

Sulfonated Honeycomb Coral (HC-SO₃H): a new, green and highly efficient heterogeneous catalyst for the rapid one-pot pseudo-five component synthesis of 4,4'-(aryl methylene)bis(3-methyl-1*H*-pyrazol-5-ol)s

Roya Jahanshahi¹ · Batool Akhlaghinia¹

Received: 6 August 2016 / Accepted: 28 December 2016 / Published online: 24 January 2017
© Institute of Chemistry, Slovak Academy of Sciences 2017

Abstract Sulfonated Honeycomb Coral (HC-SO₃H), has been synthesized from the reaction of Honeycomb Coral with chlorosulfonic acid as sulfonating agent. The as-synthesized catalyst was characterized via XRF, FT-IR, TGA, SEM-EDS, XRD, BET and pH analysis. The superior catalytic activity of HC-SO₃H was investigated for the synthesis of 4,4'-(aryl methylene)bis(3-methyl-1*H*-pyrazol-5-ol) derivatives through the one-pot pseudo-five component reactions. The main advantages of this protocol include simple procedure, excellent yields and short reaction times besides the non-toxicity, high stability and reusability of the catalyst.

Keywords Sulfonated Honeycomb Coral (HC-SO₃H) · 4,4'-(Aryl methylene)bis(3-methyl-1*H*-pyrazol-5-ol)s · One-pot pseudo-five component reaction · Heterogeneous catalysis · Green chemistry

Introduction

According to the “green and sustainable chemistry”, one of the most appealing developments in the synthetic organic chemistry is applying the environmentally benign reagents and reaction conditions (Anastas and Williamson 1998).

Electronic supplementary material The online version of this article (doi:10.1007/s11696-016-0127-y) contains supplementary material, which is available to authorized users.

✉ Batool Akhlaghinia
akhlaghinia@um.ac.ir

¹ Department of Chemistry, Faculty of Sciences, Ferdowsi University of Mashhad, P. O. Box 9177948974, Mashhad, Iran

Since catalysis organizes the basis of chemical industry nowadays, the development of novel, eco-friendly, non-toxic, inexpensive, stable, selective and recyclable catalysts with improved efficiency has attracted a great deal of interest, regarding to the green chemistry demands (Haile et al. 2001; Shylesh et al. 2009; Dabral et al. 2014; Pagadala et al. 2014; Ahmed and Siddiqui 2014).

During the past decades, acid-catalyzed chemical processes have been the subject of immense investigations, with respect to the widespread applications in chemical industries (Hosseini et al. 2016). However, although the conventional homogeneous acid catalysts such as sulfuric acid, hydrofluoric acid, hydrochloric acid and phosphoric acid are commonly used in the large-scale production of industrially important chemicals (Melero et al. 2006; Hara et al. 2004; González et al. 2012; Armstrong and Glover 1908), they suffer from several drawbacks. For instance, these homogeneous acids are associated with corrosive nature, high toxicity, hazardous handling and difficulty in separation from the reaction products (Hosseini et al. 2016). These disadvantages lead to wasting energy, besides the formation of immense amounts of waste products, which are far from the concept of “Green Chemistry”. In this context, to overcome the problems caused by such catalysts, heterogenization of these homogeneous catalysts through their immobilization on various solid supports has been developed (Parella et al. 2012; Siddiqui and Ahmed 2013; Zolfigol et al. 2013; Kuo et al. 2014; Mobaraki et al. 2014). This process leads to improve the aspects of environmental compatibility, as well as economic, in numerous industrial manufacturing.

Sulfonation with chlorosulfonic acid has been received considerable attention due to the suitable, convenient, fast and efficient approach involved in the heterogenization

process of the corresponding homogeneous catalysts (Kolvari et al. 2015).

In recent years, multi-component reactions (MCRs) have played crucial role in the combinatorial chemistry to assemble complex target structures with attractive biological aspects using simple and readily available starting materials, through a one-pot process. The one-pot character delivers fewer by-products, besides the lower costs, time and energy involved, in comparison with classical stepwise synthetic routes and leads to the formation of interesting heterocyclic scaffolds (Zhu and Bienayme 2005).

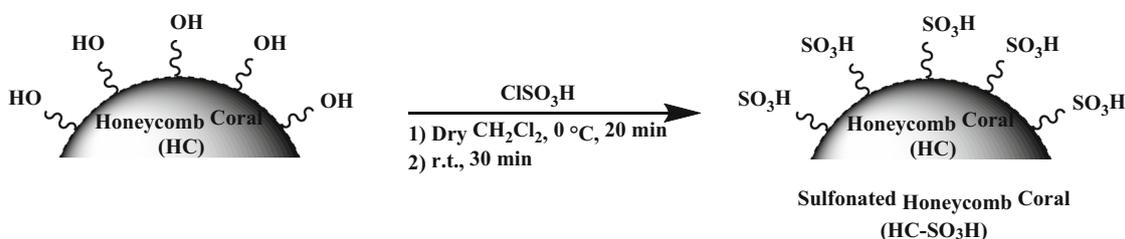
Synthesis of pyrazolone derivatives has attracted great attention recently in synthetic organic chemistry due to their therapeutic and pharmacological features (Elguero 1996). Among these significant class of heterocyclic compounds, 4,4'-(aryl methylene)bis(1*H*-pyrazol-5-ol)s have numerous biological activities including anti-inflammatory (Sugiura et al. 1977), antinociceptive (Carlsson and Jurna 1987), antipyretic (Behr et al. 1967), antidepressant (Bailey et al. 1985), antimalarial (Acharya et al. 2010), antitumor (Antre et al. 2012), antiviral (Sujatha et al. 2009) and bactericidal (Mahajan et al. 1991) activities. In addition to these, 4,4'-(aryl methylene)bis(1*H*-pyrazol-5-ol)s are widely used as insecticides (Lecher 1955), pesticides (Londershausen 1996), fungicides (Singh and Singh 1991), dyestuffs (Uzoukwu 1993), bis-Schiff bases (Ren et al. 2012), ligands (Abbasi-Tarighat et al. 2013) and important intermediates in organic synthesis (Hamama 2001). The most common route for the synthesis of 4,4'-(aryl methylene)bis(1*H*-pyrazol-5-ol)s is the one-pot pseudo three-component reaction of aldehydes with the initially formed 3-methyl-5-pyrazolone derivatives from the condensation reaction of hydrazine/aryl hydrazine and ethyl acetoacetate, in the presence of various catalytic systems (Sujatha et al. 2009; Singh and Singh 1984; Wang et al. 2005; Shi et al. 2005; Niknam et al. 2010; Hasaninejad et al. 2011a, b; Elinson et al. 2008). However, most of these synthetic approaches have restrictions including the utilization of intense acidic or basic conditions, toxic or expensive catalysts or reagents, lower yields of the products and prolonged reaction times. Nevertheless, limited methods have been described for the synthesis of these compounds through the one-pot pseudo-five

component condensation reactions in the presence of a variety of catalyst such as pyridine trifluoroacetate (Soleimani et al. 2012), 2-hydroxyethylammonium propionate (2-HEAP) (Zhou and Zhang 2014), sulfonated rice husk ash (RHA-SO₃H) (Seddighi et al. 2013), *N*,2-dibromo-6-chloro-3,4-dihydro-2*H* benzo[*e*][1,2,4]thiadiazine-7-sulfonamide 1,1-dioxide (DCDBTSD) (Khazaei et al. 2014), silica-bonded *N*-propylpiperazine sulfamic acid (SBPPSA) (Tayebi and Niknam 2012), ultrasonic irradiation (Hasaninejad et al. 2013) and sulfonated nanohydroxyapatite functionalized with 2-aminoethyl dihydrogen phosphate (HAP@AEPH₂-SO₃H) (Zarghani and Akhlaghinia 2015a).

Considering the above points and as part of our continued interest in the development of efficient and environmentally benign heterogeneous catalysts (Zarghani and Akhlaghinia 2015a, b, 2016a, b; Razavi and Akhlaghinia 2015, 2016; Ghodsinia and Akhlaghinia 2015; Zarei and Akhlaghinia 2015; Jahanshahi and Akhlaghinia 2015, 2016; Yousefi Siavashi et al. 2016; Karimian et al. 2016; Ghodsinia et al. 2016), herein, we are willing to report a novel, green and efficient heterogeneous catalyst which was prepared through the immobilization of chlorosulfonic acid on Honeycomb Coral (HC) as a new, sustainable, green and natural platform (Scheme 1). The superior catalytic activity of sulfonated Honeycomb Coral (HC-SO₃H) was proved for the synthesis of 4,4'-(aryl methylene)-bis(3-methyl-1-phenyl-1*H*-pyrazol-5-ol)s via a one-pot pseudo-five component condensation reaction (see Scheme 2).

Experimental

All chemical reagents and solvents were purchased from Merck and Sigma-Aldrich chemical companies and were used as received without further purification. Honeycomb Coral was obtained from the Persian Gulf in Iran. The purity determinations of the products and the progress of the reactions were accomplished by TLC on silica gel polygram STL G/UV 254 plates. The melting points of the products were determined with an Electrothermal Type 9100 melting point apparatus. The FT-IR spectra were recorded on pressed KBr pellets using an AVATAR 370 FT-IR spectrometer



Scheme 1 Preparation of sulfonated Honeycomb Coral (HC-SO₃H)

(Thermo Nicolet spectrometer, USA) at room temperature in the range between 4000 and 400 cm^{-1} with a resolution of 4 cm^{-1} , and each spectrum was the average of 32 scans. NMR spectra were recorded on an NMR Bruker Avance spectrometer at 400 and 300 MHz in DMSO- d_6 as solvent in the presence of tetramethylsilane as internal standard and the coupling constants (J values) are given in Hz. Elemental analysis was performed using a Thermo Finnigan Flash EA 1112 Series instrument (furnace 900 °C, oven: 65 °C, flow carrier 140 mL min^{-1} , flow reference 100 mL min^{-1}). Mass spectra were recorded with a CH7A Varianmat Bremen instrument at 70 eV electron impact ionization, in m/z (rel %). The chemical compositions of the Honeycomb Coral were specified with X-ray fluorescence spectroscopy (XRF), using BRUKER axs-S4 EXPLORER spectrometer. The crystal structure of the catalyst was analyzed by XRD using a D8 ADVANCE-Bruker diffractometer operated at 40 kV and 30 mA, utilizing $\text{CuK}\alpha$ radiation ($\lambda = 0.154 \text{ \AA}$), at a step size of 0.040° and step time of 1.5 s. The diffraction angles (2θ) were scanned from 10° to 80° . Elemental compositions were determined with a Leo 1450 VP scanning electron microscope equipped with an SC7620 energy dispersive spectrometer (SEM-EDS) presenting a 133 eV resolution at 20 kV. Thermogravimetric analysis (TGA) was carried out using a Shimadzu Thermogravimetric Analyzer (TG-50) in the temperature range of 25–900 °C at a heating rate of $10 \text{ }^\circ\text{C min}^{-1}$, under air atmosphere. Nitrogen adsorption–desorption isotherms and BET analysis results were obtained using a Belsorp mini II system at $-196 \text{ }^\circ\text{C}$ utilizing N_2 as adsorbate. All yields refer to the isolated products after purification by recrystallization.

