

# Reusable photoresponsive Ag/AgCl nanocube-catalyzed one-pot synthesis of seleno[2,3-b]pyridine derivatives

Yasser Attia Attia<sup>1</sup> · Shams H. Abdel-Hafez<sup>2,3</sup>

Received: 14 January 2020 / Accepted: 27 March 2020 © Springer Nature B.V. 2020

# Abstract

In this study, a facile and rapid method was developed to synthesize intensely organoselenium compounds, namely ethylseleno[2,3-b]pyridine carboxylate, seleno[2,3b]pyridine-2-carbonitrile and 2-benzoylseleno[2,3-b]pyridine derivatives from starting compound, 2-chloro-3-cyano-4,6-dimethylpyridine, in one-pot synthesis using Ag/AgCl nanoparticles (NPs) under visible light irradiation. Three different shapes of Ag/AgCl nanoparticles (nanospheres (NS), nanocubes (NC) and nanowires (NW)) were synthesized by controlling the concentration ratio between silver nitrate (AgNO<sub>3</sub>) and hydrochloric acid. The Ag/AgCl NPs were characterized using different tools such as scanning electron microscopy, UV-Vis spectrophotometry and X-ray diffraction. The catalytic activity of the photoresponsive Ag/AgCl nanoparticles with different morphology was evaluated towards organoselenium compounds production. The following rate order of seleno[2,3-b]pyridine derivatives production and organic dye degradation under visible light irradiation was Ag/AgCl-NC>Ag/ AgCl-NW>Ag/AgCl-NS. The mechanism of the production of seleno[2,3-b]pyridine derivatives has been proposed. It is clearly shown from the results that high yield of selective organoselenium compounds (>90%) was obtained under mild conditions with short reaction time and the photocatalytic activity of the prepared Ag/AgCl nanoparticles depends on their morphology.

**Keywords** Ag/AgCl nanoparticles · Catalysis · Organoselenium compounds · Pyridines · Selective reaction

Yasser Attia Attia yasserniles@niles.edu.eg

> Shams H. Abdel-Hafez shams\_abdelhafez@yahoo.com

<sup>1</sup> National Institute of Laser Enhanced Sciences, Cairo University, Giza 12613, Egypt

<sup>2</sup> Department of Chemistry, Faculty of Science, Assiut University, Assiut 71516, Egypt

<sup>3</sup> Department of Chemistry, Faculty of Science, Taif University, Taif 21974, Saudi Arabia

#### Introduction

The development of high-performance catalysts with aimed catalytic activity, selectivity, and prolonged lifetime would benefit the chemical industry enormously; such research endeavors have been persistently pursued by both academia and industry [1]. A new understanding and mastery of catalysis could have broad societal impacts since about 80% of the processes in the chemical industry depend on catalysts to work efficiently [2–7]. The advent of nanoscience and nanotechnology is providing the ability to create controlled structures and geometries to investigate and optimize a broad range of catalytic processes [8, 9]. As a result, researchers are obtaining fundamental insight into key features that influence the activity, selectivity and lifetime of nanocatalysts [10, 11]. In recent years, heterocyclic compounds based on selenium atom have attracted the attention of scientists working in a variety of fields due to their reactivity, chemical properties and pharmaceutical applications [12–17]. Abdel-Hafez et al. tried to prepare seleno[2,3-b]pyridine derivatives (2-4) in onestep from compound (1) after 3 h of refluxing (harsh reaction conditions) and unfortunately poor chemoselectivity with low yield obtained (<15%) [18–20]. Hence, in this report we wonder if there is a relation between the shape of Ag/AgCl NPs and their catalytic performance towards organoselenum compounds production and the possibilities to develop an approach for the synthesis of valuable seleno[2,3-b]pyridine derivatives.

