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Article

Preparation and characterization of nano-CaO based on eggshell waste: Novel and green catalytic approach to highly efficient synthesis of pyrano[4,3-*b*]pyrans

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ABSTRACT

Nano-CaO was prepared by calcination of ball-milled chicken eggshell waste. This novel, bioactive, heterogeneous catalyst, which had high catalytic activity and reusability, was used in the green synthesis of pyrano[4,3-*b*]pyrans via condensation of various aromatic aldehydes, malononitrile, and 4-hydroxy-6-methyl-2*H*-pyran-2-one at 120 °C under solvent-free conditions. The reaction proceeded to completion within 5–45 min in 93%–98% yield. The nano-CaO was fully characterized by scanning electron microscopy, X-ray powder diffraction, infrared spectroscopy, X-ray fluorescence spectroscopy, and thermal gravimetric, surface area, and elemental analyses.

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1. Introduction

Recently, there has been increasing interest in the development of clean technology to replace the use of hazardous reagents and catalysts with relatively environmentally benign compounds. Additionally, “green chemistry” emphasizes the optimization of synthetic methodologies to reduce pollution, costs, and tedious work-ups [1–3]. This new challenge has led to a growing interest in the use of natural and bio compounds for organic and inorganic application. Eggs, an abundant natural food source, are consumed worldwide because they contain essential amino acids, vitamins, and minerals. Chicken eggshell is totally biodegradable, recyclable, and biocompatible, with good osteoconductivity [4]. It consists of more than 90% CaCO₃ and has emerged as a novel bone substitute in its natural form [5–8]. This natural solid waste is non-hazardous, and is commonly disposed of in landfills without any pretreatment be-

cause it has no traditional uses [9]. The eggshell structure is mesoporous, with the ability to form a nanoporous structure [10]. Substrates with nanostructures, dense nanopores, and high surface areas have found many application in biosensors, proteomics, light-emitting diodes [4,11–14], and tissue engineering [15–17]. We previously reported the first ultrasonic-assisted preparation of nano-CaCO₃ based on eggshell waste, and its use as a heterogeneous catalyst in the green synthesis of 2-aminochromenes [16]. Eggshells have previously been used to synthesize nanoparticle apatite, hydroxyapatite nanopowders, and nano-CaCl₂, but these require sintering or the use of acidic and hazardous solvents to make porous scaffolds [18–20]. In this paper, we report a green, simple, and cheap approach to making nano-CaO based on chicken eggshell waste. We also characterized the nano-CaO structure and investigated its use as a catalyst in the green synthesis of pyrano[4,3-*b*]pyrans.

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Scheme 1. Synthesis of 2-amino-7-methyl-5-oxo-4-phenyl-4,5-dihydropyrano[4,3-*b*]pyran-3-carbonitrile derivatives.

It is known that many pyran derivatives exhibit a wide spectrum of pharmacological and biological activity [21–23]. Moreover, they have been shown to have important medicinal properties such as antimicrobial [24], antiviral [25,26], antiproliferative [27], antitumor [28], anticancer [29], anti-HIV, antituberculosis, anti-inflammatory, and antifungal activity [30–35]. Despite their wide range of pharmacological and industrial application, the synthesis of pyrano[4,3-*b*]pyrans has received little attention. Recently, members of this important class of pyran derivatives have been synthesized via one-pot multicomponent condensation reactions of aryl aldehydes, malononitrile, and 4-hydroxy-6-methyl-2*H*-pyran-2-one in the presence of different reagents. Various reagents such as $\text{KF} \cdot \text{Al}_2\text{O}_3$ [36], $[\text{bmim}]\text{BF}_4$ [28], piperidine [37], and NH_4OAc [38] have been used to accomplish this transformation. However, in spite of their potential utility, all of these methods suffer from one or more disadvantages, such as unsatisfactory yields, very prolonged reaction time, and the use of organic solvents. So, in a continuation of our efforts to develop new green chemistry methods [39,40], we decided to explore the green synthesis of 2-amino-7-methyl-5-oxo-4-phenyl-4,5-dihydropyrano[4,3-*b*]pyran-3-carbonitrile derivatives in the presence of nano-CaO based on eggshell waste as a novel and green biocatalyst, under solvent-free and thermal conditions (Scheme 1).

