

Synthesis, characterization and application of a novel nanorod-structured organic–inorganic hybrid material as an efficient catalyst for the preparation of aminouracil derivatives

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Abstract

In this work, a novel nanorod-structured organic–inorganic hybrid material namely nanorod-[SiO₂-Pr-Im-SO₃H][TFA] (N-[SPIS][TFA]) has been synthesized, and characterized by FT-IR, energy-dispersive X-ray spectroscopy, field emission scanning electron microscopy, thermal gravimetric analysis and X-ray diffraction analyses. Thereafter, it has been applied as an efficient, recyclable and dual-functional catalyst to promote the following organic transformations: (1) the preparation of (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes by the one-pot multi-component reaction of 6-amino-1,3-dimethyluracil, 2-hydroxy-1,4-naphthoquinone and arylaldehydes; and (2) the production of bis(6-amino-1,3-dimethyluracil-5-yl)methanes via the pseudo-three-component reaction of 6-amino-1,3-dimethyluracil (2 eq.) and arylaldehydes (1 eq.).

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Graphic abstract



Keywords Nanorod-structured organic–inorganic hybrid material · Nanorod-[SiO₂-Pr-Im-SO₃H][TFA] (N-[SPIS][TFA]) · Aminouracil derivatives

Introduction

Hybrid materials consist of two or more different components in which inorganic and organic components are brought together by specific interactions, and this subject causes the synergistic enhancement of their functional properties [1]. The inorganic part can be oxides, metal clusters or particles, salts, metal ions and nonmetallic elements, and the organic moiety can be various organic groups or molecules [1]. These materials have extensive applications in different scientific, pharmaceutical and industrial fields [1–23]; some their uses include: (1) utilization as antitumor drug [2], (2) application for in vivo dual-modal imaging-guided synergistic photothermal/radiation therapy [3], (3) application as potential carrier for combined delivery of drugs [4], (4) cryogenic application [5], (5) usage as sensor and electrode [6–9], (6) possessing resistive switching behavior for resistive random access memory devices [10] and (7) utilization for absorbance of heavy metals [11].

Recently, much attention has been attracted on the utilization of organic–inorganic hybrid materials as catalysts in organic synthesis, because they have several advantages, including easy separation from reaction mixture, having large surface-to-volume ratio (nanomaterials), high activity, efficiency, ability to design for various catalytic uses by functionalization, recoverability and eco-friendly nature [24–36].

Among the different inorganic compounds [24–27, 37–45], silica is usually preferable to apply as inorganic moiety for synthesis of hybrid materials, because it has some unique properties, consisting of low cost, proper thermal and chemical stability, safety, green nature, non-corrosiveness, simple functionalization and easy separation from reaction medium [28–36].

A significant, simple, useful and practical way for synthesis of complex molecules is one-pot multi-component reaction (MCR); the benefits of MCRs have been well-mentioned in the literature [46–49].

Uracil derivatives are essential moieties of nucleic acids in living cells [50], and play significant roles in our life cycle [51]. They also show various medicinal and biological activities; e.g., antifungal [52], adenosine receptor antagonist [52], anticancer [53], antiviral [54], bactericidal [55], thymidylate synthase inhibitor [56] and acaricidal [57] properties. Among the uracil derivatives, 6-aminouracil is a common building block of several bioactive natural products, and is a main scaffold of various biologically active heterocycles [58]. This moiety has been also utilized as a key precursor for the preparation of diverse pharmaceutical and bioactive compounds [59]. Moreover, the compounds bearing aminouracil and hydroxynaphthoquinone have been used as proliferative [60], angiogenetic [60], anticoagulant [61] and antibiofilm [62] agents.

Two important classes of uracil derivatives are (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes and bis(6-amino-1,3-dimethyluracil-5-yl)methanes. The first kind has been prepared via the one-pot multi-component reaction of 6-amino-1,3-dimethyluracil, 2-hydroxy-1,4-naphthoquinone and arylaldehydes using a catalyst [63, 64], and the second type has been synthesized by the pseudo-three-component reaction of 6-amino-1,3-dimethyluracil (2 eq.) and arylaldehydes (1 eq.) in the presence of a catalyst [65–72].