The Ag/AgX NPs (Cl, Br and I) are being widely used instead of the highly dispersed AgX species that can improve the separation efficiency of photogenerated charge carriers and enhance the photocatalytic activity of the substrates. Furthermore, under visible light irradiation, the generated electron-hole pairs are separated on the surface of Ag NPs due to the surface plasmon resonance (SPR) effect. Hence, recently these plasmonic photocatalysts have been developed for the high adsorption of visible light and excellent photodegradation of organic pollutants due to the strong surface plasmon resonance (SPR) effect of metallic Ag nanoparticles (Ag NPs) [21-25]. Among Ag/AgX hybrid photocatalysts, considerable attention has been paid to Ag/AgCl due to its relatively high stability and excellent photocatalytic activity under UV and visible light irradiation. Although the band gap energy of AgCl is higher than the edge of visible light (the direct and indirect band gaps of AgCl are 5.15 eV and 3.25 eV, and the edge of visible light is located at 3.1 eV), it is a photosensitive compound and can adsorb photons and then electron-hole pairs can be generated and subsequently the Ag<sup>+</sup> on the surface of AgCl particle can be reduced to metallic Ag to form Ag/AgCl composite and extend the light response into the visible light region [26]. However, some of the reported synthesis procedures are multi-steps and time-consuming, and some need high temperature [27]. Together, the size and the shape introducing sharp corners and edges to the shape of the nanocatalysts are considered as influencing parameters that can increase the catalytic efficiency because of the presence of surface atoms that can be displayed as active sites [28]. Herein, the catalytic synthesis of seleno[2,3-b]pyridine derivatives was investigated to study the catalytic efficiency of Ag/AgCl nanocatalysts in different shapes (sphere, wires and cubes) under visible light.

# Experimental

All chemicals were obtained from Sigma-Aldrich company and used as received. UV–Vis spectra were measured with a PerkinElmer Lambda 40 UV–visible spectrophotometer using 1-cm-path length Hellma quartz cuvettes. X-ray diffraction (XRD) measurements were performed using a Philips PW1710 X-ray diffractometer using Cu Ka radiation (k = 1.54186 Å). The XRD patterns were recorded from 20° to 70° 2H with a step size of 0.020° 2 $\theta$  and collecting 10 s per step. Scanning electron microscopy (SEM) images were obtained with a ZEISS FE-SEM ULTRA Plus (equipped with EDX analyzer) microscope with a Philips CM20 microscope, operating at an accelerating voltage of 200 kV. Several drops from the sample dispersion were deposited onto an aluminium pin stubs and left to evaporate at room temperature. Melting points (m.p.) were uncorrected using IA9100M-Digital Melting Point Apparatus. Thin-layer chromatography (TLC) was performed by silica gel plates 60 GF254, cellulose plates (20×20 cm). <sup>1</sup>H NMR and <sup>13</sup>C NMR spectra were determined on Bruker Avance DPX spectrometer at 300 MHZ for <sup>1</sup>H NMR and 75 MHz for <sup>13</sup>C NMR.

### Preparation of Ag/AgCl nanoparticles (spheres, cubes and wires)

AgCl and Ag/AgCl nanoparticles were synthesized via the reaction of AgNO<sub>3</sub> and HCl in ethylene glycol in the presence of a capping agent (PVP); 425 mg of AgNO<sub>3</sub> (~50 mM) and 415 mg of PVP (~75 mM) were dissolved in 50 mL of ethylene glycol (EG). After mixing the solution with a magnetic stirrer for 5 min, the solution was kept without motion to age for 1 h. Then a small amount of HCl was added to the solution. Final concentration of HCl was adjusted to 50 mM, 150 mM and 300 mM with 1:1, 1:3 and 1:6 ratio, respectively, to produce Ag/AgCl nanoparticles with different shapes. The solution was then heated to 150 °C. The reaction lasted at this temperature for 20 min unless specified. After the solution was cooled down to room temperature, 100 mL of acetone and 150 mL of deionized (DI) water were added and centrifuged at 2000 rpm for 20 min. The resulting precipitates were white and dark white powders, and after that the powder was dried in an oven for 3 h. The formed powders were characterized using SEM, XRD and UV–Vis measurements for further work.

