**ORIGINAL PAPER** 



# ompg-C<sub>3</sub>N<sub>4</sub>/SO<sub>3</sub>H organocatalyst-mediated green synthesis of 1,2-dihydro-1-arylnaphtho[1,2-*e*][1,3] oxazin-3-ones under solvent-free and mild conditions: a fast and facile one-pot three-component approach

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#### Abstract

In this research, we have described the synthesis of the well-ordered mesoporous graphite carbon nitride (ompg- $C_3N_4$ ) by applying SBA-15 as a potential hard silica template, and the catalytic performance of sulfonated well-ordered mesoporous graphite carbon nitride (ompg- $C_3N_4/SO_3H$ ) as an environment-friendly and efficient polymeric solid acid catalyst was investigated in the one-pot preparation of 1,2-dihydro-1-arylnaphtho[1,2-*e*][1,3]oxazin-3-ones. This cyclocondensation reaction was performed in the presence of various substituted aldehydes, urea, and 2-naphthol through mild and efficient solvent-free method. The structure and morphology of ompg- $C_3N_4/SO_3H$  were characterized using various instrumental analysis methods including FT-IR, EDS, FESEM, TEM, TGA, DTG, XRD, and BET. The simplicity of the process, low reaction times, simple workup, high to quantitative yields, avoiding the utilization of organic solvents, and reusability of the as-prepared catalyst are several prominent advantages of this present synthetic method.

#### **Graphic abstract**



Keywords Carbon nitride · Organocatalyst · Condensation reaction · Naphthoxazinone · Green synthesis

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## Introduction

Ordered mesoporous materials (OMMs) with tunable pore sizes, high surface active sites, and uniform pore structures indicate potential performances in the novel catalytic processes. In particular, surface modification is an interesting feature of these materials for improving their catalytic performance [1, 2]. Accordingly, functionalized ordered mesoporous materials with covalently bound sulfonic acid have attracted a great amount of attention as an appropriate solid acid catalyst [3, 4].

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Over the recent few years, porous carbon materials have been widely used in the various categories of science including supercapacitors, electrode materials, sorbents, gas storages, catalyzers, and fuel cells due to the excellent physical and chemical features such as stability, low density, broad availability, and electric and thermal conductivity [5]. Polymeric graphitic carbon nitride  $(g-C_3N_4)$  is the main class of carbonaceous materials with electron-rich surface and environment-friendly nature. Generally, g-C<sub>3</sub>N<sub>4</sub> substructure, based on aromatic C-N heterocycles and optimized van der Waals forces between its two-dimensional conjugated planes, can be prepared by polymerization of affordable nitrogen-containing materials like melamine, urea, cyanamide, thiourea, and dicyandiamide [6]. Reasonable physical and chemical property, unique electronic property, exclusive thermal and chemical resistance, and high specific surface area [7] make this material be applied in many scientific fields such as fuel cell [8], sensor [9], solar cell [10], metal-free catalyst [11], heterogeneous photocatalyst [12], energy storage [13], oxygen reduction reaction (ORR) [14], hydrogen evolution [15], photocatalytic degradation of pollutants [16, 17], and oxidation [18]. The preparation of wellordered mesoporous g-C<sub>3</sub>N<sub>4</sub> leads to higher specific surface area, stronger adsorption capacity, and larger pore volume and increases active chemical sites, thereby enhancing the performance of g-C<sub>3</sub>N<sub>4</sub> as an efficient catalyst and catalyst support [19, 20]. As a result of the tremendous properties of the ordered mesoporous  $g-C_3N_4$ , a variety of researches have been reported about the synthesis and catalytic application of this material during the past few decades [21–24].

Given the increasing importance of designing atom economic strategies in synthetic organic chemistry, multicomponent reactions (MCRs) emerged as the convergent, simple, time and energy efficient, and selective processes [25]. In this regard, MCRs could be extremely useful in the ideal synthesis of heterocyclic compounds. Considering the important activities of N-containing heterocyclic compounds in the biological and pharmaceutical fields, chemical industries, and also as the applicable intermediates in organic syntheses, numerous methodologies have been focused on the efficient synthesis of these materials [26].