In spite of high importance of (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes and bis(6-amino-1,3-dimethyluracil-5-yl) methanes, a few catalysts have been reported for their synthesis by the mentioned methods, especially for (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphtho-quinone-3-yl)methanes. Thus, introducing new catalysts for the production of the aminouracil derivatives is highly desirable.

Considering the above issues, we have synthesized a novel nanorod-structured organic–inorganic hybrid material namely nanorod-[SiO₂-Pr-Im-SO₃H][TFA] (N-[SPIS][TFA]), and characterized it by FT-IR, energy-dispersive X-ray spectroscopy (EDS), field emission scanning electron microscopy (FE-SEM), thermal

gravimetric analysis (TGA) and X-ray diffraction (XRD) analyses. Thereafter, we have applied N-[SPIS][TFA] as a highly efficient, recyclable and dual-functional catalyst to prepare two important classes of aminouracil derivatives, i.e., (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes and bis(6-amino-1,3-dimethyluracil-5-yl)methanes

Experimental

Materials and instruments

The used reactants and solvents were purchased from Merck or Fluka Chemical Companies. The nanorod-silica for the production of N-[SPIS][TFA] was prepared according to the reported method [73, 74]. Progress of the reactions was monitored by thin-layer chromatography (TLC) using silica gel SIL G/UV 254 plates. Melting points were measured using a Buchi B-545 apparatus in open capillary tubes. FT-IR spectra were recorded by Shimadzu IR-60 instrument. ¹H and ¹³C NMR spectra were run on a Bruker Avance DPX FT-NMR spectrometer. Energy-dispersive X-ray spectroscopy (EDS) was carried out by SAMx-EDS (France system). The morphologies and particles sizes of N-[SPIS][TFA] were characterized by field emission scanning electron microscopy, model MIRA3TESCAN-XMU. Thermal gravimetric analysis (TGA) was performed by Bahr STA 504 instrument (Germany), at 25–600 °C, with temperature increase rate of 10 °C min⁻¹ in argon atmosphere. The X-ray diffraction (XRD) analysis was performed using an apparatus model X'Pert PRO MPD, PANalytical, the Netherlands (Cu K α radiation, $\lambda = 1.5408$).

Production of N-[SPIS][TFA] (Scheme 1)

A mixture of imidazole (0.34 g, 5 mmol), (3-chloropropyl)trimethoxysilane (0.99 g, 5 mmol) and toluene (15 mL) was stirred under reflux conditions for 12 h; afterward, the solvent was evaporated under vacuum at 100 °C to give **I**. Intermediate **I** and nanorod-silica (0.30 g, 5 mmol) were added to EtOAc (15 mL), and stirred



Scheme 1 Production of N-[SPIS][TFA]

under reflux conditions for 18 h; the resulting mixture was centrifuged, decanted, washed by EtOAc (2×5 mL), and dried under vacuum at 80 °C to give intermediate **II**. Then, **II** was added gradually to a stirring solution of chlorosulfonic acid (0.58 g, 5 mmol) in dry CH_2Cl_2 (10 mL) at 10 °C, and stirred for 3 h at room temperature. The obtained mixture was centrifuged, decanted, triturated by dry CH_2Cl_2 (2×10 mL), and dried to afford intermediate **III**. Subsequently, trifluoroacetic acid (5 mmol) was added to a stirring solution of **III** in dry CH_2Cl_2 (10 mL) at room temperature, and stirred for 10 h at the same temperature, and 2 h at 60 °C; the solvent was evaporated to give N-[SPIS][TFA].

General procedure for the synthesis of (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes **1a**–**d**

6-Amino-1,3-dimethyluracil (0.155 g, 1 mmol), aldehyde (1 mmol), 2-hydroxy-1,4-naphthoquinone (0.174 g, 1 mmol) and N-[SPIS][TFA] (0.040 g) were added to absolute EtOH (8 mL), and the resulting mixture was stirred and refluxed. The reaction progress was monitored by TLC (EtOAc/*n*-hexane: 1/1); after consuming the reactants, the solvent was evaporated, EtOAc (20 mL) was added, stirred for 2 min under reflux conditions, followed by centrifugation and decanting to separate the insoluble nanocatalyst. The EtOAc resulted from the decanting was evaporated, and the solid residue was recrystallized from EtOH/H₂O (4/1) to afford the pure product.