Pre-preparation of Honeycomb Coral

To remove the probable contaminants trapped inside the Honeycomb Coral structure, it was powdered thoroughly, followed by washing with distilled water several times and air-dried for 24 h.

Preparation of sulfonated Honeycomb Coral (HC-SO₃H)

Chlorosulfonic acid 0.4 mL (6.5 mmol) was added dropwise to a magnetically stirred mixture of Honeycomb Coral (1 g) in dry dichloromethane (20 mL), in an ice bath ($0 \text{ }^\circ\text{C}$). After a period of 20 min, the mixture was stirred for an additional 30 min at room temperature. Afterward, the suspension was filtered and washed with dichloromethane ($2 \times 15 \text{ mL}$) and dried at $50 \text{ }^\circ\text{C}$ for 1 h to afford the HC-SO₃H as a pale brown powder.

Typical procedure for preparation of 4,4'-(phenyl methylene) bis(3-methyl-1 phenyl-1H-pyrazol-5-ol)

A mixture of phenylhydrazine (2 mmol, 0.216 g), ethyl acetoacetate (2 mmol, 0.260 g) and HC-SO₃H (0.04 g) was stirred at $70 \text{ }^\circ\text{C}$ for 1 min. Then, benzaldehyde (1 mmol, 0.106 g) was added to the reaction mixture. The reaction was completed in less than 1 min, as monitored by TLC. After that, hot ethanol ($2 \times 5 \text{ mL}$) was poured to the reaction mixture and the mixture was stirred for additional 3 min. The resultant hot suspension was filtered off. The filtrate was cooled to room temperature and the crude product was precipitated. Thereafter, the crude product was purified by recrystallization from ethanol (0.42 g, 98%). In the following, to reuse the catalyst in the next runs, the solid residue (HC-SO₃H) was refluxed in EtOAc ($3 \times 10 \text{ mL}$) for 15 min and centrifuged consecutively. The recovered catalyst was then dried at $50 \text{ }^\circ\text{C}$ under vacuum for 2 h and reused for several times without significant loss of activity.

Results and discussion

Corals are marine invertebrates of the class Anthozoa, which are known as unique natural solids that can efficiently catalyze organic reactions (Roschat et al. 2012; Bigdeli et al. 2015), as well as have beneficial applications in medical (Hamza et al. 2013). The principal components of Corals are calcium carbonate (CaCO_3) and also chitin (Bennett et al. 2016; Juárez-de la Rosa et al. 2015). They are mostly found in clear tropical oceans such as the Indian Ocean, the Red Sea, the Gulf of Aden, the Persian Gulf, the East China Sea and the West and Central Pacific Oceans. The Coral species used in the present study is Honeycomb Coral (Fig. 1).

Characterization of the catalyst

HC-SO₃H as a novel potent and stable solid acid heterogeneous catalyst was synthesized according to Scheme 1. The chemical composition of Honeycomb Coral was determined by X-ray fluorescence analysis (XRF). Likewise, the structure and morphology of the newly synthesized catalyst were fully characterized by different techniques such as Fourier transform infrared (FT-IR) spectroscopy, thermogravimetric (TGA) analysis, scanning electron microscopy equipped with an energy dispersive spectrometry (SEM-EDS), X-ray powder diffraction (XRD), Brunauer, Emmett and Teller (BET) surface area analysis and pH analysis. The results obtained from these

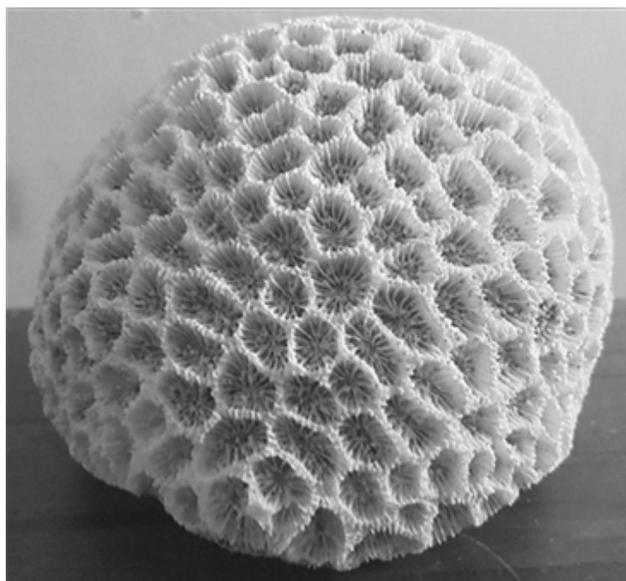


Fig. 1 The Honeycomb Coral image

techniques, confirmed the successful preparation of the new catalyst.

XRF analysis

The elemental composition analysis of Honeycomb Coral was determined by XRF spectroscopy (see electronic supplementary information). The obtained results showed that the predominant composition of Honeycomb Coral is CaO. Accordingly, the principal inorganic component of Honeycomb Coral is considered to be a natural calcium carbonate (CaCO_3).

FT-IR spectroscopy

To evaluate the incorporation of sulfonic groups on the Honeycomb Coral structure, FT-IR spectra of the respective Honeycomb Coral and HC- SO_3H have been investigated (Fig. 2). As can be clearly inferred from spectroscopic data, calcium carbonate and chitin are the main Honeycomb Coral components (Bennett et al. 2016; Juárez-de la Rosa et al. 2015). The FT-IR spectrum of Honeycomb Coral, shown in Fig. 2a exhibits the characteristic absorptions bands for aragonite phase (calcium carbonate) in the Honeycomb Coral structure, which are related to the planar CO_3^{2-} ions. There are four vibrational modes in the free CO_3^{2-} ions (Plavsic et al. 1999), which were established by the following absorption bands: ν_1 (for the split in-plane bending vibrations at about 711 cm^{-1}); ν_2 (for the out-of-plane bending absorption at about 852 cm^{-1}); ν_3 (for the symmetric

stretching vibration of the carbonate ion at about 1082 cm^{-1}); ν_4 (for the asymmetric stretching vibrations at about $1400\text{--}1500\text{ cm}^{-1}$).

In the case of the chitin segment of Honeycomb Coral, a broad peak centered at 3421 cm^{-1} represented the combined O–H and N–H stretching vibrations. Moreover, the adsorption band centered at 2922 cm^{-1} was attributed to the C–H stretching vibrations of CH_2 and CH_3 groups (Rwei and Lien 2014). The indicative absorption bands regarding to amide groups in the chitin structure are usually observed at 1662 cm^{-1} (amide I), 1550 cm^{-1} (amide II) and 1315 cm^{-1} (amide III) (Zarghani and Akhlaghinia 2016a). However, these absorption bands were covered by broad and strong asymmetric stretching vibrations of CO_3^{2-} ions (ν_4).

In the FT-IR spectrum of HC- SO_3H (Fig. 2b), the absorption bands at 593, 617 and 674 cm^{-1} can be assigned to the asymmetric bending vibrations of sulfate ions (Liu et al. 2009) that have been created as a result of ion exchange during the sulfonation process. In the other words, the appropriate exchange of carbonate ions with sulfate ions has occurred.

In addition, the FT-IR spectrum of HC- SO_3H shows the appearance of new absorption bands at about 1012, 1112, 1151 and 1174, which are attributed to the symmetric and asymmetric stretching frequencies of S=O in the sulfonated chitin. The spectrum also demonstrates a relatively broad band at around $3200\text{--}3600\text{ cm}^{-1}$ due to the OH stretching absorption of SO_3H groups. Furthermore, the stretching vibration band of C–N (related to the chitin groups), was observed around 1470 cm^{-1} (Zarghani and Akhlaghinia 2016a). Besides, the other strong chitin band at 858 cm^{-1} (related to $-\text{CH}_3$ in acetylamide groups) (Skołucka-Szary et al. 2016; Ehrlich et al. 2007) can be evidently perceived in Fig. 2b, c.

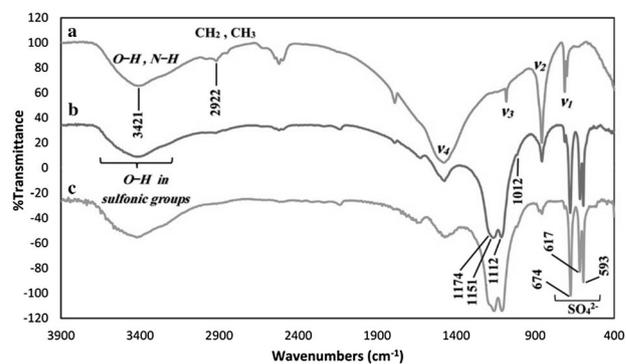


Fig. 2 FT-IR spectrum of **a** Honeycomb Coral; **b** HC- SO_3H and **c** 7th recovered HC- SO_3H

Thermogravimetric analysis

Thermogravimetric analysis (TGA) was performed to evaluate the thermal stability of bare Honeycomb Coral and the as-synthesized acidic catalyst (Fig. 3). As it is evident in Fig. 3a, TGA thermogram of Honeycomb Coral exhibited a weight loss of about 0.5% at temperatures below 100 °C corresponding to the removal of physically adsorbed water. The next weight loss of about 2.5% at 300 °C, is relating to the elimination of CO₂ from the Honeycomb Coral structure (Cuif et al. 2004). Also, the simultaneous release of H₂O in this temperature can be explained either by the decomposition of hydrated chitin or by water molecules strongly bound to the skeletal matrix which cannot be released at lower temperatures (Cuif et al. 2004). The most prominent weight loss starting at approximately 650 °C, is related to the decomposition of CaCO₃ to CaO (Cuif et al. 2004).