2. Experimental

2.1. Materials and Instruments

All chemicals were of analytical grade, purchased from Merck, and used as received. Melting points were determined using a Gallenkamp melting-point apparatus and are uncorrected. Nuclear magnetic resonance (NMR) spectra were recorded at 500 (^1H) and 125.77 (^{13}C) MHz using a Bruker DRX-500 Avance spectrometer. Fourier-transform infrared (FT-IR) spectra were obtained using a MATSON 1000 FT-IR spectrophotometer. X-ray diffraction (XRD) was performed using a D8 Bruker diffractometer (40 kV and 40 mA) with $\text{Cu } K\alpha$ radiation ($\lambda = 0.154 \text{ nm}$) to analyze the crystal structure of the milled powders. The XRD patterns were recorded in the 2θ range 20° – 80° with a step size of 0.01° . The mean size and size distribution of the eggshell powder were measured using a dynamic laser light scattering apparatus (FRITTSCH Analysette 22 NanoTec Laser Particle Sizer). The chemical composition of the catalyst was determined using X-ray fluorescence (XRF) spectroscopy (Microanalyser Unisantis XMF-104, Germany) operated at 40 kV and 300 mA, with Mo radiation. Thermo-

gravimetric analysis-differential thermal analysis (TGA-DTA) experiments were carried out using an STA 409 PC Luxx thermal analysis instrument (NETZSCH, Germany) under a flow of nitrogen. The sample mass used was about 20 mg, and the temperature ranged from 25 to 900°C , with a rising rate of $10^\circ\text{C}/\text{min}$. The film cross-section morphology was examined using field-emission scanning electron microscopy (FESEM) after fracturing in liquid nitrogen. Dried samples were coated with gold ions using an ion coater for 150 s. The surface structure was visualized using FESEM (Hitachi S4160) at an accelerating voltage of 15 kV. Transmission electron microscopy (TEM) images were obtained using a LEO912-AB (LEO, Germany) transmission electron microscope with an accelerating voltage of 120 kV. Particles were deposited on carbon foil supported by a copper grid. Energy-dispersive X-ray analysis (EDX) was performed using an Oxford instruments EDX detector (UK) with an accelerating voltage of 10.0 kV. Milling was carried out in a planetary ball-mill using a hardened chromium steel vial (250 mL) at room temperature in an argon atmosphere. The ball-to-powder mass ratio and the rotation speed of the vial were 10:1 and 350 r/min, respectively.

2.2. Catalyst preparation

Empty chicken eggshells were collected from household waste and washed with warm tap-water. The adhering membranes were separated manually. The eggshells were then washed with distilled water and dried at 120°C for 1 h. The eggshells were milled in a planetary ball-mill for 2 h, and the eggshell powder was calcined at 900°C for 1 h. The resulting material was denoted by nano-CaO.

2.3. General procedure for synthesis of pyrano[4,3-*b*]pyrans

A mixture of 4-chlorobenzaldehyde (0.14 g, 1 mmol), malononitrile (0.07 g, 1 mmol), and 4-hydroxy-6-methyl-2*H*-pyran-2-one (0.126 g, 1 mmol) was stirred thoroughly at 120°C under solvent-free conditions in the presence of a catalyst amount of nano-CaO (0.1 g) to afford the corresponding pyrano[4,3-*b*]pyran in excellent yield. After completion of the reaction (thin-layer chromatography), hot EtOH was added and the reaction mixture was stirred for 5 min. Then the solid catalyst was filtered from the soluble products and washed with hot EtOH. After cooling, the crude products were precipitated. Pure pyrano[4,3-*b*]pyrans were obtained in high yields without further purification. All compounds were known in the literature [28,36–38] and the NMR and IR spectra of the products were in agreement with earlier data [28,36–38].

Spectra data of two selected compounds are as following.