General procedure for the preparation of bis(6-amino-1,3-dimethyluracil-5-yl) methanes **2a**-f

A mixture of 6-amino-1,3-dimethyluracil (0310 g, 2 mmol), aldehyde (1 mmol) and N-[SPIS][TFA] (0.020 g) in absolute EtOH (8 mL) was stirred under reflux conditions. After consuming the starting materials (as observed by TLC eluted with EtOAc/*n*-hexane: 1/1), the solvent was evaporated, EtOAc (20 mL) was added, and stirred for 2 min under reflux conditions; the obtained mixture was centrifuged and decanted to separate the insoluble N-[SPIS][TFA] {the catalyst was washed by EtOAc (2×3 mL), dried and used for next run}. The resulted EtOAc from the decanting was evaporated, and the solid residue was purified by recrystallization from EtOH/H₂O (4/1) to give the product.

Note: Selected spectral data and original spectrums of the synthesized aminouracil derivatives have been given in supplementary material.

Results and discussion

Characterization of the nanocatalyst

Our novel nanorod-structured organic-inorganic hybrid material {nanorod-[SiO₂-Pr-Im-SO₃H][TFA] (N-[SPIS][TFA])} was characterized by FT-IR, EDS, FE-SEM, TGA and XRD analyses.

Peak (cm ⁻¹) Bond or functional group	
466	Rocking of Si–O
802	Bending of OH (silanol)
902	Stretching of N-S
1120	Symmetric stretching of -SO ₂ -
1201	Asymmetric stretching of -SO ₂ -
1455	Bending of aliphatic C-H
1682	Stretching of C=N
3149	Stretching of aromatic C-H
2956	Symmetric stretching of aliphatic C-H
2400-3700	Stretching of OH group of the SO ₃ H and OH groups on silica surface



Fig. 1 EDX spectrum of N-[SPIS][TFA]

Table 1 FT-IR data of N-[SPIS]

[TFA]

The FT-IR spectrum (supplementary material, Fig. S1) confirmed the presence of the expected bonds and functional groups in the structure of N-[SPIS][TFA]. The peaks related to the bonds and functional groups of the catalyst are shown in Table 1; the results are in accordance with the literature [31, 34].

In the structure of N-[SPIS][TFA], there are silicon, oxygen, carbon, nitrogen, sulfur, chlorine and fluorine elements; the EDS spectrum confirmed this topic (Fig. 1).

The FE-SEM micrographs of the nanorod silica and N-[SPIS][TFA] are shown in Figs. 2 and 3. In both materials, the particles were observed as nanorod with different sizes; however, the nanorods lengths have shortened in N-[SPIS][TFA].

The TG (thermal gravimetric) and DTG (differential thermal gravimetric) analyses of the organic-inorganic hybrid nanomaterial were also studied (Fig. 4). Weight losses of N-[SPIS][TFA] were occurred during three steps: (1)



Fig. 2 FE-SEM micrographs of the nanorod-silica

low weight loss up to 150 °C can be related to evaporation of the adsorbed solvents (or water) on the silica surface, (2) weight loss at about 150–425 °C can be due to decomposition of the organic moieties anchored to the silica surface and (3) weight loss at about 425–600 °C can be attributed to condensation of the silanol groups. The literature data confirmed the above interpretations [34, 75, 76].

XRD analysis of N-[SPIS][TFA] was accomplished in a domain of $2\theta \approx 7-80$ degrees (Fig. 5). In the XRD spectrum, two broad peaks were observed at $2\theta \approx 9.6-13.0^{\circ}$ and $2\theta \approx 15.0-30.0^{\circ}$. Furthermore, some diffraction lines were seen at $2\theta \approx 8.9^{\circ}$, 11.2° , 12.4° , 13.7° , 20.1° , 21.2° , 22.2° , 22.5° , 24.0° , 26.0° , 28.2° , 41.8° , 45.4° , 50.5° , 53.6° , 54.3° , 58.1° , 67.2° , 69.0° , 71.6° , 73.7° and 77.1° . The results showed that N-[SPIS][TFA] is in amorphous and also crystal-line forms; the literature data confirmed the explanations [34, 77].