For HC-SO₃H, it is clear that there are three steps of weight loss (Fig. 3b). (1) Below 150 °C, the representative mass loss is ascribed to the removal of physically adsorbed water (about 3%). (2) Around 150–550 °C, a large weight loss occurred, which can be predominantly attributed to decomposition of SO₃H groups (Naeimi and Mohamadabadi 2014) (about 9%). (3) Above 550 °C, the occurrence of further mass losses at higher temperature resulted from the decomposition of the Honeycomb Coral structure (about 19%). According to the TGA thermogram, it can be estimated that the amount of sulfonic acid groups delivered to the Honeycomb Coral structure is about 0.82 mmol g⁻¹.

PH analysis

The total number concentrations of acidic sites of the HC-SO₃H were determined by acid–base back potentiometric

titration of the catalyst. For this purpose, 100 mg of catalyst was added to an aqueous solution of sodium hydroxide (0.1 N, 15 mL). Then, the resulting mixture was stirred at room temperature for 12 h. Finally, the leftover basic solution was filtered and the filtrate was neutralized using a standard solution of HCl (0.1 M). According to the consumed volume of HCl (14.2 mL), the number of acidic sites for HC-SO₃H was found to be 0.80 mmol g⁻¹. This result was in a good agreement with those obtained from TGA.

SEM–EDS analysis

Figure 4 depicts the scanning electron microscopy (SEM) images of non-powdered Honeycomb Coral (Fig. 4a), finely powdered Honeycomb Coral (Fig. 4b) and HC-SO₃H catalyst (Fig. 4c, d). Interestingly, SEM image of the cross-sectional disc of non-powdered Honeycomb Coral reveals a structure that looks like a honeycomb (Fig. 4a). In comparing Fig. 4b with Fig. 4c, d, the surface morphological changes were clearly observed on the material due to the modification process. In the other words, while the finely powdered Honeycomb Coral has a smoothed morphology (Fig. 4b), the surface of HC-SO₃H is rough to a certain extent. Accordingly, it can be concluded that the functionalization procedure has been accomplished successfully.

Energy dispersive spectrum (EDS) of HC-SO₃H (Fig. 5) indicates the presence of Ca, S and O as the main elements of HC-SO₃H structure. Beside these, a few other minerals were also found in low contents (Cl, Na, Mg and Si). This analysis approves the successful functionalization of the Honeycomb Coral (see also XRF results in electronic supplementary information).

Fig. 3 TGA thermograms of **a** Honeycomb Coral and **b** HC-SO₃H

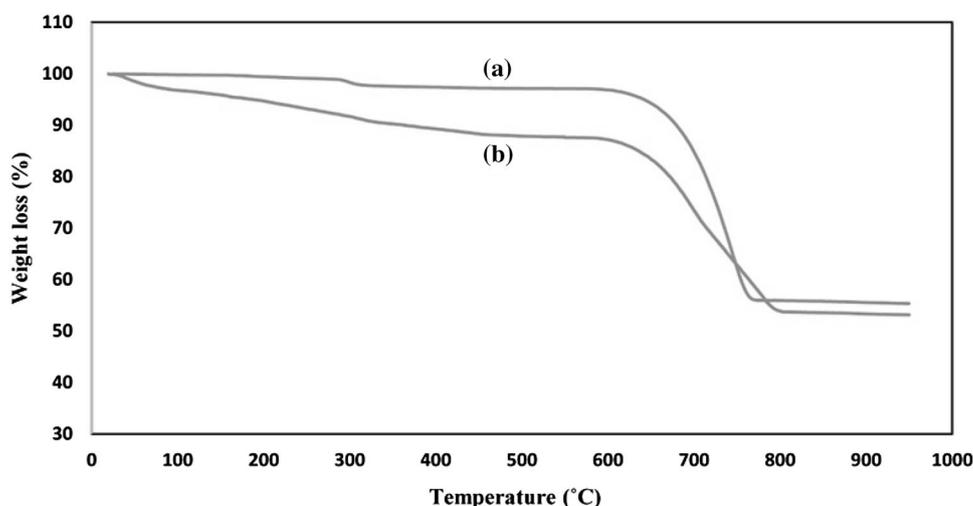


Fig. 4 SEM images of a cross-sectional disc of **a** non-powdered Honeycomb Coral; **b** finely powdered Honeycomb Coral and **c, d** HC-SO₃H

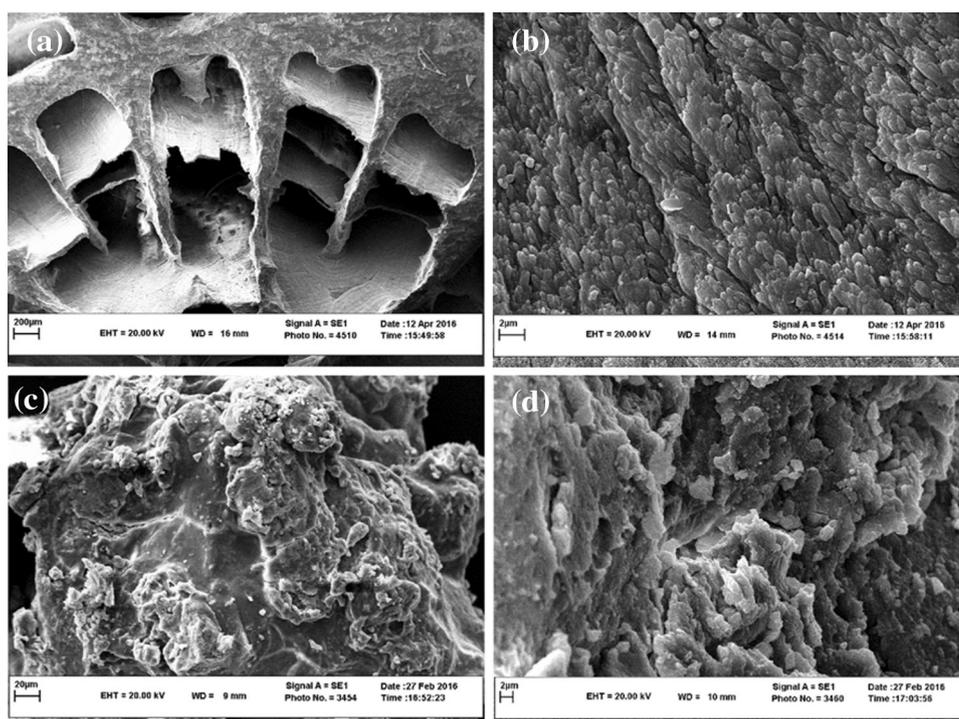
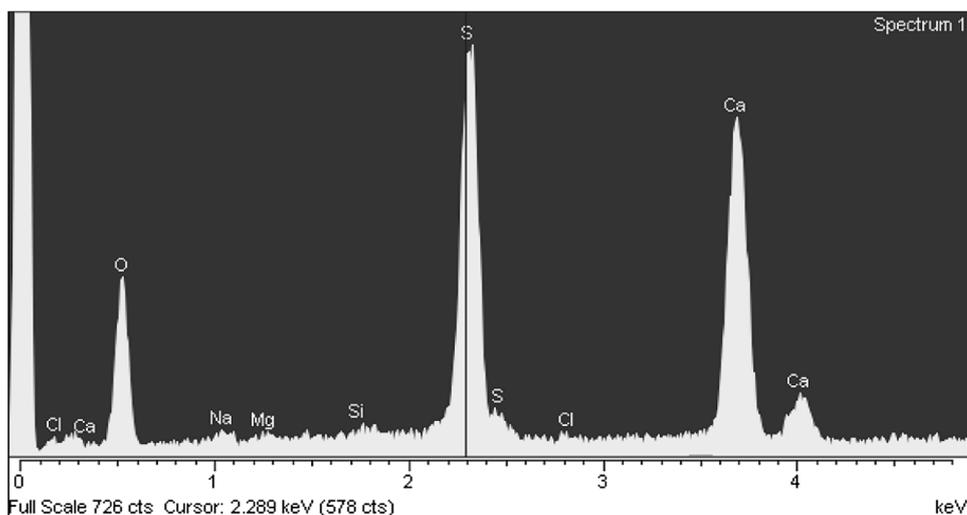


Fig. 5 EDS analysis of HC-SO₃H

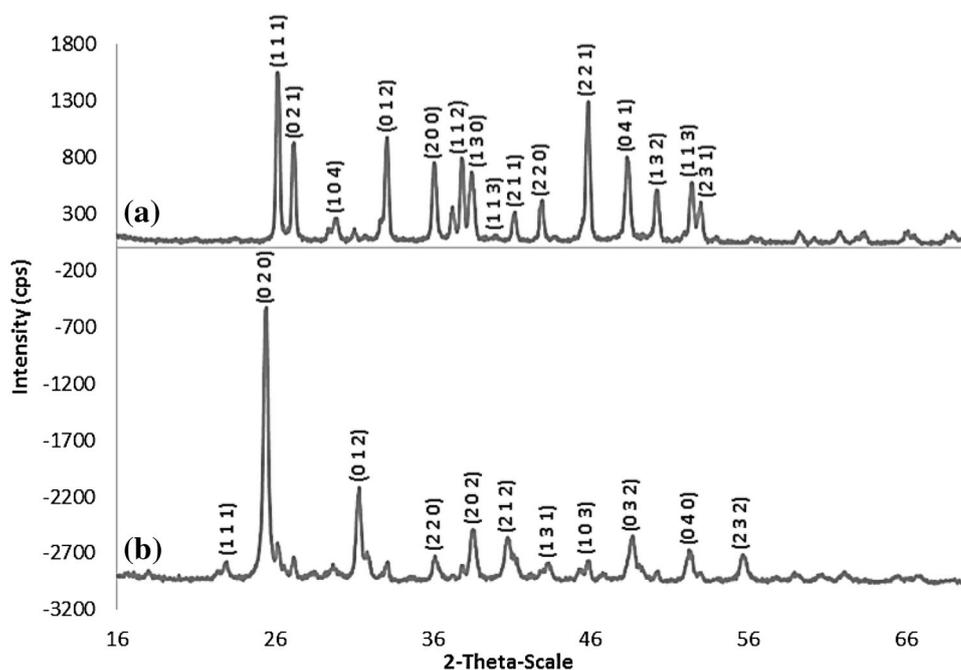


X-ray powder diffraction analysis

The crystallinity and phase identification of Honeycomb Coral and HC-SO₃H were determined using XRD. As illustrated in Fig. 6a, the most intense diffraction peaks appearing at angles corresponding to (1 1 1), (0 2 1), (0 1 2), (2 0 0), (1 1 2), (1 3 0), (2 1 1), (2 2 0), (2 2 1), (0 4 1), (1 3 2), (1 1 3) and (2 3 1) reflections were in good agreement with the standard pattern for crystalline aragonite (CaCO₃) with orthorhombic structure (JCPDS: 05-0453). In addition, weak diffraction peaks appeared at

angles attributing to (1 0 4) and (1 1 3) crystallographic faces, could be assigned to calcite (CaCO₃) XRD diffraction peaks (JCPDS: 05-0586). However, XRD analysis of HC-SO₃H (Fig. 6b) revealed that CaCO₃ with the orthorhombic crystalline structure was converted to CaSO₄ with preserving the orthorhombic crystalline structure (JCPDS: 37-1496). The results confirm that although the bona fide exchange of carbonate ions with sulfate ions has occurred, the crystalline structure of catalyst was maintained, under the conditions used for the modification process.