One of the important types of N-containing heterocyclic compounds is aromatic-condensed oxazinone with various promising biological activities such as antimicrobial [27], anticancer [28], analgesic, anti-inflammatory, antipyretic, and anticonvulsant [29]. Moreover, naphthalene-condensed 1,3-oxazin-3-ones with antimicrobial properties [30] are applied as the potential starting materials in the synthesis of phosphonic ligands for asymmetric catalysis [31]. Previously, some naphthalene-condensed 1,3-oxazin-3-ones were prepared through reaction between aminoalkylnaphthols with phosgene [32] or carbonyl diimidazole in the presence of triethylamine [33]. On the other hand, designing a safer synthetic method in the presence of less harmful reagents for the synthesis of naphthoxazinone derivatives has attracted a remarkable amount of attention during recent years. In this context, some syntheses of 1-aryl-1,2-dihydronaphtho[1,2-e]-[1,3]oxazin-3-ones have been reported using various catalysts such as [PyPS][HSO<sub>4</sub>] [34], TMSCI [35], Cu nanoparticles [36], Zn (OTF)<sub>2</sub> [37], HClO<sub>4</sub>/SiO<sub>2</sub> [38], [bmim] Br [39], TMSCl/NaI [40], and ZnO NPs [41], via cyclocondensation reaction of  $\beta$ -naphthol with substituted aldehydes and urea. However, the mentioned methods are associated with various drawbacks such as wearisome reaction time, use of hazardous organic solvent, high reaction temperature, and lower yield of products. Therefore, the development of a novel synthetic methodology for the synthesis of these compounds under milder conditions is still in great demand. Accordingly, in connection with our previous efforts toward the synthesis of ompg-C<sub>3</sub>N<sub>4</sub>-based heterogeneous organocatalysts [42], we have recently reported the synthesis of pharmaceutically interesting compounds catalyzed by superactive sulfonated highly ordered mesoporous graphitic carbon nitride (ompg-C<sub>3</sub>N<sub>4</sub>/SO<sub>3</sub>H) as an efficient heterogeneous solid acid catalyst [43, 44]. Herein, we report the application of  $ompg-C_3N_4/SO_3H$  as a more practical and efficient catalyst for the facile and green synthesis of 1,2-dihydro-1-arylnaphtho[1,2-e][1,3]oxazin-3-one derivatives. Owing to the several superior properties of  $ompg-C_3N_4/SO_3H$  such as strong acidity strength, high activity, and environmentally friendly nature, the mentioned reaction was conducted under milder conditions and in the absence of solvent with high to quantitative yields of products (Scheme 1).

#### **Results and discussion**

Sulfonated ordered mesoporous graphitic carbon nitride (ompg- $C_3N_4/SO_3H$ ) was prepared and characterized through the method that we have recently reported (further details



and characterization information are available in the supporting information) [43, 44]. Preservation of the original framework of ompg-C<sub>3</sub>N<sub>4</sub> after immobilization of the-SO<sub>3</sub>H groups is indicated in Fig. S2, S3. Moreover, the exact amounts of C (27.83%), H (2.91%), N (47.06%), and S (2.72%) elements in the ompg- $C_3N_4/SO_3H$  composition was identified by elemental analysis. It should be noted that a significant decrease in the BET surface area of  $ompg-C_3N_4$ as compared with the silica template may be related to the partial pore collapse of the mesostructure due to the poor diffusion of cyanamide in the pores of the mesoporous silica template, also the high shrinkage as a result of the condensation at high temperature, and in the process of the elimination of the silica template (Fig. S6) [45-47]. According to the TGA and DTA analyses of ompg- $C_3N_4$  and ompg- $C_3N_4$ / SO<sub>3</sub>H (Fig. S5), ompg-C<sub>3</sub>N<sub>4</sub>/SO<sub>3</sub>H possesses high thermal stability due to the presence of van der Waals forces between the sulfonic acid groups and mesoporous graphitic carbon nitride support. FESEM image of ompg-C<sub>3</sub>N<sub>4</sub>/SO<sub>3</sub>H (Fig. S4) and TEM image of  $ompg-C_3N_4/SO_3H$  (Fig. 1) clearly confirmed the rod-like mesoporous structure and uniform framework of ompg- $C_3N_4/SO_3H$ .