#### Photocatalytic degradation of amaranth dye (C.I. Food Red 9)

Ten milligrams of the prepared Ag/AgCl nanoparticles (nanospheres, nanowires and nanocubes) was added to 50 mL of 0.1 mM of amaranth dye under stirring and then irradiated with halogen lamp (HALOPAR 20 75 W 230 V 30-GU10, Italy). The photodegradation of the dye was followed by measuring the UV–Vis absorption at different times.

General Procedure for the production of 3-amino-2-substituted seleno[2,3-b]pyridine (2; C<sub>12</sub>H<sub>14</sub>N<sub>2</sub>O<sub>2</sub>Se) (3; C<sub>10</sub>H<sub>9</sub>N<sub>3</sub>Se) and (4; C<sub>16</sub>H<sub>14</sub>N<sub>2</sub>OSe) from 2-chloro-3-cyano-4,6-dimethylpyridine (1)

**4,6-Dimethyl-2-chloro-3-cyanopyridine 1** (1 mmol) was added stepwise in a mixture of selenium metal (1 g, 12 mmol) and sodium borohydride (1.2 g, 32 mmol) in ethanol. The reaction mixture was stirred for 15 min at room temperature after the addition of Ag/AgCl NPs (0.05 mmol); then, 3 mmol of chloroethylacetate or chloroacetonitrile or benzoyl chloride was added instead of halo ester or alkyl halide. The resulting mixture was irradiated with halogen lamp (HALOPAR 20 75 W 230 V 30-GU10, Italy) for different times (0–2 h) and then poured onto an ice water. The precipitated compounds were collected and the yield was measured. m.p.s., and all spectral data were in agreement with those of the reported compounds [29].

3-Amino-4,6-dimethyl-2-ethylseleno[2,3-b]pyridine carboxylate (5a) m.p. 155–156 °C (crystallization of ethanol).<sup>1</sup>H NMR:  $\delta$ =1.38–1.68 (t, *J*=9.00 Hz, 3H, CH<sub>3</sub> ester), 2.50, 2.75 (2 s, 6H, 2CH<sub>3</sub> pyridine), 4.30 (q, *J*=7.50 Hz, 2H, CH<sub>2</sub>), 6.88 (s, 1H, CH pyridine), 7.28 (s, 2H, NH2) ppm; mass spectra of compounds 2 exhibited molecular ion peak at *m/z*, (%) 298 (M<sup>+</sup> + f $_{\rm h}$  100%).

**3-Amino-4,6-dimethylseleno[2,3-b]pyridine-2-carbonitrile (5b)** m.p. 208–209 °C (crystallization of ethanol).<sup>1</sup>H NMR:  $\delta$ =2.55, 2.75 (2 s, 6H, 2CH<sub>3</sub> pyridine), 6.88 (s, 1H, CH pyridine), 7.28 (s, 2H, NH<sub>2</sub>) ppm; mass spectra of compounds 6a exhibited molecular ion peak at *m/z*, (%) 251 (M<sup>+</sup> + fl, 100%).

**2-Benzoyl-3-amino-4,6-dimethylseleno[2,3-b]pyridine (5c)** m.p. 250–252 °C (Crystallization ethanol).<sup>1</sup>H NMR:  $\delta$ =2.50, 2.70 (2 s, 6H, 2CH<sub>3</sub> pyridine), 6.85 (s, 1H, CH pyridine), 7.30 (s, 2H, NH<sub>2</sub>), 7.55–8.00 (m, 5H, Ph-H) ppm; mass spectra of compounds **6a** exhibited molecular ion peak at *m/z*, (%) 330 (M<sup>+</sup> + f, 100%).