Fig. 6 XRD patterns of **a** Honeycomb Coral and **b** HC-SO₃H



BET analysis

The BET surface area measurement was conducted for Honeycomb Coral (HC) and sulfonated Honeycomb Coral (HC-SO₃H) (see electronic supplementary information). Table 1 illustrates the respective average surface area, pore volume and mean pore diameter of both HC and HC-SO₃H. The BET surface area, pore volume and pore diameter of HC are 120.25, 1.006 and 14.27, respectively. According to the obtained data from Table 1, it can be concluded that the introduction of sulfonic acid to the HC structure, shifted the pore diameter to the smaller amounts and also decreased the surface area and pore volume. These results confirm the successful modification of HC with chlorosulfonic acid.

Catalytic synthesis of 4,4'-(aryl methylene) bis(3-methyl-1H-pyrazol-5-ols)

On the basis of the information obtained from the studies on the natural Honeycomb Coral, we anticipated that this marine coral can be used as an efficient and green platform for heterogenization of sulfonic acid, to prepare a superlative solid acid

Table 1 Specific surface area (S_{BET}), pore volume and mean pore diameter of Honeycomb Coral (HC) and sulfonated Honeycomb Coral (HC-SO₃H)

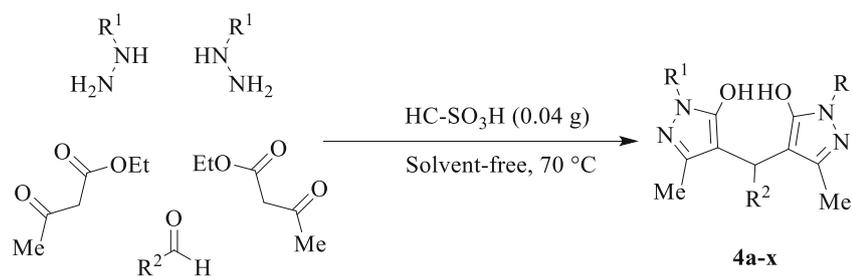
Sample	S_{BET} ($\text{m}^2 \text{g}^{-1}$)	Pore volume ($\text{cm}^3 \text{g}^{-1}$)	Mean pore diameter (nm)
HC	120.25	1.006	14.27
HC-SO ₃ H	90.38	0.504	12.67

catalyst which would promote the reactions that need an acidic catalyst to speed-up. So, we have investigated the applicability of HC-SO₃H in developing the rapid one-pot pseudo-five component synthesis of 4,4'-(aryl methylene)-bis-(3-methyl-1-phenyl-1H-pyrazol-5-ols) from phenylhydrazine/or hydrazine hydrate, ethyl acetoacetate and aldehydes (Scheme 2).

To find an appropriate reaction medium for the synthesis of these compounds in the presence of the catalytic amount of HC-SO₃H, one-pot pseudo-five component reaction between phenylhydrazine (2 mmol), ethyl acetoacetate (2 mmol) and benzaldehyde (1 mmol) was selected as a model reaction.

Various reaction conditions including different solvents, temperatures and amount of the catalyst were examined and the results are listed in Table 2. When the model reaction was carried out in the absence of catalyst, either in solvent-free condition or in H₂O, at temperature ranging from 70 to 90 °C, the progress of the reaction was sluggish, even after a long reaction time (Table 2, entry 1–4). Interestingly, by applying the model reaction at 70 °C, in the presence of 0.05 g of the HC-SO₃H, the desired product was obtained with excellent yield, in less than 1 min (Table 2, entry 5). This result denotes to the essential role of HC-SO₃H in the synthesis of 4,4'-(phenyl methylene)bis(3-methyl-1H-pyrazol-5-ol). Furthermore, the results show that the lower the reaction temperature, the less efficiently the reaction could proceed (Table 2, entries 6–8). However, any further increase in the temperature did not improve the reaction progress (Table 2, entry 9). To determine the optimal amount of catalyst, we have explored the model reaction at lower catalytic amounts of HC-SO₃H (0.04 and 0.03 g), under solvent-free conditions

Scheme 2 One-pot pseudo-five component synthesis of 4,4'-(aryl methylene)bis(3-methyl-1-phenyl-1*H*-pyrazol-5-ol)s in the presence of HC-SO₃H



R¹ = H, C₆H₅

R² = C₆H₅, 4-(F)C₆H₄, 4-(Cl)C₆H₄, 2-(Cl)C₆H₄, 2,4-(Cl)₂C₆H₃, 4-(Br)C₆H₄, 3-(NO₂)C₆H₄, 2-(NO₂)C₆H₄, 4-(OH)C₆H₄, 3-(OH)C₆H₄, 2-(OH)C₆H₄, 4-(OMe)C₆H₄, 3-(OMe)C₆H₄, 4-(Me)C₆H₄, 3-(Me)C₆H₄, 5-(Br)-2-(OH)C₆H₃, 4-(ⁱPr)C₆H₄, 1-Naphthyl, 3-Pyridyl, 2-Pyridyl, C₆H₅CH=CH

Table 2 Synthesis of 4,4'-(phenyl methylene)bis(3-methyl-1*H*-pyrazol-5-ol) in the presence of HC-SO₃H, under different reaction conditions

Entry	Catalyst (g)	Solvent	Temperature (°C)	Time (min)	Isolated yield (%)
1	–	Solvent-free	70	36 h	15
2	–	Solvent-free	90	36 h	15
3	–	H ₂ O	70	36 h	15
4	–	H ₂ O	90	36 h	15
5	0.05	Solvent-free	70	<1	98
6	0.05	Solvent-free	60	10	90
7	0.05	Solvent-free	40	20	65
8	0.05	Solvent-free	r.t.	4 h	40
9	0.05	Solvent-free	80	<1	98
10	0.04	Solvent-free	70	<1	98
11	0.03	Solvent-free	70	10	94
12	0.04	H ₂ O	70	15	78
13	0.04	EtOH	70	25	72
14	0.04	H ₂ O/EtOH (1:1)	70	25	68
15 ^a	0.04	Solvent-free	70	5 h	25
16 ^b	0.04	Solvent-free	70	5 h	15
17 ^c	0.04	Solvent-free	70	2 h	79
18 ^d	0.04	Solvent-free	70	7 h	15

^a The reaction was performed in the presence of the thoroughly powdered Honeycomb Coral

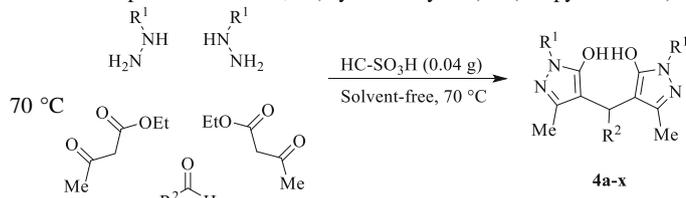
^b The reaction was performed in the presence of the non-powdered Honeycomb Coral

^c The reaction was performed in the presence of the non-powdered sulfonated Honeycomb Coral

^d The reaction was performed in the presence of the CaCO₃

at 70 °C (Table 2, entries 10, 11). The results revealed that 0.04 g of HC-SO₃H was found to be the optimum amount of catalyst in terms of yield and reaction time (Table 2, entry 10). Likewise, the reaction was carried out in solvents such as H₂O, EtOH and H₂O/EtOH (1:1). The slow rate of such a transformation in the presence of these solvents (maybe due to the solvation effects), offered that the solvent-free condition is more appropriate to improve the reaction rate, in this protocol (Table 2, entry 10). In another experiment, the activity of the intact Honeycomb Coral both in the thoroughly powdered form (as we have utilized it in our study) and also

the non-powdered form was tested for the same reaction condition and only a scant yield of the product was obtained (Table 2, entry 15, 16). To get more insight into the impact of the structural form of the prime Honeycomb Coral on the final catalyst activity, the sulfonation process was implemented on the non-powdered form of the Honeycomb Coral (exactly based on the mentioned procedure in the experimental section) and next the model reaction was conducted in the presence of the non-powdered HC-SO₃H as catalyst. As it is clear in Table 2, the results were far from satisfactory in this context (Table 2, entry 17). These findings suggested that

Table 3 Preparation of 4,4'-(aryl methylene)bis(1*H*-pyrazol-5-ol)s catalyzed by HC-SO₃H under solvent-free conditions at