To evaluate the performance of ompg- $C_3N_4/SO_3H$  in the preparation of 1,2-dihydro-1-arylnaphtho[1,2-*e*][1,3]oxazin-3-ones, a one-pot cyclocondensation multicomponent reaction was investigated over a systematic study. For this purpose, the three-component reaction between benzaldehyde (1) (1.0 mmol), urea (2) (1.2 mmol), and 2-naphthol (3) (1.0 mmol) was considered as a model reaction. The optimal conditions were determined through screening the effect of various solvents at several temperatures and different amounts of the catalyst (Table 1). It seems remarkable that the reaction could not afford the desired product in the absence of the catalyst after 2 h (Table 1, entries 1–6). Significantly, using ompg- $C_3N_4/SO_3H$  as a catalyst



Fig. 1 TEM micrographs of ompg-C<sub>3</sub>N<sub>4</sub>/SO<sub>3</sub>H

led to completion of the reaction in 5 min with 87% yield of the desired product (Table 1, entry 7). For evaluation of the solvent effect, the model reaction was investigated by applying various solvents (including EtOH, H<sub>2</sub>O, MeOH, CH<sub>3</sub>CN, toluene) and in solvent-free conditions (Table 1, entries 8–12). The results revealed that, in the presence of both types of protic and aprotic solvents, only a trace amount of product was obtained and the best result was achieved in the absence of solvent. In continuance, the influence of temperature was investigated (Table 1, entries 13-17). Relying on the obtained results, as the temperature was conducted to 100 °C, the desired product was formed at a shorter reaction time and the yield increased to 87% (Table 1, entry 17). Moreover, by increasing the temperature, no noticeable change occurred in the time and yield of the reaction. To acquire a suitable amount of catalyst, the model reaction was examined by applying 5, 10, 15, 20, and 30 mg of ompg- $C_3N_4/SO_3H$  at 100 °C (Table 1, entries 17–21). It was found that 20 mg of ompg- $C_3N_4/SO_3H$  was sufficient to give the desired product in 97% yield and very short reaction time (Table 1, entry 20).

The catalytic activity of ompg- $C_3N_4/SO_3H$  and the role of the  $-SO_3H$  group were investigated using various forms of g- $C_3N_4$  in the model reaction (Table 2). The results clearly proved that functionalization of well-ordered mesoporous graphitic carbon nitride with the  $-SO_3H$  group led to a significant improvement in the model reaction in terms of time and yield. In particular, because of the incorporation of nitrogen atoms in the carbon architecture, high amounts of  $-SO_3H$  groups were loaded on the ompg- $C_3N_4$ , which led to increase in the acidity strength of the catalyst. Also, it is anticipated that the development of positive charge on the nitrogenous framework after  $-SO_3H$  immobilization leads to the high acidity strength of ompg- $C_3N_4/SO_3H$  and thus enhances its catalytic performance.

After determining the optimum conditions, the generality of this method was investigated using various substituted aromatic aldehydes in the presence of ompg- $C_3N_4/SO_3H$  at 100 °C under solvent-free conditions (Table 3, entries 1–11). The results proved that all of the substituted aldehydes with electron-withdrawing groups (Cl, F, NO<sub>2</sub>, CN) and electrondonating groups (OH, Me, OMe,) at diverse positions of the aromatic ring afforded the desired products in high yields and reasonable times.

The reusability of ompg- $C_3N_4/SO_3H$  as a heterogeneous organocatalyst in the model reaction was also investigated. After completing, ompg- $C_3N_4/SO_3H$  was filtered off, rinsed, and dried and then reused in the next reaction. According to the obtained results, ompg- $C_3N_4/SO_3H$  could be reused up to five cycles with insignificant loss of activity (Fig. 2).