Fig. 3 FE-SEM micrographs of N-[SPIS][TFA]

The synthesis of aminouracil derivatives using N-[SPIS][TFA]

To investigate catalytic activity of N-[SPIS][TFA] for the synthesis of the aminouracil derivatives, at first, the following model reactions were chosen: (1) the onepot multi-component reaction of 6-amino-1,3-dimethyluracil (1 mmol), 2-hydroxy-1,4-naphthoquinone (1 mmol) and 4-chlorobenzaldehyde (1 mmol) for the preparation of (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes (Scheme 2), and (2) the one-pot pseudo-three-component reaction of 6-amino-1,3-dimethyluracil (2 mmol) and 4-chlorobenzaldehyde (1 mmol) for the production of bis(6-amino-1,3-dimethyluracil-5-yl)methanes (Scheme 2). Influence of the catalyst amount and solvent on the model reactions were studied (8 mL of the solvents were used); the obtained results are briefed in Table 2. As the data in



Fig. 4 TG and DTG diagrams of N-[SPIS][TFA]



Fig. 5 XRD pattern of N-[SPIS][TFA]

Table 2 indicate, for the synthesis of (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes, utilization of 0.040 g of N-[SPIS][TFA] in refluxed EtOH afforded higher yield and shorter reaction time (Table 2, entry 2), and for the preparation of bis(6-amino-1,3-dimethyluracil-5-yl)methanes, application of



Scheme 2 Production of (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes (1a–d) and bis(6-amino-1,3-dimethyluracil-5-yl)methanes (2a–f)

Entry	Product	The catalyst amount (g)	Solvent	Temp. (°C)	Time (h)	Yield (%)
1	1a	0.032	EtOH	Reflux	4	69
2	1a	0.040	EtOH	Reflux	4	86
3	1a	0.048	EtOH	Reflux	4	81
4	1a	0.040	THF	Reflux	7	57
5	1a	0.040	MeCN	Reflux	7	51
6	1a	0.040	EtOAc	Reflux	7	79
7	1a	0.040	H_2O	80	7	43
8	2b	0.012	EtOH	Reflux	2	84
9	2b	0.020	EtOH	Reflux	1	95
10	2b	0.032	EtOH	Reflux	1	95
11	2b	0.020	THF	Reflux	3	37
12	2b	0.020	MeCN	Reflux	3	72
13	2b	0.020	EtOAc	Reflux	3	61
14	2b	0.020	H_2O	80	3	76

Table 2 Effect of the catalyst amount and solvent on the model reactions

0.020 g of the hybrid nanomaterial in refluxed EtOH gave the better results (Table 2, entry 9).

After finding the best reactions conditions, different aminouracil derivatives were prepared by varying arylaldehydes in the reactions; the products structures, melting points, the reaction times and yields are illustrated in Table 3. As it can be seen in the table, arylaldehydes bearing halogen, electron-withdrawing and

Product No.	Product	Time (h)	Yield ^a (%)	M.p. (°C) [Ref.]
1a	H_3C H_2 H_0 H_1 H_2 H_0 H_3C	4	86	249–251 (254–255) [63]
1b	$H_{3}C$ H_{2} H_{0} H_{0} $H_{3}C$ H_{3	3	83	220–222 (218–220) [64]
1c	H_3C H_2 H_0 H_3C $H_$	4	79	244–246 (245–247) [64]
1d	H_3C NH_2 H_0 H_0 H_3C $H_$	4	81	239–241 (new)
2a	$H_{3}C$ H	1	96	297–299 (294–296) [67]

Table 3 Synthesis of (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphthoquinone-3-yl)methanes(1a-d) and bis(6-amino-1,3-dimethyluracil-5-yl)methanes(2a-f) using N-[SPIS][TFA]

Table 3 (c	continued)
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Product No.	Product	Time (h)	Yield ^a (%)	M.p. (°C) [Ref.]
2b	$H_{3}C$ H	1	95	268–270 (267–269) [67]
2c	H_3C NO_2 H_2C H_2N H_2N CH_3 O N O O N O CH_3	1	94	284–286 (282–283) [65]
2d	$H_{3}C$ $H_{3}C$ H_{2} $H_{2}N$ $H_{2}N$ $H_{2}N$ $H_{3}C$	1	96	276–278 (274–276) [65]
2e	$H_{3}C$ H	1	97	274–276 (new)
2f	$H_{3}CO$ $H_{2}OCH_{3}$ $H_{2}N$ $H_{2}N$ $H_{2}N$ $H_{3}C$ $H_{3}C$ $H_{3}C$ CH_{3}	1	94	272–274 (270–271) [67]