Entry	R ¹	R ²	Product	Time (min)	Isolated yield (%)	M.p. (°C) Found reported (references)
1	C ₆ H ₅	C ₆ H ₅	4a	<1	98	173–174 171–172 (Hasaninejad et al. 2011a)
2	C ₆ H ₅	4-FC ₆ H ₄	4b	<1	98	180–181 180–182 (Keshavarz and Vafaei-Nezhad 2016)
3	C ₆ H ₅	4-ClC ₆ H ₄	4c	<1	97	205–207 207–209 (Hasaninejad et al. 2011a)
4	C ₆ H ₅	2-ClC ₆ H ₄	4d	18	84	235–237 236–237 (Hasaninejad et al. 2011a)
5	C ₆ H ₅	2,4-(Cl) ₂ C ₆ H ₃	4e	5	82	227–229 229–231 (Keshavarz and Vafaei-Nezhad 2016)
6	C ₆ H ₅	4-BrC ₆ H ₄	4f	<1	95	181–183 183–185 (Hasaninejad et al. 2011a)
7	C ₆ H ₅	3-NO ₂ C ₆ H ₄	4g	5	83	148–149 150–151 (Zolfigol et al. 2015)
8	C ₆ H ₅	2-NO ₂ C ₆ H ₄	4h	8	83	219–221 222–224 (Zolfigol et al. 2015)
9	C ₆ H ₅	4-OHC ₆ H ₄	4i	2	96	159–160 160–162 (Thummar et al. 2014)
10	C ₆ H ₅	3-OHC ₆ H ₄	4j	3	96	166–167 165–168 (Niknam et al. 2010)
11	C ₆ H ₅	2-OHC ₆ H ₄	4k	7	92	225–226 227–228 (Zolfigol et al. 2015)
12	C ₆ H ₅	4-OMeC ₆ H ₄	4l	<1	97	172–174 171–173 (Nader Ghaffari et al. 2016)
13	C ₆ H ₅	3-OMeC ₆ H ₄	4m	10	95	179–181 180–182 (Phatangare et al. 2012)
14	C ₆ H ₅	4-MeC ₆ H ₄	4n	8	95	202–204 203–205 (Keshavarz and Vafaei-Nezhad 2016)
15	C ₆ H ₅	3-MeC ₆ H ₄	4o	12	87	236–237 238–241 (Karimi-Jaberi et al. 2012)
16	C ₆ H ₅	5-Br-2-OHC ₆ H ₃	4p	10	91	265–267 266–268 (Baghernejad and Niknam 2012)
17	C ₆ H ₅	4- ⁱ PrC ₆ H ₄	4q	15	83	134–136 132–134 (Keshavarz and Vafaei-Nezhad 2016)
18	C ₆ H ₅	1-Naphthyl	4r	5	93	210–212 213–215 (Zolfigol et al. 2015)
19	C ₆ H ₅	3-Pyridyl	4s	7	90	238–239 238–240 (Niknam et al. 2013)
20	C ₆ H ₅	2-Pyridyl	4t	4	95	230–233 228–231 (Moosavi-Zare et al. 2013)
21	C ₆ H ₅	C ₆ H ₅ CH = CH ₂	4u	10	88	217–219 220–222 (Zarghani and Akhlaghinia 2015a)
22	H	C ₆ H ₅	4v	12	95	231–233 228–230 (Nader Ghaffari et al. 2016)
23	H	4-ClC ₆ H ₄	4w	7	94	223–225 224–226 (Nader Ghaffari et al. 2016)
24	H	4-MeC ₆ H ₄	4x	15	89	197–199 202–204 (Nader Ghaffari et al. 2016)

the sulfonation process was much better done for the thoroughly powdered Honeycomb Coral. This might be due to the more available surface area and also porosity of the thoroughly powdered Honeycomb Coral (see BET analysis results in Table 1), in comparison with the non-powdered one, that improves the successful incorporation of the sulfonic groups on its structure. In continuing our study, by considering calcium carbonate as the main inorganic component of Honeycomb Coral (see XRF results in electronic supplementary information), we decided to probe the reactivity of CaCO₃ as catalyst in this transformation. As demonstrated in Table 2, the desired product was poorly obtained in the presence of CaCO₃ under solvent-free conditions at 70 °C (Table 2, entry 18). These results confirm the superior catalytic performance of the sulfonated Honeycomb Coral (HC-SO₃H), in this protocol. Afterward, in a separate experiment, to compare the catalytic activity of HC-SO₃H with its

homogenous counterparts, the model reaction was performed under the optimized conditions in the presence of chlorosulfonic acid, *p*-toluene sulfonic acid and methane-sulfonic acid, respectively. It was observed that the catalytic activity of ClSO₃H, PTSA and MeSO₃H was very close to HC-SO₃H and the corresponding product was obtained in less than one minute, in excellent isolated yield (98%). However, as previously mentioned, the main challenging problems in using such catalysts are their homogeneous feature which leads to difficult and expensive catalyst recovery process, along with their corrosive nature that makes a troublesome handling. Nevertheless, these problems have been eliminated in the HC-SO₃H as a new heterogeneous catalytic system.

Using the optimized reaction conditions, the activity of HC-SO₃H as catalyst was further confirmed in the green and efficient preparation of 4,4'-(aryl methylene)bis(1*H*-pyrazol-5-ol)s (Table 3). For this purpose, phenyl hydrazine/or

hydrazine (2 mmol) and ethyl acetoacetate (2 mmol) were treated with a broad range of structurally diverse aromatic aldehydes (1 mmol) in the presence of HC-SO₃H to achieve the intended products. This study showed that both electron poor (Table 3, entries 2–8) and electron rich (Table 3, entries 9–18) aromatic aldehydes afforded the corresponding products rapidly, in excellent isolated yields. It is noteworthy that heteroaromatic aldehydes such as pyridine carboxaldehydes and allylic aldehydes such as cinnamaldehyde led to the desired products, as well (Table 3, entries 19–21). Satisfactorily, we found that utilizing hydrazine instead of phenylhydrazine in this transformation also resulted in the rapid formation of the intended products, in high yields (Table 3, entries 22–24).

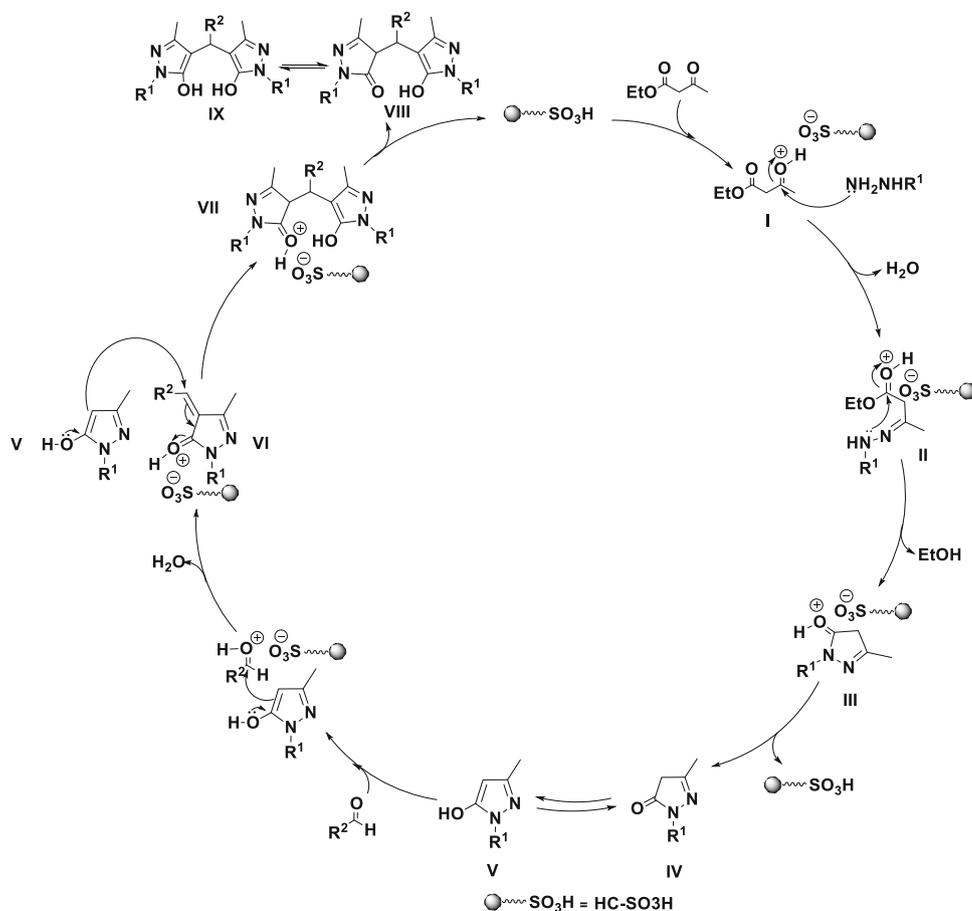
All of the synthesized products (**4a–x**) were known compounds and their structures were confirmed by comparison of their melting points, FT-IR spectroscopy and ¹H NMR spectroscopy with those of authentic compounds. Likewise, the selected compounds were further identified by ¹³C NMR spectroscopy, mass spectrometry and elemental analysis (see electronic supplementary information). It is noteworthy that in the FT-IR spectrum of all purified products the appearance of absorption bands at about 3450–2500, 1600 and 1499 cm⁻¹ was assigned to

OH, C=N and C=C bonds, respectively. Moreover, the ¹H NMR spectra displayed a sharp singlet resonating at around 5.50–4.89 ppm attributed to aryl methylene proton and also two broad peaks around 13.91 and 12.40 ppm, that revealed two –OH groups. Besides, the existence of a signal at 32 ppm in ¹³C NMR spectra of the products, is allocated to aryl methylene carbon. The elemental analysis of the synthesized compounds was also in a very good conformity with the presented structures. To more clarification of the products structures, mass spectrometry was carefully evaluated. As can be seen in the mass spectra, molecular ion was not obvious in some cases which was related to the very facile cleavage of C–C bond between aryl methylene carbon and pyrazole ring. However, some useful fragmentation information for each compound has been found, which can be beneficial for the verification of the desired products.

By analogy with our investigation, a plausible mechanism for the synthesis of 4,4'-(phenyl methylene)bis(3-methyl-1*H*-pyrazol-5-ol) derivatives in the presence of HC-SO₃H catalyst is proposed in Scheme 3.