2-amino-7-methyl-5-oxo-4-(4-chlorophenyl)-4*H*,5*H*-pyrano[4,3-*b*]pyran-3-carbonitrile (Table 2, Entry 2): pale-yellow crystals, mp 227 – 229°C . IR (KBr, cm^{-1}): 3383, 3324, 3195, 2201, 1710, 1674, 1645, 1597, 1488, 1445, 1414, 1384, 1261, 1141, 1092, 1015, 981, 854, 830, 807, 777, 511. ^1H NMR (400.2 MHz, DMSO, δ): 2.23 (s, 3H, CH_3), 4.33 (s, 1H, CH), 6.29 (s, 1H, =CH), 7.23 (d, 2H, $J = 8.4 \text{ Hz}$, ArH), 7.26 (s, 2H, NH_2), 7.38 (d, 2H, $J = 8.4 \text{ Hz}$, ArH). ^{13}C NMR (400.2 MHz, DMSO, δ): 19.8, 36.2,

57.9, 98.4, 100.7, 119.6, 128.8, 129.9, 132.1, 143.0, 158.5, 158.7, 161.8, 163.6.

2-amino-7-methyl-5-oxo-4-(3-nitrophenyl)-4*H*,5*H*-pyrano[4,3-*b*]pyran-3-carbonitrile (Table 2, Entry 3): pale-yellow crystals, mp 230–232 °C. IR (KBr, cm^{-1}): 3400, 3327, 2198, 1716, 1615, 1526, 1448, 1385, 1263, 1200, 1144, 1024, 978, 817, 759, 733. ^1H NMR (400.2 MHz, DMSO, δ): 2.24 (s, 3H, CH_3), 4.53 (s, 1H, CH), 6.75 (s, 1H, =CH), 7.35 (s, 2H, NH_2), 7.67 (t, $J = 8.0$ Hz, 1H, ArH), 7.72 (tt, $J = 8.0$ Hz, $J = 1.2$ Hz, 1H, ArH), 8.15 (t, $J = 2.0$ Hz, 1H, ArH), 8.17 (dd, dd, $J = 8.0$ Hz, $J = 2.0$ Hz, $J = 1.2$ Hz, 1H, ArH). ^{13}C NMR (400.2 MHz, DMSO, δ): 19.9, 36.4, 58.2, 98.3, 100.6, 119.7, 128.6, 129.8, 132.2, 143.1, 158.7, 159.0, 162.3, 163.7.

3. Results and discussion

The characterization results showed that the CaO was the most abundant component (98.6%) in the nanocatalyst; this was associated with the presence of CaCO_3 . The nano-eggshell catalyst also contained small amounts of Mg (0.39%), P (0.35%), Sr (0.3%), Si (0.3%), K (0.014%), Na (0.023%), and Zn (0.003%). Waste eggshell can therefore be considered chemically to be a relatively pure, natural carbonate-based material.

Figure 1(3) shows the IR spectra of commercially available CaCO_3 . The broad transmission band at approximately 3436 cm^{-1} can be attributed to OH stretching vibration from residual water. The weak band at 1632 cm^{-1} corresponds to C=O bonds from carbonate. Two well-defined IR bands at 1426, 873, and 700 cm^{-1} are attributed to asymmetric C–O stretching and out-of-plane and in-plane bending modes, respectively, for CO_3^{2-} molecules.

Figure 1(2) shows the spectrum of calcined commercially available CaCO_3 . The presence of a peak at 3647 cm^{-1} is attributable to OH in Ca(OH)_2 formed during adsorption of water by CaO. The wide and strong band at around 500 cm^{-1} corresponds to the Ca–O bond. The IR spectrum of the nano-CaO (Fig. 1(1)) had peaks at the same wavenumbers as that of calcined CaCO_3 , indicating that the nano-CaO based on eggshells and the calcined commercially available CaCO_3 are chemically very similar. Our results regarding uncalcined and calcined

Fig. 1. FT-IR spectra of nano-CaO (1), calcined commercially available CaCO_3 (2), and commercially available CaCO_3 (3).

Fig. 2. XRD patterns of calcined commercially available CaCO_3 (1), nano-CaO (2), and commercially available CaCO_3 (3).

eggshells agree with those reported in the literature [5].

The XRD patterns of the raw eggshell powder and commercially available CaCO_3 were identical, with peaks at $2\theta = 29.4^\circ$, indicating that calcite (CaCO_3) is the major phase in the waste eggshell (Fig. 2(3)). The XRD pattern of the nano-eggshell calcined at 900°C for 1 h had a peak at $2\theta = 34.2^\circ$ (Fig. 2(2)). The major peak of the calcite phase ($2\theta = 29.4^\circ$) was not observed in the XRD pattern of the nano-CaO, implying that the CaCO_3 phase was completely transformed to the CaO phase (Fig. 2(2)). The XRD pattern of calcined commercially available CaCO_3 (Fig. 2(1)) had a peak at the same 2θ angle as that of the calcined eggshell.