^aIsolated yield

Table 4Results on reusabilityof N-[SPIS][TFA] for theproduction of compound 2b	Recycle	Time (min)	Yield (%)
	Fresh catalyst	1	95
	1	1.5	90
	2	2	87

electron-releasing substituents afforded the corresponding products in high yields and relatively short reaction times. According to the results, we could claim that N-[SPIS][TFA] was a highly efficient catalyst to promote the synthesis of the aminouracil derivatives.

Recyclability of N-[SPIS][TFA] was tested for the synthesis of bis(6-amino-1,3-dimethyluracil-5-yl)methane **2b**. Some reactions were performed for the preparation of this compound, the reactions mixtures were combined, and the catalyst was recycled according to the procedure mentioned in the experimental section; the results are given in Table 4. The catalyst was reusable for two times without significant decrement in the yields; nevertheless, the reaction times were enhanced during reusing.



Scheme 3 Mechanism for the synthesis of (6-amino-1,3-dimethyluracil-5-yl)-(2-hydroxy-1,4-naphtho-quinone-3-yl)methanes



Scheme 4 Proposed mechanism for the production of bis(6-amino-1,3-dimethyluracil-5-yl)methanes

Based on dual-functionality of the catalyst {possessing acidic (SO₃H) and weak basic (trifluoroacetate) sites} and the literature [63, 65, 67], logical mechanisms were proposed for the synthesis of the aminouracil derivatives (Schemes 3 and 4). The catalyst tasks are obviously shown in the mechanisms, the tasks include: (1) activating the electrophiles by the acidic moiety (SO₃H) to accept nucleophilic attacks (Scheme 3: steps 1 and 3; Scheme 4: steps 1' and 3'), (2) assistance to remove H₂O molecule (Scheme 3: step 2; Scheme 4: step 2'), (3) activation of nucleophiles by the basic moiety (trifluoroacetate) (Scheme 3: steps 1 and 3; Scheme 4: steps 1' and 3'), and (4) accelerating the tautomerization steps. Dual-functionality of catalysts bearing SO₃H as acidic moiety and anions like trifluoroacetate, mesylate and hydrogen sulfate as weak basic moiety has been discussed in the literature [78, 79].

Conclusions

Briefly, we have prepared and characterized a novel nanorod-structured organic–inorganic hybrid material; it can use as catalyst to promote organic transformations which need acidic catalyst. Herein, we have successfully applied the nanorod material as catalyst for the synthesis of aminouracil derivatives; the advantages of the presented catalytic processes consist of high performance, relatively short reactions times, high yields, no need to column chromatography for purification of the products, relatively mild conditions, utilization of few amounts of the catalyst and reusability of the catalyst.