According to this mechanism, the initial condensation reaction between phenylhydrazine/hydrazine and protonated form of ethyl acetoacetate (**I**), eventually leads to the

Scheme 3 Plausible mechanism for the one-pot pseudo-five component synthesis of 4,4'-(phenyl methylene)bis(3-methyl-1*H*-pyrazol-5-ol) using HC-SO₃H catalyst



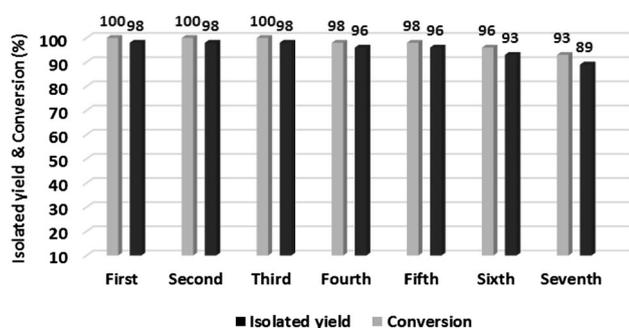


Fig. 7 Synthesis of 4,4'-(phenyl methylene)bis(3-methyl-1*H*-pyrazol-5-ol) in the presence of the reused HC-SO₃H

formation of pyrazolone (**IV**), which is in equilibrium with its tautomeric form (**V**). In the next step, the condensation reaction between intermediate **V** and aldehyde in the acidic condition, followed by dehydration, affords intermediate **VI**. Thereupon, a Michael addition reaction between **V** and **VI** happens to furnish the product **VIII** which undergoes a tautomeric proton shift to deliver the desired product (**IX**). Afterward, the released acidic catalyst re-enters the catalytic cycle. It is assumed that the main catalytic performance of catalyst was implemented through the sulfonated active sites on the chitin matrix and the calcium sulfate groups existing in its inorganic matrix, as well. Further studies to elucidate the details of the mechanism are ongoing.

The reusability of the catalyst is a very important subject, particularly for commercial and industrial applications. Therefore, the recovery and reusability of HC-SO₃H were scrutinized for the synthesis of 4,4'-(phenyl methylene)bis(3-methyl-1*H*-pyrazol-5-ol), under the optimized reaction conditions. Upon completion of the reaction, the heterogeneous catalyst was easily separated from the reaction mixture by vacuum filtration, followed by washing with ethanol sequentially to remove the organic

compounds and dried at 70 °C for 1 h. Next, the recovered catalyst was reused in the consecutive runs, under the same reaction conditions. The catalyst was successfully used in seven subsequent reactions with undiminished efficiency (Fig. 7). The average isolated yield of the product for seven consecutive runs was 93.8%, which clearly proves the outstanding practical reusability of the present catalyst.

According to the FT-IR spectrum of the 7th recovered HC-SO₃H (Fig. 2c), all of the characteristic peaks are well preserved in terms of shape, position and relative intensity, which is another evidence that demonstrates no substantial changes occurred in the chemical structure of functional groups and hydrogen bonding network of the catalyst.

The catalytic efficiency of HC-SO₃H was compared with the previously reported catalysts in literature that have been employed for the one-pot pseudo-five component preparation of 4,4'-(phenyl methylene)bis(3-methyl-1*H*-pyrazol-5-ol) and the related results are listed in Table 4. Although, each of these methods has their own advantages, but they often suffer from one or more of the following drawbacks, such as higher temperatures (Zhou and Zhang 2014; Seddighi et al. 2013; Khazaei et al. 2014; Tayebi and Niknam 2012; Zarghani and Akhlaghinia 2015a), certain and difficult reaction conditions as ultrasonic irradiation along with using organic solvent (Hasaninejad et al. 2013), require longer reaction times to achieve reasonable yield of the product (Zhou and Zhang 2014; Seddighi et al. 2013; Khazaei et al. 2014; Tayebi and Niknam 2012; Hasaninejad et al. 2013; Zarghani and Akhlaghinia 2015a) and most importantly, the necessity of applying strict condition (Zhou and Zhang 2014; Seddighi et al. 2013; Khazaei et al. 2014; Tayebi and Niknam 2012; Hasaninejad et al. 2013; Zarghani and Akhlaghinia 2015a) and expensive precursors (Zhou and Zhang 2014; Khazaei et al. 2014; Tayebi and Niknam 2012; Hasaninejad et al. 2013; Zarghani and Akhlaghinia 2015a) to prepare the corresponding catalysts.

Table 4 A comparative study regarding the catalytic efficiency of HC-SO₃H and some previously reported catalytic systems, in the one-pot pseudo-five component synthesis of 4,4'-(phenyl methylene)bis(3-methyl-1*H*-pyrazol-5-ol)

Entry	Catalyst	Reaction conditions	Yield (%)	References
1	2-HEAP ^a	Solvent-free, 90 °C, 30 min	91	Zhou and Zhang (2014)
2	RHA-SO ₃ H	Solvent-free, 80 °C, 3 min	91	Seddighi et al. (2013)
3	DCDBTSD ^b	Solvent-free, 80 °C, 100 min	74	Khazaei et al. (2014)
4	SBPPSA ^c	Solvent-free, 80 °C, 45 min	93	Tayebi and Niknam (2012)
5	–	Ultrasonic irradiation, H ₂ O/EtOH (1:1), r.t., 15 min	98	Hasaninejad et al. (2013)
6	HAP@AEPH ₂ -SO ₃ H ^d	Solvent-free, 80 °C, 3 min	98	Zarghani and Akhlaghinia (2015a)
7	HC-SO ₃ H	Solvent-free, 70 °C, <1 min	98	Present study

^a 2-Hydroxy ethylammonium propionate

^b *N*,2-Dibromo-6-chloro-3,4-dihydro-2*H* benzo[*e*][1,2,4]thiadiazine-7-sulfonamide 1,1-dioxide

^c Silica-bonded *N*-propylpiperazine sulfamic acid

^d Sulfonated nanohydroxyapatite functionalized with 2-aminoethyl dihydrogen phosphate

However, compared with these catalytic systems, the current work shows unique advantages such as simplification of the catalyst system and its synthesis and the application of inexpensive natural, nontoxic and available precursor for the preparation of a green and highly efficient heterogeneous catalyst with ease of handling, as well as the fast and clean synthetic route and also the milder reaction conditions.

Conclusions

In conclusion, we have introduced HC-SO₃H as a novel, green and highly powerful heterogeneous and recoverable solid acid catalyst. The as-synthesized catalyst was fully characterized by XRF, FT-IR, TGA, SEM-EDS, XRD and pH analysis and then was utilized for simple, efficient and rapid one-pot pseudo-five component synthesis of 4,4'-(aryl methylene)bis(1*H*-pyrazol-5-ol)s. The promising features that have distinguished this approach from other reported methods regarding this transformation are using the highly efficient, green, inexpensive, easy handling and recoverable catalyst, as well as simple reaction work-up, which make the present methodology more economical and industrially important. Furthermore, excellent yields, quick reaction times and non-toxicity of the catalyst, besides the solvent-free conditions are the other advantages that support the present method towards the green chemistry, as well.

Acknowledgements The authors gratefully acknowledge the partial support of this study by Ferdowsi University of Mashhad Research Council (Grant no. p/3/39490).

References

- Abbasi-Tarighat M, Shahbazi E, Niknam K (2013) Simultaneous determination of Mn²⁺ and Fe³⁺ as 4,4'[(4-chlorophenyl)methylene] bis(3-methyl-1-phenyl-1*H*-pyrazol-5-ol) complexes in some foods, vegetable and water samples by artificial neural networks. *Food Chem* 138:991–997
- Acharya BN, Saraswat D, Tiwari M, Shrivastava AK, Ghorpade R, Apna S, Kaushik MP (2010) Synthesis and antimalarial evaluation of 1, 3, 5-trisubstituted pyrazolines. *Eur J Med Chem* 45:430–438. doi:10.1016/j.ejmech.2009.10.023
- Ahmed N, Siddiqui ZN (2014) Sulphated silica tungstic acid as a highly efficient and recyclable solid acid catalyst for the synthesis of tetrahydropyrimidines and dihydropyrimidines. *J Mol Catal A Chem* 387:45–56. doi:10.1016/j.molcata.2014.02.019
- Anastas PT, Williamson TC (1998) *Green chemistry: frontiers in benign chemical synthesis and process*. Oxford University Press, Oxford
- Antre RV, Cendilkumar A, Nagarajan R, Goli D, Oswal RJ (2012) Synthesis, antitumor and antimicrobial activities of some novel 1-(substituted)-3-methyl-1*H*-pyrazol-5(4*H*)-one. *J Sci Res* 4:183–192. doi:10.3329/jsr.v4i1.7027
- Armstrong HE, Glover WH (1908) Studies on Enzyme Action. XI.-Hydrolysis of Raffinose by Acids and Enzymes. *Proc R Soc Lond Ser B* 80:312–321
- Baghernejad M, Niknam K (2012) Synthesis of 4,4'-(aryl-methylene)bis(1*H*-pyrazol-5-ols) using silica-bonded ionic liquid as recyclable catalyst. *Int J Chem* 4:52–60. doi:10.5539/ijc.v4n3p52
- Bailey DM, Hansen PE, Hlavac AG, Baizman ER, Pearl J, Defelice AF, Feigenson ME (1985) 3,4-Diphenyl-1*H*-pyrazole-1-propylamine antidepressants. *J Med Chem* 28:256–260. doi:10.1021/jm00380a020
- Behr LC, Fusco R, Jarboe CH (1967) The chemistry of heterocyclic compounds, pyrazoles, pyrazolines, pyrazolidines, indazoles and condensed rings. In: Weissberger A (ed), vol 7. Interscience Publishers, New York
- Bennett JA, Wilson K, Lee AF (2016) Catalytic applications of waste derived materials. *J Mater Chem A* 4:3617–3637. doi:10.1039/C5TA09613H
- Bigdeli MR, Shushizadeh MR, Mohandespur B (2015) The Persian Gulf Calcinic Coral, *Acropora* species: an efficient catalyst for aldol condensation. *Jundishapur J Nat Pharmaceut Prod* 10:26073–26078. doi:10.17795/jjnpp-26073
- Carlsson KH, Jurna I (1987) The role of descending inhibition in the antinociceptive effects of the pyrazolone derivatives, metamizol (dipyrone) and aminophenazone (“Pyramidon”). *Naunyn-Schmiedeberg's Arch Pharmacol* 335:154–159. doi:10.1007/BF00177717
- Cuif JP, Dauphin Y, Berthet P, Jegoudez J (2004) Associated water and organic compounds in coral skeletons: quantitative thermogravimetry coupled to infrared absorption spectrometry. *Geochim Geophys Geosyst* 5:1–9. doi:10.1029/2004GC000783
- Dabral S, Nishimura S, Ebitani K (2014) One-pot conversions of raffinose into furfural derivatives and sugar alcohols by using heterogeneous catalysts. *ChemSusChem* 7:260–267. doi:10.1002/cssc.201300939
- Ehrlich H, Krautter M, Hanke T, Simon P, Knieb C, Heinemann S, Worch H (2007) First evidence of the presence of chitin in skeletons of marine sponges. Part II. Glass sponges (Hexactinellida: Porifera). *J Exp Zool Part B* 308:347–356. doi:10.1002/jez.b.21174
- Elguero J (1996) *Comprehensive heterocyclic chemistry II*. In: Katritzky AR, Rees CW, Scriven EFV (eds), vol 3. Pergamon Press, Oxford
- Elinson MN, Dorofeev AS, Nasybullin RF, Nikishin GI (2008) Facile and convenient synthesis of 4,4'-(arylmethylene)bis(1*H*-pyrazol-5-ols) by electrocatalytic tandem Knoevenagel–Michael reaction. *Synthesis*, 1933–1937. doi:10.1055/s-2008-1067079
- Ghodsinia SSE, Akhlaghinia B (2015) A rapid metal free synthesis of 5-substituted-1*H*-tetrazoles using cuttlebone as a natural high effective and low cost heterogeneous catalyst. *RSC Adv* 5:49849–49860. doi:10.1039/C5RA08147E
- Ghodsinia SSE, Akhlaghinia B, Jahanshahi R (2016) Direct access to stabilized CuI using cuttlebone as a natural-reducing support for efficient CuAAC click reactions in water. *RSC Adv* 6:63613–63623. doi:10.1039/C6RA13314B
- González MD, Cesteros Y, Llorca J, Salagre P (2012) Boosted selectivity toward high glycerol tertiary butyl ethers by microwave-assisted sulfonic acid-functionalization of SBA-15 and beta zeolite. *J Catal* 290:202–209. doi:10.1016/j.jcat.2012.03.019
- Haile SM, Boysen DA, Chisholm CRI, Merle RB (2001) Solid acids as fuel cell electrolytes. *Nature* 410:910–913. doi:10.1038/35073536
- Hamama WS (2001) Pyrazolones as versatile precursors for the synthesis of fused and binary heterocycles. *Synth Commun* 31:1335–1345. doi:10.1081/SCC-100104042