# **Results and discussion**

Different shapes of Ag/AgCl nanoparticles were prepared by controlling the concentration ration between AgNO<sub>3</sub> and HCl. The morphology of the prepared shapes is shown in Fig. 1. Ag/AgCl nanospheres (Fig. 1a) were prepared with equal concentrations of AgNO3 and HCl (1:1), while Ag/AgCl (Fig. 1b) nanowires and nanocubes (Fig. 1c) were formed with ratios 1:3 and 1:6, respectively. The synthesis of mono dispersed silver nanocubes using polyol method via the EG reduction of silver nitrate at 140 °C in the presence of PVP and HCl was reported by Im and Km et al., in which the selective etching and dissolution of twinned-crystal silver seeds was proposed to play the key role [28, 30]. In this work, we report an interesting finding that this synthesis route for silver chloride nanocubes can be modified to synthesize silver clusters at the corners of silver chloride nanocubes at a very high yield only by





aging the fresh AgNO<sub>3</sub>/PVP/EG for 1 h solution under ambient atmosphere without the change in any other reaction parameters and also without any further reducing process as described by Kim et al. [30]. Morphologies of the final products were greatly affected by the molar ratio of AgNO<sub>3</sub> and HCl. Uniform nanospheres with size distribution ranging from 45 nm to 386 nm were formed when the Ag:Cl ratio was 1:1. Non-uniform nanowires with an aspect ratio of  $18 \pm 2.1$  nm and various forms with a wide size distribution were obtained when the AgNO<sub>3</sub>/HCl ratio was 1:3. At the ratio of 1:6, uniform nanocubes with smaller size ( $1=241\pm46$  nm) were observed together with small silver clusters (<5 nm) as shown in Fig. 1c.

As shown previously, the maximum absorption peak depends on the shape of the nanostructures [8]. The absorbance spectra of the prepared samples are shown in Fig. 2. Ag/AgCINSs showed a maximum absorbance at 427 nm (Fig. 2a) that shifted to shorter wavelength at 362 nm with another peak appears at 549 nm when the concentration ratio AgNO<sub>3</sub>/HCl changed to 1:2 as Ag/AgClNCs formed (Fig. 2c) while, increasing the concentration ratio to 1:6, Ag/AgCINWs were formed with maximum absorbance at 358 nm with prediction appearance of longitudinal band at more than 1200 nm (Fig. 1e). When the ratio of Ag<sup>+</sup> ions to Cl<sup>-</sup> ions is above a certain level, small Ag atom clusters may form locally in the solution and act as nucleation seeds, of which nucleation kinetics could be different from that of silver chloride seeds. Therefore, the presence of different nucleation seeds under high Ag/Cl ratio may explain the wide size distribution of the AgCl particles at the initial stage of growth. The band gap of the Ag/AgCln anocatalysts can be calculated from the estimated absorption edge wavelength of the spherical, cubic and wire shapes by using Tauc plot to be 2.96, 2.23, 5.25 eV, respectively (Fig. 2b, d and e). The photoluminescence of the formed Ag/AgCl NPs are shown in Fig. 1g. The sample Ag/AgCl NCs has shown the highest intensity of luminescence in visible light range.

The Ag/AgCl has a porous and uniform morphology, cluster at the face of the cube and concentrated at the corners of the cubes while concentrated at the tips of the wires which can enlarge the specific surface area and accelerate the photocatalytic activity of the photocatalyst. To confirm the morphology of the as-prepared particles, XRD analysis was carried out as shown in Fig. 3. The XRD patterns of the photocatalysts Ag/AgCl are mainly composed of AgCl nanoparticle with the peaks at  $(2\theta = 29.23^\circ, 35.95^\circ, 44.74^\circ, 54.7^\circ \text{ and } 57.3^\circ)$  corresponding to planes {(111), (200), (220), (311) and (222)} in addition to the peaks of silver cluster sat the peaks  $(2\theta = 38.05^\circ, 44.24^\circ, 64.39^\circ \text{ and } 73.6^\circ)$  corresponding to the planes {(111), (200), (220) and (420)} [28, 30].