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References

- 1. V.P. Ananikov, Nanomaterials 9, 1197 (2019)
- 2. L. Fu, H. Gao, M. Yan, S. Li, X. Li, Z. Dai, S. Liu, Small 11, 2938 (2015)
- 3. J. Wang, X. Tan, X. Pang, L. Liu, F. Tan, N. Li, A.C.S. Appl, Mater. Interfaces 8, 24331 (2016)
- 4. B.B. Caravieri, N.A.M. de Jesus, L.K. de Oliveira, M.D. Araujo, G.P. Andrade, E.F. Molina, A.C.S. Appl, Bio Mater. 2, 1875 (2019)
- Y. He, Q. Chen, S. Yang, C. Lu, M. Feng, Y. Jiang, G. Cao, J. Zhang, C. Liu, Compos. Part A Appl. Sci. Manuf. 108, 12 (2018)
- 6. N. Lashgari, A. Badiei, G. Mohammadi Ziarani, Nanochem. Res. 1, 127 (2016)
- J. Chen, Q. Yu, X. Cui, M. Dong, J. Zhang, C. Wang, J. Fan, Y. Zhu, Z. Guo, J. Mater. Chem. C 7, 11710 (2019)
- C. Lou, T. Jing, J. Tian, Y. Zheng, J. Zhang, M. Dong, C. Wang, C. Hou, J. Fan, Z. Guo, J. Mater. Res. 34, 2964 (2019)
- 9. Q. Wang, Y. Zhao, Q. Yang, D. Du, H. Yang, Y. Lin, Biosens. Bioelectron. 141, 111431 (2019)
- 10. E.J. Yoo, M. Lyu, J.-H. Yun, C.J. Kang, Y.J. Choi, L. Wang, Adv. Mater. 27, 6170 (2015)
- 11. A. Kayan, Adv. Compos. Hybrid Mater. **2**, 34 (2019)
- 12. Y. He, Q. Chen, H. Liu, L. Zhang, D. Wu, C. Lu, W.O. Yang, D. Jiang, M. Wu, J. Zhang, Y. Li, J. Fan, C. Liu, Z. Guo, Macromol. Mater. Eng. **304**, 1900166 (2019)
- 13. Y. He, D. Wu, M. Zhou, H. Liu, L. Zhang, Q. Chen, B. Yao, D. Yao, D. Jiang, C. Liu, Z. Guo, Appl. Surf. Sci. **506**, 144946 (2020)
- 14. Y. Zheng, X. Wang, G. Wu, Polym. Adv. Technol. 31, 527 (2020)
- 15. Y. Zheng, L. Chen, X. Wang, G. Wu, Polymers 12, 45 (2020)
- J. Hu, J. Lin, Y. Zhang, Z. Lin, Z. Qiao, Z. Liu, W. Yang, X. Liu, M. Dong, Z. Guo, J. Mater. Chem. A 7, 26039 (2019)
- J. Lin, X.Y. Chen, C.Y. Chen, J.T. Hu, C.L. Zhou, X.F. Cai, W. Wang, C. Zheng, P. Zhang, J. Cheng, Z.H. Guo, H. Liu, A.C.S. Appl, Mater. Interfaces 10, 6124 (2018)
- Y. Zhang, Y. An, L. Wu, H. Chen, Z. Li, H. Dou, V. Murugadoss, J. Fan, X. Zhang, X. Mai, Z. Guo, J. Mater. Chem. A. 7, 19668 (2019)
- 19. H. Gu, X. Xu, J. Cai, S. Wei, H. Wei, H. Liu, D.P. Young, Q. Shao, S. Wu, T. Dingi, Z. Guo, Chem. Commun. 55, 10068 (2019)
- G. Zhu, X. Cui, Y. Zhang, Sh Chen, M. Dong, H. Liu, Q. Shao, T. Dinge, S. Wuf, Z. Guo, Polymer 172, 415 (2019)
- Q. Chen, Q. Yin, A. Dong, Y. Gao, Y. Qian, D. Wang, M. Dong, Q. Shao, H. Liu, B.-H. Han, T. Ding, Z. Guo, N. Wang, Polymer 169, 255 (2019)
- 22. H. Wei, H. Wang, Y. Xia, D. Cui, Y. Shi, M. Dong, C. Liu, T. Ding, J. Zhang, Y. Ma, N. Wang, Z. Wang, Y. Sun, R. Wei, Z. Guo, J. Mater. Chem. C 6, 12446 (2018)
- 23. J.-N. Chen, S.-P. Zhao, W.-H. Hu, J. Zhang, M.-Y. Dong, H. Liu, Z. Huang, Y.-Q. Liu, Z. Wang, Z. Guo, Sci. Adv. Mater. **11**, 1340 (2019)
- 24. A.P. Shah, A.S. Sharma, S. Jain, N.G. Shimpi, New J. Chem. 42, 8724 (2018)