- Hamza S, Slimane N, Azari Z, Pluvina G (2013) Structural and mechanical properties of the coral and nacre and the potentiality of their use as bone substitutes. *Appl Surf Sci* 264:485–491. doi:10.1016/j.apsusc.2012.10.049
- Hara M, Yoshida T, Takagaki A, Takata T, Kondo JN, Hayashi S, Domen K (2004) A carbon material as a strong protonic acid. *Angew Chem Int Ed* 43:2955–2958. doi:10.1002/anie.200453947
- Hasaninejad A, Shekouhy M, Zare A, Hoseini Ghattali SMS, Golzar N (2011a) PEG-SO₃H as a new, highly efficient and homogeneous polymeric catalyst for the synthesis of bis(indolyl)methanes and 4,4'-(arylmethylene)-bis(3-methyl-1-phenyl-1H-pyrazol-5-ols) in water. *J Iran Chem Soc* 8:411–423. doi:10.1007/BF03249075
- Hasaninejad A, Zare A, Shekouhy M, Golzar N (2011b) Efficient synthesis of 4,4'-(arylmethylene)-bis(3-methyl-1-phenylpyrazol-5-ol) derivatives in PEG-400 under catalyst-free conditions. *Org Prep Proc Int* 43:131–137. doi:10.1080/00304948.2010.526827
- Hasaninejad A, Rasekhi Kazerooni M, Zare A (2013) Room-temperature, catalyst-free, one-pot pseudo-five-component synthesis of 4,4'-(arylmethylene)-bis(3-methyl-1-phenyl-1H-pyrazol-5-ols) under ultrasonic irradiation. *ACS Sustain Chem Eng* 1:679–684. doi:10.1021/sc400081c
- Hosseini MM, Kolvari E, Koukabi N, Ziyaei M, Zolfigol MA (2016) Zirconia sulfuric acid: an efficient heterogeneous catalyst for the one-pot synthesis of 3,4-dihydropyrimidinones under solvent-free conditions. *Catal Lett* 146:1040–1049. doi:10.1007/s10562-016-1723-8
- Jahanshahi R, Akhlaghinia B (2015) Expanded perlite: an inexpensive natural efficient heterogeneous catalyst for the green and highly accelerated solvent-free synthesis of 5-substituted-1H-tetrazoles using [bmim]N₃ and nitriles. *RSC Adv* 5:104087–104094. doi:10.1039/C5RA21481E
- Jahanshahi R, Akhlaghinia B (2016) Cu^{II} immobilized on guanidinated epibromohydrin functionalized γ -Fe₂O₃@TiO₂ (γ -Fe₂O₃@TiO₂-EG-Cu^{II}): a novel magnetically recyclable heterogeneous nanocatalyst for the green one-pot synthesis of 1,4-disubstituted 1,2,3-triazoles through alkyne-azide cycloaddition in water. *RSC Adv* 6:29210–29219. doi:10.1039/C6RA05468D
- Juárez-de la Rosa BA, May-Crespo J, Quintana-Owen P, González-Gómez WS, Yañez-Limón JM, Alvarado-Gil JJ (2015) Thermal analysis and structural characterization of chitinous exoskeleton from two marine invertebrates. *Thermochim Acta* 610:16–22. doi:10.1016/j.tca.2015.04.015
- Karimian E, Akhlaghinia B, Ghodsini SSE (2016) An efficient and convenient synthesis of N-substituted amides under heterogeneous condition using Al(H₂O)₄ via Ritter reaction. *J Chem Sci* 128:429–439. doi:10.1007/s12039-016-1036-x
- Karimi-Jaberi Z, Pooladian B, Moradi M, Ghasemi E (2012) 1,3,5-tris(hydrogensulfato) benzene: a new and efficient catalyst for synthesis of 4,4'-(arylmethylene)bis(1H-pyrazol-5-ol) derivatives. *Chin J Catal* 33:1945–1949. doi:10.1016/S1872-2067(11)60477-4
- Keshavarz M, Vafaei-Nezhad M (2016) Design and characterization of l-proline-amberlite as a novel heterogeneous organocatalyst and its catalytic application in the synthesis of pyrazol-derivates. *Catal Lett* 146:353–363. doi:10.1007/s10562-015-1668-3
- Khazaei A, Abbasi F, Moosavi-Zare AR (2014) Tandem cyclocondensation-Knoevenagel-Michael reaction of phenyl hydrazine, acetoacetate derivatives and arylaldehydes. *N J Chem* 38:5287–5292. doi:10.1039/C4NJ01079E
- Kolvari E, Koukabi N, Hosseini MM (2015) Perlite: a cheap natural support for immobilization of sulfonic acid as a heterogeneous solid acid catalyst for the heterocyclic multicomponent reaction. *J Mol Catal A Chem* 397:68–75. doi:10.1016/j.molcata.2014.10.026
- Kuo CH, Poyraz AS, Jin L, Meng Y, Pahalagedara L, Chen SY, Kriz DA, Guild C, Gudz A, Suib SL (2014) Heterogeneous acidic TiO₂ nanoparticles for efficient conversion of biomass derived carbohydrates. *Green Chem* 16:785–791. doi:10.1039/C3GC40909K
- Lecher HZ (1955) The chemistry of synthetic dyes and pigments. *J Am Chem Soc* 77:6089. doi:10.1021/ja01627a110
- Liu Y, Wang A, Freeman JJ (2009) 40th lunar and planetary science conference. Washington University, Saint Louis, p 2128
- Londershausen M (1996) Review: approaches to new parasiticides. *Pestic Sci* 48:269–292. doi:10.1002/(SICI)1096-9063(199612)48:4<269:AID-PS478>3.0.CO;2-B
- Mahajan RN, Havaladar FH, Fernandes PS (1991) Syntheses and biological activity of heterocycles derived from 3-methoxy-1-phenyl-1H-pyrazole-5-carboxylate. *J Indian Chem Soc* 68:245–246
- Melero JA, van Grieken R, Morales G (2006) Advances in the synthesis and catalytic applications of organosulfonic-functionalized mesostructured materials. *Chem Rev* 106:3790–3812. doi:10.1021/cr050994h
- Mobaraki A, Movassagh B, Karimi B (2014) Hydrophobicity-enhanced magnetic solid sulfonic acid: a simple approach to improve the mass transfer of reaction partners on the surface of the heterogeneous catalyst in water-generating reactions. *Appl Catal A* 472:123–133. doi:10.1016/j.apcata.2013.12.018
- Moosavi-Zare AR, Zolfigol MA, Zarei M, Zare A, Khakyzadeh V, Hasaninejad A (2013) Design, characterization and application of new ionic liquid 1-sulfonypyridinium chloride as an efficient catalyst for tandem Knoevenagel-Michael reaction of 3-methyl-1-phenyl-1H-pyrazol-5(4H)-one with aldehydes. *Appl Catal A* 467:61–68. doi:10.1016/j.apcata.2013.07.004
- Nader Ghaffari K, Sharifah Bee Abd H, Salam JJ (2016) N-Methylimidazolium perchlorate as a new ionic liquid for the synthesis of bis(pyrazol-5-ols) under solvent-free conditions. *Chin Chem Lett* 27:104–108. doi:10.1016/j.ccllet.2015.07.027
- Naeimi H, Mohamadabadi S (2014) Sulfonic acid-functionalized silica-coated magnetic nanoparticles as an efficient reusable catalyst for the synthesis of 1-substituted 1H-tetrazoles under solvent-free conditions. *Dalton Trans* 43:12967–12973. doi:10.1039/C4DT01664E
- Niknam K, Saberi D, Sadegheyan M, Deris A (2010) Silica-bonded S-sulfonic acid: an efficient and recyclable solid acid catalyst for the synthesis of 4,4'-(arylmethylene)bis(1H-pyrazol-5-ols). *Tetrahedron Lett* 51:692–694. doi:10.1016/j.tetlet.2009.11.114
- Niknam K, Sadeghi Habibabad M, Deris A, Aeinjamshid N (2013) Preparation of silica-bonded N-propyltriethylenetetramine as a recyclable solid base catalyst for the synthesis of 4,4'-(arylmethylene)bis(1H-pyrazol-5-ols). *Monatsh Chem* 144:987–992. doi:10.1007/s00706-012-0910-6
- Pagadala R, Maddila S, Dasireddy VDBC, Jonnalagadda SB (2014) Zn-VCO₃ hydrotalcite: a highly efficient and reusable heterogeneous catalyst for the Hantzsch dihydropyridine reaction. *Catal Commun* 45:148–152. doi:10.1016/j.catcom.2013.11.012
- Parella R, Naveen R, Babu SA (2012) Magnetic nano Fe₃O₄ and CuFe₂O₄ as heterogeneous catalysts: a green method for the stereo- and regioselective reactions of epoxides with indoles/pyrroles. *Catal Commun* 29:118–121. doi:10.1016/j.catcom.2012.09.030
- Phatangare KR, Padalkar VS, Gupta VD, Patil VS, Umape PG, Sekar N (2012) Phosphomolybdic acid: an efficient and recyclable solid acid catalyst for the synthesis of 4,4'-(arylmethylene)bis(1H-pyrazol-5-ols). *Synth Commun* 42:1349–1358. doi:10.1080/00397911.2010.539759
- Plavsic B, Kobe S, Orel B (1999) Identification of crystallization forms of CaCO₃ with FTIR spectroscopy. *KZLTET* 33:517–521
- Razavi N, Akhlaghinia B (2015) Cu (II) immobilized on aminated epichlorohydrin activated silica (CAES): as a new, green and