The CaO crystallite size was calculated using the Scherrer equation. The calcined eggshell generated nanocrystalline CaO with a crystallite size of 40 nm, whereas the calcined commercially available CaCO_3 showed a very high degree of crystallinity with a crystallite size of more than 100 nm.

A suitable eggshell calcination temperature was determined using TGA-DTA. As shown in Fig. 3, calcination below 600°C did not lead to the formation of CaO. Complete conversion was obtained for calcination temperatures above 600°C , and nanocrystalline CaO was the major phase. The mass loss between 600 and 867°C is 47.2% and is caused mainly by decomposition of calcite, with the formation of CaO and CO_2 .

Release of CO_2 led to the creation of nanocrystalline CaO.

Fig. 3. TGA-DTA curves of nano-CaO based on eggshell.

Fig. 4. FESEM images of nano-CaO (a), raw eggshell (b), calcined commercially available CaCO_3 (c), and TEM image of nano-CaO (d).

The specimens also had high apparent porosities as a result of decomposition of CaCO_3 with evolution of CO_2 outside the eggshell powder structure. The effect of carbonate decomposition is clearly observed in the TEM and FESEM images of the sintered specimens, as shown in Fig. 4. The FESEM images of raw eggshell, nano-CaO obtained by thermal decomposition of eggshell, and calcined CaCO_3 were compared. The images show that the porosity of the nano-CaO is higher than that of raw eggshell because of release of CO_2 from inside the structure as a result of calcination. The mesoporous nature of the nanocatalyst, compared with the low porosity of the calcined CaCO_3 surface, is responsible for the catalytic effect of the nano-eggshell. This effect is a result of the larger contact area resulting from the large number of pores and pits distributed over the entire eggshell surface.

Nitrogen physisorption analysis was performed to compare the surface areas of the nanocatalyst and calcined commercially available CaCO_3 . Brunauer-Emmett-Teller surface area analysis showed a high surface area of $8.0142 \text{ m}^2/\text{g}$, with an average particle size of $11 \mu\text{m}$, for the nanocatalyst, whereas the values were $3.5421 \text{ m}^2/\text{g}$ and $23 \mu\text{m}$ for eggshell that was only calcined. This is because ball-milling reduced the eggshell particle size. As shown in Table 1, the low surface area ($1.7364 \text{ m}^2/\text{g}$) and larger particle size ($26 \mu\text{m}$) of the calcined CaCO_3 led to low porosity and low catalytic activity.

We then explored the catalytic activity of nano-CaO in the green synthesis of pyrano[4,3-*b*]pyran derivatives, using condensation reactions of various aromatic aldehydes (1 mmol), 4-hydroxy-6-methyl-2*H*-pyran-2-one (1 mmol), and malononitrile (1.2 mmol) under solvent-free conditions. Without the addition of a catalyst, no pyrano[4,3-*b*]pyrans were formed, even after 10 h, under the reaction conditions used.

To identify the optimum conditions, first, the effect of temperature on the reaction rate was studied for the preparation of pyrano[4,3-*b*]pyrans (Table 2). At 120°C , the reaction over nano-CaO proceeded to completion very rapid. Decreasing the

Table 1

Effect of average particle size of catalysts on the synthesis of 2-amino-7-methyl-5-oxo-4-(4-chlorophenyl)-4*H*,5*H*-pyrano[4,3-*b*]pyran-3-carbonitrile.

Catalyst	Ball milling Time (h)	Average particle size ^a (μm)	Time (min)	Yield ^b (%)
Nano-CaO	2	11	45	96
Calcined eggshell	1	23	300	75
Calcined eggshell	0.5	47	300	20
Calcined CaCO_3	2	26	300	35

^a Determined by laser particle sizer.

^b Yield refers to isolated pure product.

Table 2

Nano-CaO-catalyzed synthesis of 2-amino-7-methyl-5-oxo-4-phenyl-4*H*,5*H*-pyrano[4,3-*b*]pyran-3-carbonitrile derivatives.