Relying on our experimental results and using the pathways previously described in the literature [34, 48, 52], a probable mechanism for the formation of

#### Table 1 Determination of the optimal conditions



Entry	Solvent	Amount of catalyst/mg	Temp/°C	Time/min	Yield/% <sup>a</sup>
1	_	_	150	120	_
2	EtOH	_	Reflux	120	_
3	H <sub>2</sub> O	_	Reflux	120	_
4	MeOH	_	Reflux	120	_
5	CH <sub>3</sub> CN	_	Reflux	120	_
6	Toluene	_	Reflux	120	_
7	_	10	150	5	87
8	EtOH	10	Reflux	120	Trace
9	H <sub>2</sub> O	10	Reflux	120	Trace
10	MeOH	10	Reflux	120	32
11	CH <sub>3</sub> CN	10	Reflux	120	25
12	Toluene	10	Reflux	120	_
13	_	10	_	120	_
14	MeOH	10	_	120	_
15	-	10	160	5	87
16	-	10	120	5	87
17	_	10	100	5	87
18	-	5	100	5	81
19	-	15	100	5	93
20	-	20	100	5	97
21	-	30	100	5	97

Reaction conditions: benzaldehyde (1, 1.0 mmol), urea (2, 1.2 mmol), 2-naphthol (3, 1.0 mmol), 3.0 cm<sup>3</sup> solvent, and catalyst: ompg- $C_3N_4/SO_3H$  <sup>a</sup>Isolated yield

Table 2 A comparison of the catalytic performance of ompg-  $C_3N_4/SO_3H$  with other forms of  $g\text{-}C_3N_4$ 

Entry	Catalyst	Amount of cata- lyst/mg	Solvent	Time/min	Yield/% <sup>a</sup>
1	ompg-C <sub>3</sub> N <sub>4</sub>	20	_	80	_
2	Bulk g-C <sub>3</sub> N <sub>4</sub>	20	-	80	-
3	Nanosheet g-C <sub>3</sub> N <sub>4</sub>	20	-	80	Trace
4	ompg-C <sub>3</sub> N <sub>4</sub> /SO <sub>3</sub> H	20	-	5	97
5	Bulk ompg-C <sub>3</sub> N <sub>4</sub> /SO <sub>3</sub> H	20	-	5	51
6	Nanosheet g-C <sub>3</sub> N <sub>4</sub> /SO <sub>3</sub> H	20	-	5	69

Reaction conditions: benzaldehyde (1, 1.0 mmol), urea (2, 1.2 mmol), 2-naphthol (3, 1.0 mmol) <sup>a</sup>Isolated yield

1,2-dihydro-1-arylnaphtho[1,2-e][1,3]oxazin-3-ones has been proposed in Scheme 2. The reaction is started by the activation of the carbonyl functional group of benzaldehyde (2) through protonation with  $ompg-C_3N_4/SO_3H$  as a Bronsted acid that increases the electrophilic nature, followed by the nucleophilic attack of urea (2)

**Table 3** ompg- $C_3N_4/SO_3H$  catalyzed reaction for the synthesis of 1,2-dihydro-1-arylnaphtho[1,2-*e*][1,3]oxazin-3-ones in the presence of various aldehydes



Entry	R	Product	Time/min	Yield/% <sup>a</sup>	M.p. /°C	Lit. m.p./°C
1	Н	<b>4</b> a	5	97	220-222	210–222 [48]
2	4-Cl	<b>4</b> b	5	95	210-213	212–214 [38]
3	4-Me	<b>4</b> c	5	91	164-165	164–166 [41]
4	4-OH	<b>4d</b>	8	89	180-183	181–183 [49]
5	4-OMe	<b>4e</b>	5	93	188-190	188–190 [41]
6	3-NO <sub>2</sub>	<b>4f</b>	10	75	210-212	210–212 [48]
7	4-F	4g	13	78	199-201	198–200 [41]
8	2-Cl	<b>4h</b>	5	89	247-250	248-250 [50]
9	$4-NO_2$	4i	5	81	171–174	172–174 [51]
10	3-OH	4j	8	87	189–191	189 [ <mark>40</mark> ]
11	4-CN	4k	5	96	189–190	This work

Reaction conditions: aldehyde 1 (1.0 mmol), urea (2, 1.2 mmol), 2-naphthol (3, 1.0 mmol), 100 °C, catalyst: ompg- $C_3N_4/SO_3H$  (20 mg) <sup>a</sup>Isolated yield



Fig. 2 Recycling of the ompg- $C_3N_4/SO_3H$  in the model reaction

forming intermediate I. Thereafter, proton transfer leads to intermediate II, which upon dehydration generates reactive acylium intermediate III. The subsequent reaction of  $\beta$ -naphthol (3) with the resulting acylium forms intermediate IV. Simultaneously, a proton transfer from  $\beta$ -naphthol (3) to the sulfanic group missing from intermediate III to intermediate IV leads to the resumption of catalytically active  $-SO_3H$ . Subsequently, conversion of IV into its activated enolate form V (through tautomerization) and proton transfer afford intermediate VI. Eventually, intramolecular cyclization forms the desired products 4 with removal of ammonia.