- efficient nanocatalyst for preparation of 5-substituted -1*H*-tetrazoles. RSC Adv 5:12372–12381. doi:10.1039/C4RA15148H
- Razavi N, Akhlaghinia B (2016) Hydroxyapatite nanoparticles (HAP NPs): a green and efficient heterogeneous catalyst for three-component one-pot synthesis of 2,3-dihydroquinazolin-4(1*H*)-one derivatives in aqueous media. N J Chem 40:447–457. doi:10.1039/C5NJ02123E
- Ren T, Liu S, Li G, Zhang J, Guo J, Li W, Yang L (2012) Synthesis, spectroscopic properties and theoretical studies of bis-Schiff bases derived from polyamine and pyrazolones. Spectrochim Acta Part A 97:167–175
- Roschat W, Kacha M, Yoosuk B, Sudyoasuk T, Promarak V (2012) Biodiesel production based on heterogeneous process catalyzed by solid waste coral fragment. Fuel 98:194–202. doi:10.1016/j.fuel.2012.04.009
- Rwei SP, Lien CC (2014) Synthesis and viscoelastic characterization of sulfonated chitosan solutions. Colloid Polym Sci 292:785–795. doi:10.1007/s00396-013-3115-6
- Seddighi M, Shirini F, Mamaghani M (2013) Sulfonated rice husk ash (RHA-SO₃H) as a highly efficient and reusable catalyst for the synthesis of some bis-heterocyclic compounds. RSC Adv 3:24046–24053. doi:10.1039/C3RA44053B
- Shi DQ, Chen J, Wu N, Zhuang QY, Wang XS (2005) Condensation of aromatic aldehyde with 1-phenyl-3-methylpyrazol-5-one in aqueous media. Chin J Organ Chem 25:405–408. http://sioc-journal.cn/jwk_yjhx/EN/abstract/abstract337595.shtml#
- Shylesh S, Schweizer J, Demeshko S, Schünemann V, Ernst S, Thiel WR (2009) Nanoparticle supported, magnetically recoverable oxodiperoxo molybdenum complexes: efficient catalysts for selective epoxidation reactions. Adv Synth Catal 351:1789–1795. doi:10.1002/adsc.200900416
- Siddiqui ZN, Ahmed N (2013) NH₂SO₃H-SiO₂ as a new water-compatible, recyclable heterogeneous catalyst for the synthesis of novel (α , β -unsaturated) β -amino ketones via aza-Michael reaction. Appl Organomet Chem 27:553–561. doi:10.1002/aoc.3031
- Singh D, Singh D (1984) Syntheses of 1,3-disubstituted 4-arylidene-pyrazolin-5-ones and the keto and enol forms of 4,4'-arylidenebis(1,3-disubstituted pyrazolin-5-ones). J Chem Eng Data 29:355–356. doi:10.1021/je00037a040
- Singh D, Singh D (1991) Synthesis and antifungal activity of some 4-arylmethylene derivatives of substituted pyrazolones. J Indian Chem Soc 68:165–167
- Skotucka-Szary K, Ramiega A, Piaskowska W, Janicki B, Grala M, Rieske P, Bartczak Z, Piaskowski S (2016) Synthesis and physicochemical characterization of chitin dihexanoate—A new biocompatible chitin derivative—In comparison to chitin dibutyrate. Mater Sci Eng C 60:489–502. doi:10.1016/j.msec.2015.11.078
- Soleimani E, Ghorbani S, Taran M, Sarvary A (2012) Synthesis of 4,4'-(arylmethylene)bis(3-methyl-1*H*-pyrazol-5-ol) derivatives in water. C R Chim 15:955–961. doi:10.1016/j.crci.2012.07.003
- Sugiura S, Ohno S, Ohtani O, Izumi K, Kitamikado T, Asai H, Kato K, Hori M, Fujimura H (1977) Syntheses and antiinflammatory and hypnotic activity of 5-alkoxy-3-(*N*-substituted carbamoyl)-1-phenylpyrazoles. 4. J Med Chem 20:80–85. doi:10.1021/jm00211a016
- Sujatha K, Shanthi G, Selvam NP, Manoharan S, Perumal PT, Rajendran M (2009) Synthesis and antiviral activity of 4,4'-(arylmethylene)bis(1*H*-pyrazol-5-ols) against peste des petits ruminant virus (PPRV). Bioorg Med Chem Lett 19:4501–4503. doi:10.1016/j.bmcl.2009.02.113
- Tayebi S, Niknam K (2012) Synthesis of 4,4'-(arylmethylene)bis(1*H*-pyrazol-5-ols) via multi-component reactions by using silica-bonded sulfamic acid derivatives. Iran J Catal 2:69–74
- Thummar BB, Tarpada UP, Raval DK (2014) Study on one-pot biginelli-like synthesis of pyrazolo[3,4-*d*]pyrimidines in bronsted acidic ionic liquid under sonication and its mechanism. J Heterocycl Chem 51:1740–1746. doi:10.1002/jhet.1870
- Uzoukwu AB (1993) The synthesis and crystal structures of 1-phenyl-3-methyl-4-butanolopyrazol-5-one and of two pyrazolonato complexes of iron. Polyhedron 12:2719–2724. doi:10.1016/S0277-5387(00)80123-0.Uzoukwu
- Wang W, Wang SX, Qin XY, Li JT (2005) Reaction of aldehydes and pyrazolones in the presence of sodium dodecyl sulfate in aqueous media. Synth Commun 35:1263–1269. doi:10.1081/SCC-200054854
- Yousefi Siavashi N, Akhlaghinia B, Zarghani M (2016) Sulfonated nanohydroxyapatite functionalized with 2-aminoethyl dihydrogen phosphate (HAP@AEPH₂-SO₃H) as a reusable solid acid for direct esterification of carboxylic acids with alcohols. Res Chem Intermed 42:5789–5806. doi:10.1007/s11164-015-2404-8
- Zarei Z, Akhlaghinia B (2015) Ce(III) immobilised on aminated epichlorohydrin-activated agarose matrix – “green” and efficient catalyst for transamidation of carboxamides. Chem Pap 69:1421–1437. doi:10.1515/chempap-2015-0168
- Zarghani M, Akhlaghinia B (2015a) Sulfonated nanohydroxyapatite functionalized with 2-aminoethyl dihydrogen phosphate (HAP@AEPH₂-SO₃H) as a new recyclable and eco-friendly catalyst for rapid one-pot synthesis of 4,4'-(aryl methylene)bis(3-methyl-1*H*-pyrazol-5-ol)s. RSC Adv 5:87769–87780. doi:10.1039/c5ra16236j
- Zarghani M, Akhlaghinia B (2015b) Copper immobilized on aminated ferrite nanoparticles by 2-aminoethyl dihydrogen phosphate (Fe₃O₄@AEPH₂-Cu^{II}) catalyses the conversion of aldoximes to nitriles. Appl Organomet Chem 29:683–689. doi:10.1002/aoc.3351
- Zarghani M, Akhlaghinia B (2016a) Magnetically separable Fe₃O₄@-chitin as an eco-friendly nanocatalyst with high efficiency for green synthesis of 5-substituted-1*H*-tetrazoles under solvent-free conditions. RSC Adv 6:31850–31860. doi:10.1039/C6RA07252F
- Zarghani M, Akhlaghinia B (2016b) Green and efficient procedure for Suzuki–Miyaura and Mizoroki–Heck coupling reactions using palladium catalyst supported on phosphine functionalized ZrO₂ NPs (ZrO₂@ECP-Pd) as a new reusable nanocatalyst. Bull Chem Soc Japan. doi:10.1246/bcsj.20160163
- Zhou Z, Zhang Y (2014) An efficient and green one-pot three-component synthesis of 4,4'-(arylmethylene)bis(1*H*-pyrazol-5-ol)s catalyzed by 2-hydroxy ethylammonium propionate. Green Chem Lett Rev 7:18–23. doi:10.1080/17518253.2014.894142
- Zhu J, Bienayme H (2005). Multicomponent reactions. In: Zhu J, Bienayme H (eds), vol 3. Wiley-VCH, Weinheim
- Zolfigol MA, Khazaei A, Safaiee M, Mokhlesi M, Rostamian R, Bagheri M, Shiri M, Kruger HG (2013) Application of silica vanadic acid as a heterogeneous, selective and highly reusable catalyst for oxidation of sulfides at room temperature. J Mol Catal A Chem 370:80–86. doi:10.1016/j.molcata.2012.12.015
- Zolfigol MA, Ayazi-Nasrabadi R, Bagheri S (2015) Synthesis and characterization of two novel biological-based nano organo solid acids with urea moiety and their catalytic applications in the synthesis of 4,4'-(arylmethylene)bis(1*H*-pyrazol-5-ol), coumarin-3-carboxylic acid and cinnamic acid derivatives under mild and green conditions. RSC Adv 5:71942–71954. doi:10.1039/C5RA14001C