The photocatalytic performance of the samples Ag/AgCl (nanospheres, nanocubes and nanowires) was monitored by degradation of amaranth dye in aqueous solution under visible irradiation as recorded in Fig. 4. The amaranth dye under visible light for 3 h without catalyst (Fig. 4a) and with Ag/AgCl nanocatalyst in cubic shape under dark condition for 3 h (Fig. 4b) did not show any degradation performance. Amaranth dye is photodegraded within 240 min in the presence of Ag/AgCl NPs in spherical shape (Fig. 4c) and within 120 min with Ag/AgCl nanowires under visible light as shown in Fig. 4d. However, for complete degradation of amaranth dye, only 40 min was enough with Ag/AgCl nanocubes (Fig. 4e). The photodegradation rate order under visible light irradiation of the samples is:



**Fig. 2** Absorption spectra of the formed Ag/AgCl NSs (**a**), NCs (**c**) and NWs (**e**). Tauc plot for the prepared samples: NSs (**b**), NCs (**d**) and NWs (**f**). The photoluminescence of the formed Ag/AgCl NPs (**g**) at  $\lambda_{ex} = 271$  nm



Fig. 3 XRD patterns of the prepared Ag/AgCl nanoparticles with different morphology

nanospheres < nanowires < nanocubes. These results indicate that the photocatalytic activity can be enhanced by the presence of Ag clusters at the corners of the cubes and at the tips of nanowires.

Investigation of optical properties of the Ag/AgCINCs showed that as-synthesized Ag/AgCINCs absorb light not only in the UV but also in visible region. In addition, the absorption peak in the visible region was red-shifted as the size of NCs increased. This visible light absorption mainly due to thin Ag clusters formed on the AgCl nanocube surfaces. On the other hand, it has been shown that Ag nanoparticles deposited on AgCl show the plasmonic absorption of visible light. As the Ag/Cl ratio increases, the formation of catalytic Ag clusters on the surface of AgCl is increased. The enhancement of catalytic photodegradation of Ag/AgClNCs is also due to the cubic shape nanoparticles with the presence of semiconducting silver clusters that have two band gaps direct and indirect as reported [28]. The illumination of suspended AgCl in an aqueous solution of dye with unfiltered light (polychromatic light) leads to the possibility of two pathways. The first pathway, a part of light with energy equal to or more than the band gap of the illuminated semiconductor will cause a promotion of an electron to conduction band of the AgCl and as a result, a positive hole will be created in the valence band. The formed photoholes and photoelectrons can move to the surface of the semiconductor in the presence of light energy. The positive hole will react with adsorbed water molecules on the surface of AgCl producing OH radicals, and the electron will react with adsorbed oxygen on the surface. Moreover, they can react with deliquescent oxygen and water in suspended liquid and produce per hydroxyl radicals (HO) with high chemical activity. The processes in this pathway can be summarized by the following equations. Photocatalysis on AgCl oxides relies on the absorption of photons with energy equal to or greater than the band gap of the oxide, so that electrons are promoted from the valence



**Fig. 4** Absorption spectra showing the amaranth dye photodegradation with Ag/AgCl nanocubes under dark (**a**) and with using different shapes of Ag/AgCl NSs (**b**), NWs (**c**) and NCs (**d**) under visible light irradiation

band to the conduction band. In the second pathway, the other part of light with energy which is less than the band gap of the catalyst AgCl will be absorbed by the adsorbed dye molecules. Dye molecules will be decolorized by a photosensitization process. The photocatalytic decolorization of dyes, which is described as photosensitization processes, is also characterized by a free radical mechanism. In this process, the adsorbed dye molecules on the surface of the catalyst can absorb a radiation in the visible range in addition to the radiation with short wavelengths. The excited colored dye (dye\*) will inject an electron to the conduction band of the semiconductor.