- 25. F. Kalantari, A. Ramazani, M.R. Poor Heravi, Curr. Org. Chem. 23, 136 (2019)
- 26. N. Safajoo, B.B.F. Mirjalili, A. Bamoniri, RSC Adv. 9, 1278 (2019)
- 27. A. Maleki, F. Hassanzadeh-Afruzi, Z. Varzi, M.S. Esmaeili, Mater. Sci. Eng., C 109, 110502 (2020)
- 28. R. Kordnezhadian, M. Shekouhy, A. Khalafi-Nezhad, New J. Chem. 43, 18559 (2019)
- 29. M. Gholamhosseini-Nazari, S. Esmati, K.D. Safa, A. Khataee, R. Teimuri-Mofrad, Res. Chem. Intermed. 45, 1841 (2019)
- 30. H. Sharghi, M. Aberi, P. Shiri, Appl. Organomet. Chem. 33, e4974 (2019)
- 31. A. Zare, M. Merajoddin, A.R. Moosavi-Zare, M. Zarei, M.H. Beyzavi, M.A. Zolfigol, Res. Chem. Intermed. 42, 2365 (2016)
- 32. A. Zare, A. Kohzadian, Z. Abshirini, S.S. Sajadikhah, J. Phipps, M. Benamarad, M.H. Beyzavi, New J. Chem. 43, 2247 (2019)
- 33. M. Kazemi, M. Ghobadi, A. Mirzaie, Nanotechnol. Rev. 7, 43 (2018)
- 34. A. Zare, M. Sadeghi-Takallo, M. Karami, A. Kohzadian, Res. Chem. Intermed. 45, 2999 (2019)
- 35. A. Kohzadian, A. Zare, Silicon (2019). https://doi.org/10.1007/s12633-019-00235-0.
- G. Xu, C. Jia, Z. Shi, R. Liang, C. Wu, H. Liu, C. Yan, J. Fan, H. Hou, T. Ding, Z. Guo, Sci. Adv. Mater. 12, 304 (2020)
- 37. Y. Guo, K. Ruan, X. Yang, T. Ma, J. Kong, N. Wu, J. Zhang, J. Gu, Z. Guo, J. Mater. Chem. C 7, 7035 (2019)
- X.-L. Luo, F. Pei, W. Wang, H.-M. Qian, K.-K. Miao, Z. Pan, Y.-S. Chen, G.-D. Feng, Micropor. Mesopor. Mater. 262, 148 (2018)
- 39. Y.G. Tong, Z.H. Cai, S.X. Bai, Y.L. Hu, M.Y. Hua, W. Xie, Y.C. Ye, Y. Li, Ceram. Int. 44, 16577 (2018)
- 40. Y. Tong, P. Qi, X. Liang, Y. Chen, Y. Hu, Z. Hu, Materials 11, 1250 (2018)
- 41. L. Sun, Q. Shao, Y. Zhang, H. Jiang, S. Ge, S. Lou, J. Lin, J. Zhang, S. Wu, M. Dong, Z. Guo, J. Colloid Interface Sci. 565, 142 (2020)
- 42. J. Zhang, W. Zhang, L. Wei, L. Pu, J. Liu, H. Liu, Y. Li, J. Fan, T. Ding, Z. Guo, Macromol. Mater. Eng. **304**, 1900374 (2019)
- D. Jiang, Y. Wang, B. Li, C. Sun, Z. Wu, H. Yan, L. Xing, S. Qi, Y. Li, H. Liu, W. Xie, X. Wang, T. Ding, Z. Guo, Macromol. Mater. Eng. 304, 1900074 (2019)
- 44. L. Ma, Y. Zhu, P. Feng, G. Song, Y. Huang, H. Liu, J. Zhang, J. Fan, H. Hou, Z. Guo, Compos. Part B Eng. **176**, 107078 (2019)
- 45. Gu Hongbo, Xu Xiaojiang, Mengyao Dong, Peitao Xie, Qian Shao, Runhua Fan, Chuntai Liu, Wu Shide, Renbo Wei, Zhanhu Guo, Carbon **147**, 550 (2019)
- 46. J. Krishnan, A. Jose, B.S. Sasidhar, E. Suresh, R.S. Menon, V. Nair, Org. Chem. Front. 5, 1202 (2018)
- 47. R. Kordnezhadian, M. Shekouhy, S. Karimian, A. Khalafi-Nezhad, J. Catal. 380, 91 (2019)
- 48. A. Kohzadian, A. Zare, Res. Chem. Intermed. 45, 5473 (2019)
- 49. V. Palermo, A.A. Sosa, T.S. Rivera, L.R. Pizzio, G.P. Romanelli, Org. Prep. Proced. Int. 51, 443 (2019)
- R.H. Garrett, D.M. Grisham, Principles of Biochemistry with a Human Focus (Brooks/Cole Thomson Learning, United States, 1997)
- 51. J.D. Noia, M.S. Neuberger, Nature **419**, 43 (2002)
- 52. A. Drabczynska, C.E. Muller, A. Schiedel, B. Schumacher, J.K. Wojciechowska, A. Fruzinski, W. Zobnina, O. Yuzlenko, K. Kiec-Kononowicz, Bioorg. Med. Chem. **15**, 6956 (2007)
- J.A. Valderrama, P. Colonelli, D. Vásquez, M.F. González, J.A. Rodríguez, C. Theoduloz, Bioorg. Med. Chem. 16, 10172 (2008)
- 54. V. Nair, G. Chi, Q. Shu, J. Julander, D.F. Smee, Bioorg. Med. Chem. Lett. 19, 1425 (2009)
- 55. A. Pałasz, D. Cież, Eur. J. Med. Chem. 97, 582 (2015)
- 56. G. Lu, X. Li, K. Mohamed O, D. Wang, F. Meng, Eur. J. Med. Chem. 171, 282 (2019)
- 57. K. Yagi, K. Akimoto, N. Mimori, T. Miyake, M. Kudo, K. Arai, S. Ishii, Pest Manag. Sci. 56, 65 (2000)
- 58. E. Lunt, C.G. Newton, in *Comprehensive Heterocyclic Chemistry*, vol. 3, ed. by A.R. Katritzky, C.W. Rees (Pergamon, Oxford, 1984)
- 59. G. Mohammadi Ziarani, N. Hosseini Nasab, N. Lashgari, RSC Adv. 6, 38827 (2016)
- R.A. Al-Qawasmeh, Y. Lee, M.Y. Cao, X. Gu, A. Vassilakos, J.A. Wright, A. Young, Bioorg. Med. Chem. Lett. 14, 347 (2004)
- 61. J.-C. Jung, Y.J. Jung, O.S. Park, Molecules 14, 4790 (2009)

