. 5, 477 (2003)
- 37. G. Yuan, Y. Yuan, K. Xu, Q. Luo, Int. J. Mol. Sci. 15, 18776 (2014)
- 38. E. Karaoglu, H. Kavas, A. Baykal, M.S. Toprak, H.S. Ozeri, Nano-Micro Lett. 3, 79 (2011)
- 39. E. Farzad, H. Veisi, J. Ind. Eng. Chem. 60, 114 (2018)
- 40. F. Bonyasi, M. Hekmati, H. Veisi, J. Colloid, Interface Sci. 496, 177 (2017)
- 41. P. Heidari, R. Cheraghali, H. Veisi, Appl. Organomet. Chem. 30, 991 (2016)
- 42. M. Shahriary, H. Veisi, M. Hekmati, S. Hemmati, Mater. Sci. Eng. C. 90, 57 (2018)
- 43. H. Veisi, A. Sedrpoushan, S. Hemmati, Appl. Organomet. Chem. 29, 825 (2015)
- 44. H. Veisi, A. Rashtiani, V. Barjasteh, Appl. Organomet. Chem. 30, 231 (2016)
- B. Maleki, D. Azarifar, R. Ghorbani-Vaghei, H. Veisi, S.F. Hojati, M. Gholizadeh, H. Salehabadi, M. Khodaverdian Moghadam, Monatsh Chem. 140, 1485 (2009)
- 46. H. Veisi, S.A. Mirshokraie, H. Ahmadian, Int. J. Biol. Macromol. 108, 419 (2018)
- 47. R. Ghorbani-Vaghei, M. Chegini, H. Veisi, M. Karimi-Tabar, Tetrahedron Lett. 50, 1861 (2009)
- 48. H. Veisi, M. Pirhayati, A. Kakanejadifard, P. Mohammadi, M.R. Abdi, J. Gholami, S. Hemmati, Chem-Select **3**, 1820 (2018)
- 49. H. Veisi, S. Taheri, S. Hemmati, Green Chem. 18, 6337 (2016)
- N.D. Koduri, B. Hileman, J.D. Cox, H. Scott, P. Hoang, A. Robbins, K. Bowers, L. Tsebaot, K. Miao, M. Castaneda, M. Coffin, G. Wei, T.D.W. Claridge, K.P. Roberts, S.R. Hussaini, RSC Adv. 3, 181 (2013)
- 51. K.D. Bhatte, S.-I. Fujita, M. Arai, A.B. Pandit, B.M. Bhanage, Ultrason. Sonochem. 18, 54 (2011)
- H. Veisi, R. Ghorbani-Vaghei, H. Eskandari, S. Hemmati, A. Rezaei, S. Hajinazari, M.R. Heidari Far, A. Entezari, Phosphorus Sulfur Silicon 186, 213 (2011)
- 53. L. Osiglio, G. Romanelli, M. Blanco, J. Mol. Catal. A Chem. 316, 52 (2010)
- 54. K. Niknam, D. Saberi, Appl. Catal. A Gen. 366, 220 (2009)
- 55. A.R. Hajipour, H. Karimi, Chin. J. Catal. 35, 1982 (2014)
- M.A. Bhosale, D. Ummineni, T. Sasaki, D. Nishio-Hamane, B.M. Bhanage, J. Mol. Catal. A Chem. 404–405, 8 (2015)
- 57. J. Albadi, A. Alihosseinzadeh, M. Mardani, Chin. J. Catal. 36, 308 (2015)

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