#### Chemoselective production reaction of seleno[2,3-b]pyridine derivatives

The effect of the three morphologies of Ag/AgCl nanoparticles was firstly examined on the reaction of 4,6-dimethyl-2-chloro-3-cyanopyridine(1) by using three different forms of Ag/AgCl in presence of sodium borohydride, Se metal and ClCH<sub>2</sub>X (X=-COOEt, -CN and -COPh) in ethanol under illumination with visible light (Table 1).

As shown in Table 1, firstly under catalyst-free condition and refluxing the mixture reaction for 3 h (entry 1), there was low yield of compounds 5a-c was obtained in our previously work [18]. Then, under catalyst-free conditions in dark (entry 2) and in visible light (entry 3) conditions, there was no reaction and no yield for seleno[2,3-b]pyridine derivatives. We then started to use the Ag/AgCl-NS as catalyst in dark, adducts 5a-c were not formed (entry 4). Whereas by operating the reaction under visible light irradiation, compounds 5a-c were formed in 64%, 54% and 57% isolated yield, respectively (entry 5). When Ag/AgCl-NW was used in the catalyzed reduction reaction in dark condition, the reaction did not proceed (entry 6). However, products 5a-c were resulted under visible light condition in 79%, 61% and 65% isolated yield, respectively (entry 7). Finally, again when the reaction was employed using Ag/AgCl-NC in dark (entry 8), the reaction was not performed, while high yield of products 5a-c under visible light irradiation for 1 h (94%, 82% and 85%) (entry 9) and under visible irradiation for 2 h (97%, 89% and 90%) (entry 10) was obtained.

The proposed mechanism depends on the reaction of 4,6-dimethyl-2-chloro-3-cyanopyridine (1) with ethyl chloroacetate or chloroacetonitrile or phenacyl chloride in the presence of sodium borohydride under the same conditions and gave firstly, the

Table 1 The photocatalytic activity of Ag/AgCl nanoparticles with different shapes towards the production of seleno[2,3-b]pyridine derivatives 5a–c	Entry	Entry Catalyst Rx condition		Time/h	Isolated yield% <sup>c</sup>		
					5a	5b	5c
	1	Non <sup>a</sup>	Reflux	3	15	10	11
	2	Non <sup>a</sup>	Dark	24	_	_	_
	3	Non <sup>b</sup>	Visible light	24	_	_	_
	4	Ag/AgCl-NS	Dark	24	_	_	_
	5	Ag/AgCl-NS	Visible light	2	64	54	57
	6	Ag/AgCl-NW	Dark	24	_	_	_
	7	Ag/AgCl-NW	Visible light	2	79	61	65
	8	Ag/AgCl-NC	Dark	24	_	_	_
	9	Ag/AgCl-NC	Visible light	1	94	82	85
	10	Ag/AgCl-NC	Visible light	2	97	89	90

(a) Without catalyst, (b) visible light in the range of 450–600 and (c) the crude reduced product was purified and isolated



**Scheme 1** The proposed mechanism of the production of ethyl carboxylate or carbonitrile or benzoyl seleno[2,3-b]pyridine derivatives

corresponding intermediate ethyl selenoacetate or selenoacetonitrile or benzoylseleno pyridine derivatives. Secondly, the intermediate compounds underwent smooth Thorpe–Ziegler cyclization (as shown in scheme 1), to form the corresponding compound derivatives [31]. The presence of photoresponsive Ag/AgCl NPs accelerates the reaction and enhances the yield of the products. The cube-shaped Ag/AgCl NPs have shown the highest catalytic activity for the organoselenium compounds production due to the presence of silver clusters. It was indicated that the incident light has an energetic role in heterogeneous catalyzed multi-component reaction (MCR). Ag nanoparticles helped in absorbance of the light; then, the electrons and holes in AgCl were moved to conduction band which then participated in accelerating the reaction between the produced intermediates. Under the influence of visible light, absorption of light occurs through the catalytic action of the Ag/AgCln anocomposite which in turn activates the reaction to form the sodium salt of intermediate (2) by nucleophilic substitution reaction of NaSeH and eliminates the chlorine atom in compound (1). Salt of compound 2 was generated in ethanol and reacted with