A comparison of the catalytic capability of ompg- $C_3N_4/SO_3H$  with some other reported catalysts in the literature clearly shows an excellent catalytic performance of assynthesized catalyst to other catalysts in the preparation of 1,2-dihydro-1-arylnaphtho[1,2-*e*][1,3]oxazin-3-one derivatives under mild reaction conditions in low reaction time with high yield (Table 4).

#### Conclusion

In conclusion, we have presented a highly effective and green synthetic protocol for the preparation of pharmacological interesting 1,2-dihydro-1-arylnaphtho[1,2-e][1,3]oxazin-3-one derivatives applying ompg-C<sub>3</sub>N<sub>4</sub>/SO<sub>3</sub>H as an effective superactive heterogeneous solid acid organocatalyst under mild reaction conditions. This novel procedure is associated with notable benefits, such as being environmentally safe and having short process time,



 Table 4
 Comparison between

 ompg-C<sub>3</sub>N<sub>4</sub>/SO<sub>3</sub>H performance

 with some previously reported

 performances<sup>a</sup>

Entry	Catalyst (amount of catalyst)	Solvent	Temp./°C	Time/min	Yield <sup>b</sup> /%
1	[SiO <sub>2</sub> -VO(OH) <sub>2</sub> ] (2 mg)	-	130	60	82 [49]
2	Graphene oxide (35 w%)	-	120	25	87 [ <mark>53</mark> ]
3	Silica-bonded S-sulfonic acid (20 mg)	-	150	60	90 [ <mark>48</mark> ]
4	FeCl <sub>3</sub> /SiO <sub>2</sub> NPs	-	150	10	85 [ <mark>54</mark> ]
5	ompg-C <sub>3</sub> N <sub>4</sub> /SO <sub>3</sub> H (20 mg)	-	100	5	97 This work

<sup>a</sup>Reaction conditions: benzaldehyde (**1**, 1.0 mmol), urea (**2**, 1.2 mmol), 2-naphthol (**3**, 1.0 mmol) <sup>b</sup>Isolated yield facile workup, high yield, and noticeable reusability of the catalyst.

### Experimental

All of the chemicals and solvents were commercially available and purchased from Merck and Fluka. All reactions and the purity of the products were monitored by analytical TLC on Al plates coated with 0.2 mm silica gel F254. An Electrothermal 9100 apparatus was applied to check out melting points. FT-IR spectral information was obtained by a Shimadzu spectrometer using KBr pill in the 400–4000 cm<sup>-1</sup> region. The specific surface areas and pore diameter distributions were recognized by the adsorption branch of the BJH isotherm. The FESEM images were extracted on a MRIA3 TESCAN-XMU, and TEM images were acquired by Zeiss-EM10C-100 kV model. The X-ray diffraction (XRD) measurements were taken on a PANalytical X-PERT-PRO MPD diffractometer using Cu K $\alpha$  ( $\lambda = 1.5406$  Å) in the range of  $2\theta = 5^{\circ}$  to  $80^{\circ}$  with a step size of  $0.02^{\circ}$ . Elemental analysis was examined by applying a CHNS analyzer (Thermo Flash EA 1112). Identification of products was performed with an <sup>1</sup>H and <sup>13</sup>C NMR spectra using Bruker DRX-500 Avance spectrometer in DMSO-d<sub>6</sub>. EDX spectra were obtained using Numerix DXP-X10P. TGA and DTG analyses of the as-prepared catalyst were carried out with STA504 analyzer system at 20-800 °C.

# General procedure for the synthesis of $ompg-C_3N_4/SO_3H$

Sulfonated ordered mesoporous graphitic carbon nitride (ompg- $C_3N_4/SO_3H$ ) was prepared through the method that we have recently reported [43, 44].