- 62. N.R. Emmadi, K. Atmakur, C. Bingi, N.R. Godumagadda, C.G. Kumar, J.B. Nanubolu, Bioorg. Med. Chem. Lett. 24, 485 (2014)
- 63. R. Bharti, T. Parvin, RSC Adv. 5, 66833 (2015)
- 64. P. Kumari, R. Bharti, T. Parvin, Mol. Divers. 23, 205 (2019)
- 65. G. Brahmachari, B. Banerjee, RSC Adv. 5, 39263 (2015)
- J. Azizian, M.R. Mohammadizadeh, F. Teimouri, A.A. Mohammadi, A.R. Karimi, Synth. Commun. 36, 3631 (2006)
- 67. A. Zare, A. Ghobadpoor, T. Safdari, Res. Chem. Intermed. 46, 1319 (2020)
- 68. A.R. Karimi, Z. Dalirnasab, M. Karimi, F. Bagherian, Synthesis 45, 3300 (2013)
- 69. B. Banerjee, G. Brahmachari, Curr. Organocatal. 3, 125 (2016)
- R. Bansal, R.S. Kumar, G. Kumar, S. Thota, S. Thamotharan, V. Parthasarathi, A. Linden, J. Heterocyclic Chem. 45, 1789 (2008)
- 71. D. Shi, J. Shi, S. Rong, Chin. J. Chem. 28, 791 (2010)
- 72. L. Wu, X. Jing, M. Lin, C. Yan, J. Yang, H. Zhu, Synth. Commun. 42, 849 (2012)
- F. Kamali, M.M. Eskandari, A. Rashidi, M. Baghalha, M. Hassanisadi, T. Hamzehlouyan, J. Hazard. Mater. 364, 218 (2019)
- 74. A. Sayari, B.-H. Han, Y. Yang, J. Am. Chem. Soc. 126, 14348 (2004)
- 75. A. Biabani-Ravandi, M. Rezaei, Chem. Eng. J. 184, 141 (2012)
- M. Nikoorazm, A. Ghorbani-Choghamarani, M. Khanmoradi, Appl. Organomet. Chem. 30, 705 (2016)
- 77. R.E. Morsi, R.S. Mohamed, R. Soc, Open Sci. 5, 172021 (2018)
- N. Irannejad-Gheshlaghchaei, A. Zare, S.S. Sajadikhah, A. Banaei, Res. Chem. Intermed. 44, 6253 (2018)
- 79. Z. Kordrostami, A. Zare, M. Karami, Z. Naturforsch. 74b, 641 (2019)

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