Table 2Study of the reusabilityof Ag/AgCl-NC photocatalyst	Cycle	Isolated yield%
in the production of compound <b>5a</b> under visible light irradiation for 1 h	1st	94
	2nd	93
	3rd	93
	4th	91
	5th	91

halo acid (Cl–CH<sub>2</sub>–X) via the SN<sup>2</sup> mechanism to form the intermediate (**3a–c**). The subsequent intramolecular Thrope–Ziegler cyclization proceeded via the formation of intermediate (**4a–c**) to give the final products (**5a–c**) [32]. To confirm the high stability and catalytic activity of the cube shape, catalyst recovery experiment has been done.

#### **Catalyst recovery**

The Ag/AgCl-NC was filtered and reused in 5 cycles in the production of compound **5a**; it was revealed that the catalyst was active in the 5 cycles and the yield of compound **5a** was obtained in  $ca \sim 94-91\%$  isolated yield under visible light irradiation for 1 h (Table 2).

## Conclusions

In this work, the controlled synthesis of Ag/AgCl-NSs, Ag/AgCl-NWs and Ag/AgCl-NCs with adjustable sizes was realized by controlling the concentration ratio AgNO<sub>3</sub>/HCl. We disclosed that the rate of organic dye degradation was increased in case of Ag/AgCl-NCs compared with other the Ag/AgCl-NSs and the Ag/AgCl-NWs forms. As a result, we examined the Ag/AgCl-NCs photocatalyst in chemose-lective production of organoselenium compounds. It was concluded that this catalyst displayed high catalytic activity in production of seleno[2,3-b]pyridine derivatives under mild conditions with low cost and reusable catalyst, besides the use of visible light as available energy source for performing the reaction.

Acknowledgement We would like to express special words of thanks with deepest appreciation to the team of this study. We would like to acknowledge RanaEssa, Eman Mohamed and AmanyKhalifa, NILES, Cairo University for useful participation in experimental research.

**Funding** This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

#### **Compliance with ethical standards**

Conflict of interest The authors declare that they have no conflict of interest.