#### General procedure for the synthesis of 4

To a mixture of aldehyde **1** (1.0 mmol), urea (**2**, 1.2 mmol) and 2-naphthol (**3**, 1.0 mmol), ompg- $C_3N_4/SO_3H$  (20.0 mg) was added. The reaction mixture was stirred at 100 °C in the absence of solvent (Table 2). After the reaction was complete, it was detected using TLC (hexane/EtOAc 2:1), the temperature changed from 100 to 80 °C, and 5 cm<sup>3</sup> ethanol was poured to the reaction vessel and then stirred for 10 min. The resulting reaction mixture was filtered to separate the solid catalyst and the pure products **4** were obtained by cooling the filtered solution and recrystallization with ethanol.

**1-(4-Cyanophenyl)-1,2-dihydronaphtho**[**1,2-e**][**1,3**]**oxazin-3-one** (**4k**, **C**<sub>19</sub>**H**<sub>12</sub>**N**<sub>2</sub>**O**<sub>2</sub>) White solid; m.p.: 189–190 °C; FT-IR (KBr):  $\bar{\nu}$  = 3280, 2925, 2227, 1745, 1631, 1508, 1444, 1220, 811 cm<sup>-1</sup>; <sup>1</sup>H NMR (500 MHz, DMSO-*d<sub>6</sub>*):  $\delta$  = 8.99 (d,1H, -NH, *J* = 5.15 Hz), 8.01 (d, 1H, Ar–H, *J* = 8.95 Hz), 7.96 (d, 1H, Ar–H, *J* = 1.5 Hz), 7.39–7.83 (m, 1H, Ar–H), 6.35 (d, 1H, CH, *J* = 3.15 Hz) ppm; <sup>13</sup>C NMR (125 MHz, DMSO-*d<sub>6</sub>*):  $\delta$  = 53.2, 78.03, 110.87, 113.00, 116.90, 118.42, 122.93, 125.22, 127.56, 128.02, 128.71, 130.41, 130.64, 133.02, 147.59, 147.76, 149.03 ppm.

#### References

- 1. Taguchi A, Schu F (2005) Microporous Mesoporous Mater 77:1
- Ahmadi E, Ramazani A, Hamdi Z, Mohamadnia AMZ (2015) Silicon 7:323
- 3. Mohammadi G, Lashgari N, Badiei A (2015) J Mol Catal A Chem 397:166
- 4. Wang Y, You J, Liu B (2019) React Kinet Mech Catal 128:493
- 5. Liang C, Li Z, Dai S (2008) Chem Int Edn 47:3696
- Lakhi KS, Park DH, Al-Bahily K, Cha W, Viswanathan B, Choy JH, Vinu A (2017) Chem Soc Rev 46:72
- 7. Dong G, Zhang Y, Pan Q, Qiu J (2014) Photochem Photobiol C Photochem Rev 20:33
- 8. Di Noto V, Negro E (2010) Electrochim Acta 55:7564
- 9. Lee SP, Lee JG, Chowdhury S (2008) Sensors 8:2662
- 10. Xu J, Wang G, Fan J, Liu B, Cao S, Yu J (2015) J Power Sources 274:77
- Schubert MM, Hackenberg S, Van Veen AC, Muhler M, Plzak V, Behm RJ (2001) J Catal 197:113
- 12. Wang Y, Wang X, Antonietti M (2012) Angew Chem Int Edn 51:68
- Wang D, Li F, Liu M, Lu GQ, Cheng HM (2008) Angew Chem Int Edn 120:379
- 14. Zhang Y, Huang N, Zhou F, He Q, Zhan S (2018) J Chin Chem Soc 65:1431
- 15. Wang X, Maeda K, Chen X, Takanabe K, Domen K, Hou Y, Fu X, Antonietti M (2009) J Am Chem Soc 131:1680
- Liu M, Wei S, Chen W, Gao L, Li X, Mao L, Dang H (2019) J Chin Chem Soc 66:1044
- 17. Yin J, Wu Z, Fang M, Xu Y, Zhu W, Li C (2018) J Chin Chem Soc 65:1044
- Chen X, Zhang J, Fu X, Antonietti M, Wang X (2009) J Am Chem Soc 131:11658
- Zhao H-M, Di C-M, Wang L, Chun Y, Xu Q-H (2015) Microporous Mesoporous Mater 208:98
- 20. Yang Z, Zhang Y, Schnepp Z (2015) J Mater Chem A 3:14081
- 21. Gao X, Jiao X, Zhang L, Zhu W, Xu X, Ma H, Chen T (2015) RSC Adv 5:76963
- 22. Gong Y, Zhang P, Xu X, Li Y, Li H, Wang Y (2013) J Catal 297:272
- 23. Liu Y, Yu Y-X, Zhang W-D (2014) Int J Hydrogen Energy 39:9105
- 24. Bu Y, Chen Z, Li W (2014) Appl Catal B Environ 144:622
- 25. Do A, Wang W, Wang K (2012) Chem Rev 112:3083
- Okamoto S, Iwakubo M, Kobayashi K, Sato F (1997) J Am Chem Soc 119:6984
- 27. Sunil D, Upadhya SH, Murugappan R (2013) Res J Pharm Sci 2:15
- Ouberai M, Asche C, Carrez D, Croisy A, Dumy P, Demeunynck M (2006) Bioorg Med Chem Lett 16:4641
- 29. George M, Joseph L, Sadanandan HR (2016) Int J Pharm Pharm Res 6:14