Entry	Ar	Time (min)	Yield ^a (%)
1	C_6H_5	5	94
2	4-Cl- C_6H_4	45	96
3	3-NO ₂ - C_6H_4	35	93
4	2,4-Cl ₂ - C_6H_4	25	95
5	4-Br- C_6H_4	25	94
6	2-OH- C_6H_4	5	97
7	4-OH- C_6H_4	20	98
8	4-CH ₃ O- C_6H_4	20	94
9	4-CH ₃ - C_6H_4	30	93
10	4-(CH ₃) ₂ N- C_6H_4	15	96

^a Yield refers to isolated pure product.

temperature led to decreased product yields and reaction rates. Next, the optimum amount of nanocatalyst in the range 0.02–0.2 g was evaluated. The highest yield was obtained with 0.1 g of catalyst. A further increase in the amount of catalyst up to 0.2 g did not have any significant effect on the product yield or reaction time.

To investigate the effect of particle size on the catalytic activity, calcined eggshells ball-milled for different time were used in the reaction. As shown in Table 1, the catalytic activity increased with decreasing particle size. The highest yield was obtained with nano-CaO of average particle size $11 \mu\text{m}$. In addition, a comparison reaction was carried out to show that the nano-CaO was a better catalyst than commercially available CaCO_3 . As the data in Table 1 show, the reaction proceeded to completion in 45 min, with a product yield of 96% over the nano-CaO, whereas the corresponding values were 5 h and 35% over calcined CaCO_3 . Since the catalytic activity of the catalysts agreed well with the specific surface areas and catalyst particle size, it is logical to conclude that mesoporous CaO with crystals of reduced size is a more effective catalyst than calcined CaCO_3 with a larger particle size and low porosity.

The generality of this reaction was examined using different aldehydes (Table 2). In all cases, the reactions gave the corresponding products in good to excellent yields (93%–98%) in very short reaction time (5–45 min). This method offers significant improvements with regard to the scope of the transformation, simplicity, and green aspects, by avoiding expensive, hazardous, or corrosive catalysts.

A possible mechanism for the formation of the products is shown in Scheme 2. The reaction occurs via the initial for-

Scheme 2. Plausible mechanistic pathway for synthesis of pyrano[4,3-*b*]pyran derivatives.

Fig. 5. Nano-CaO recycling experiments.

mation of benzilidenemalononitrile **3** by nucleophilic addition of malononitrile **2** to aromatic aldehyde **1**, followed by dehydration. Subsequent Michael addition of 4-hydroxy-6-methyl-2*H*-pyran-2-one **4** to **3**, followed by cyclization, affords the corresponding product **5**.

The reusability of the catalyst in the synthesis of pyrano[4,3-*b*]pyran derivatives was examined (Fig. 5). The catalyst was recovered after each run, washed three times with hot EtOH, dried in an oven at 120 °C, and tested for its activity in subsequent runs. We found that the catalyst could be reused seven times without loss of catalytic activity.

4. Conclusions

In summary, the easy and rapid ball-mill-assisted prepara-

tion of nano-CaO based on eggshell waste was explored. Also, a green, rapid, and highly efficient protocol for the one-pot synthesis of pyrano[4,3-*b*]pyrans under thermal solvent-free conditions, using an inexpensive and green catalyst, was developed. The nano-CaO was reused several times without any loss of catalytic activity and reusability. This green catalyst is a novel and biocompatible nanocatalyst based on eggshell waste; it can catalyze organic transformations and reduce environmental problems. This is the first use of eggshell waste material as a nano-sized natural CaO catalyst in organic synthesis.