# References

- 1. D. Wang, D. Astruc, Chem. Rev. 114, 6949 (2014)
- 2. M.B. Gawande, Y. Monga, R. Zboril, R.K. Sharma, Coordin. Chem. Rev. 288, 118 (2015)
- 3. A.A. Herzing, C.J. Kiely, A.F. Carley, P. Landon, G.J. Hutchings, Science 321, 1331 (2008)
- 4. Y.A. Attia, S. Abdel-Hafez, New J. Chem. 42(12), 9606 (2018)
- 5. Y.A. Attia, Y.M.A. Mohamed, Appl. Organomet. Chem. 33(3), e4757 (2019)
- 6. Y.M.A. Mohamed, Y.A. Attia, E.J. Solum, Res. Chem. Intermed. 44(12), 7173 (2018)
- 7. Y.A. Attia, C.V. Vázquez, Y.M.A. Mohamed, Res. Chem. Intermed. 43(1), 203 (2017)
- Y. Attia, D. Buceta, C. Blanco-Varela, M. Mohamed, G. Barone, M.A. López-Quintela, J. Am. Chem. Soc. 136, 1182 (2014)
- Y.A. Attia, C.V. Vázquez, M.C. Blanco, D. Buceta, M.A. López-Quintela, Faraday Discuss. 191, 205 (2016)
- 10. Y. Attia, D. Buceta, F. Requejo, L. Giovanetti, M.A. López-Quintela, Nanoscale 7, 11273 (2015)
- 11. Y.A. Attia, Mater. Express 6(3), 211 (2016)
- 12. E.V. Ratushnaya, Y.I. Kirova, M.A. Suchkov, B.I. Drevko, V.B. Borodulin, Pharm. Chem. J. **36**(12), 652 (2002)
- 13. C. Jacob, G. Giles, F. Fry, US Patent 2004, wo 200 4047925
- 14. T. Maier, S. Scheiblich, H.S. Baltruschat, US Patent 2001, 11 064; Chem. Abstr. 2001, 135, 133440w
- S.A. Armstrong, J.M. Berge, P. Brown, J.S. Elder, A.K. Forrest, O.W. Hamprecht, R.L. Jarrest, PCT Int. Appl. 1999, WO 0071524; Chem. Abstr. 2001, 134, 17496
- 16. Proctor and Gamble Ltd., US Patent 1966, 3 236733; Chem. Abstr., 1966, 64, 17364
- 17. Rasching, US Patent 1960, 2 937 118; Chem. Abstr., 1966, 54, 17807
- S.H. Abdel-Hafez, S. Abdel-Mohsen, Y.A. El-Ossaily, Phosphorus Sulfur Silicon Relat. Elem. 181(10), 2297 (2006)
- 19. S.H. Abdel-Hafez, R.A. Ahmed, M.A. Abdel-Azim, K.M. Hassan, J. Chem. Res. 2007(10), 580 (2007)
- 20. S.H. Abdel-Hafez, R.A. Ahmed, M.A. Abdel-Azim, K.M. Hassan, J. Chem. Res. 2009(1), 56 (2009)
- 21. J. Jiang, H. Li, L. Zhang, Chem. Eur. J. 18, 6360 (2012)
- 22. P. Wang, B. Huang, X. Zhang, X. Qin, Y. Dai, Z. Wang, Z. Lou, ChemCatChem 3, 360 (2011)
- 23. P. Wang, B. Huang, X. Zhang, X. Qin, H. Jin, Y. Dai, Z. Wang, J. Wei, J. Zhan, Sh Wang, J. Wang, M.-H. Whangbo, Chem. Eur. J. **15**, 1821 (2009)
- 24. T.J. Yan, H.W. Zhang, Q. Luo, Y.Y. Ma, H.X. Lin, J.M. You, Chem. Eng. J. 232, 564 (2013)
- 25. P. Wang, B. Huang, Z. Lou, X. Zhang, X. Qin, Y. Dai, Z. Zheng, X. Wang, Chem. Eur. J. 16, 538 (2010)
- 26. H. Xu, H. Li, J. Xia, S. Yin, Z. Luo, L. Liu, L. Xu, A.C.S. Appl, Mater. Interfaces 3, 22 (2011)
- 27. X. Lin, H. Liu, B. Guo, X. Zhang, J. Environ. Chem. Eng. 4(4), 4021 (2016)
- 28. S.H. Im, Y.T. Lee, B. Wiley, Y. Xia, Angew. Chem. Int. Ed. 44(14), 2154 (2005)
- 29. V.P. Litvinov, V.Y. Mortikov, Y.A. Sharanin, A.M. Shestopalov, Synthesis 1, 98 (1985)
- 30. S. Kim, H. Chung, J.H. Kwon, H.G. Yoon, W. Kim, Bull. Korean Chem. Soc. 31(10), 2918 (2010)
- 31. S.A. Ryndina, A.V. Kadushkin, N.P. Solov'eva, V.G. Granik, Russ. Chem. Bull. Int. Ed. **51**(5), 854 (2002)
- 32. A.M. Shestopalov, L.A. Rodinovskaya, A.A. Shestopalov, Tetrahedron 66(46), 8945 (2010)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.