- 30. Latif N, Mishriky N, Assad FM (1982) Aust J Chem 35:1037
- 31. Wang Y, Li X, Ding K (2002) Tetrahedron Asymmetry 13:1291
- Szatmári I, Hetényi A, Lázár L, Fülöp F (2004) J Heterocycl Chem 41:367
- 33. Cimarelli C, Palmieri G, Volpini E (2004) Can J Chem 82:1314
- Dong F, Li-Fang Y, Jin-Ming Y (2013) Res Chem Intermed 39:2505
- 35. Jiang C, Geng X, Zhang Z, Xu H, Wang C (2010) J Chem Res 34:19
- Kumar A, Saxena A, Dewan M, De A, Mozumdar S (2011) Tetrahedron Lett 52:4835
- 37. Hajra A, Kundu D, Majee A (2009) J Heterocycl Chem 46:1019
- Ahangar HA, Mahdavinia GH, Marjani K, Hafezian A (2010) J Iran Chem Soc 7:770
- 39. Dabiri M, Sadat Delbari A, Bazgir A (2007) Heterocycles 71:543
- Sabitha G, Arundhathi K, Sudhakar K, Sastry BS, Yadav JS (2010) J Heterocycl Chem 47:272
- 41. Rao GBD, Kaushik MP, Halve AK (2012) Tetrahedron Lett 53:2741
- 42. Ghafuri H, Jafari G, Rashidizadeh A, Manteghi F (2019) Mol Catal 475:110491
- Fard MAD, Ghafuri H, Rashidizadeh A (2019) Microporous Mesoporous Mater 274:83
- 44. Ghafuri H, Goodarzi N, Rashidizadeh A, Fard MAD (2019) Res Chem Intermed 45:1

- 45. Liu J, Yan J, Ji H, Xu Y, Huang L, Li Y, Song Y, Zhang Q, Xu H (2016) Mater Sci Semicond Process 46:59
- 46. Park SS, Chu S-W, Xue C, Zhao D, Ha C-S (2011) J Mater Chem 21:10801
- 47. Li X-H, Wang X, Antonietti M (2012) Chem Sci 3:2170
- 48. Nikna K, Abolpour P (2015) J Chem Sci 127:1315
- Zolfigol MA, Safaiee M, Afsharnadery F, Bahraminejad N, Baghery S, Salehzadeh S, Maleki F (2015) RSC Adv 5:100546
- Olyaei A, Sadeghpour M, Zarnegar M (2013) Chem Heterocycl Compd 49:1374
- Basavegowda N, Somai Magar KB, Mishra K, Lee YR (2014) New J Chem 38:5415
- 52. Wu J, Du X, Ma J, Zhang Y, Shi Q, Luo L, Song B, Yang S, Hu D (2014) Green Chem 16:3210
- Gupta A, Kour D, Gupta VK, Kapoor KK (2016) Tetrahedron Lett 57:4869
- 54. Safaei-Ghomi J, Zahedi S, Ghasemzadeh MA (2012) Iran J Catal 2:27

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