Acknowledgments

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References

- [1] Chavan S S, Degani M S. *Green Chem*, 2012, 14: 296
- [2] Kumar A, Gupta M K, Kumar M. *Green Chem*, 2012, 14: 290
- [3] Zhang Q, Su H, Luo J, Wei Y Y. *Green Chem*, 2012, 14: 201
- [4] Soleymani L, Fang Z C, Sargent E H, Kelley S O. *Nature Nanotechnol*, 2009, 4: 844
- [5] Liao H H, Mutvei H, Sjöström M, Hammarström L, Li J G. *Biomaterials*, 2000, 21: 457
- [6] Borrelli J Jr, Prickett W D, Ricci W M. *Clin Orthop Relat Res*, 2003, 411: 245
- [7] Bhumiratana S, Grayson W L, Castaneda A, Rockwood D N, Gil E S, Kaplan D L, Vunjak-Novakovic G. *Biomaterials*, 2011, 32: 2812
- [8] Siddharthan A, Kumar T S S, Seshadri S K. *Biomed Mater*, 2009, 4: 045010/1
- [9] Gao Y, Xu C L. *Catal Today*, 2012, 190: 107
- [10] Mosaddegh E, Hassankhani A. *Catal Commun*, 2013, 33: 70
- [11] Devabhaktuni S, Prasad S. *J Nanosci Nanotechnol*, 2009, 9: 6299
- [12] Dylewicz R, Khokhar A Z, Wasielewski R, Mazur P, Rahman F. *Nanotechnol*, 2011, 22: 055301
- [13] Wan Y, Kim Y T, Li N, Cho S K, Bachoo R, Ellington A D, Iqbal S M. *Cancer Res*, 2010, 70: 9371
- [14] Yang F, Murugan R, Ramakrishna S, Wang X, Ma Y X, Wang S. *Biomaterials*, 2004, 25: 1891
- [15] Subramanian A, Krishnan U M, Sethuraman S. *Biomed Mater*, 2011, 6: 025004/1
- [16] Yoshii T, Dumas J E, Okawa A, Spengler D M, Guelcher S A. *J Biomed Mater Res B*, 2012, 100: 32
- [17] Asghar W, Kim Y T, Ilyas A, Sankaran J, Wan Y, Iqbal S M. *Nanotechnol*, 2012, 23: 475601
- [18] Siva R K D, Siddharthan A, Seshadri S K, Sampath K T S. *J Mater Sci, Mater Med*, 2007, 18: 1735
- [19] Gergely G, Weber F, Lukacs I, Toth A L, Horvath Z E, Mihaly J, Balazsi C. *Ceram Int*, 2010, 36: 803
- [20] Witoon T. *Ceram Int*, 2011, 37: 3291
- [21] Uher M, Konecny V, Rajniakova O. *Chem Pap*, 1994, 48: 282
- [22] Perez-Perez M J, Balzarini J, Rozenski J, De-Clercq E, Herdewijn P. *Bioorg Med Chem Lett*, 1995, 5: 1115
- [23] Takao H, Murai K, Yasudomi N, Goto T, Umetsu N, Horie T. *J Pestic Sci*, 1994, 19: 131
- [24] Khafagy M M, Abd El-Wahab A H F, Eid F A, El-Agrody A M. *Far-maco*, 2002, 57: 715
- [25] Smith P W, Sollis S L, Howes P D, Cherry P C, Starkey I D, Copley K

Graphical Abstract

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Preparation and characterization of nano-CaO based on eggshell waste: Novel and green catalytic approach to highly efficient synthesis of pyrano[4,3-*b*]pyrans

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The ball-mill-assisted preparation by thermal decomposition of nano-CaO derived from chicken eggshell waste was reported as a novel, bioactive, and heterogeneous catalyst with high catalytic activity and reusability in the green synthesis of pyrano[4,3-*b*]pyrans.

- N, Weston H, Scicinski J, Merritt A, Whittington A, Wyatt P, Taylor N, Green D, Bethell R, Madar S, Fenton R J, Morley P J, Pateman T, Beresford A. *J Med Chem*, 1998, 41: 787
- [26] Martinez-Grau A, Marco J L. *Bioorg Med Chem Lett*, 1997, 7: 3165
- [27] Dell C P, Smith C W. EP Patent 537 949. 1993
- [28] Mohr S J, Chirigos M A, Fuhrman F S, Pryor J W. *Cancer Res*, 1975, 35: 3750
- [29] Fan X S, Feng D, Qu Y Y, Zhang X Y, Wang J J, Loiseau P M, Andrei G, Snoeck R, De Clercq E. *Bioorg Med Chem Lett*, 2010, 20: 809
- [30] Abrunhosa L, Costa M, Areias F, Venâncio A, Proenca F. *J Ind Microbiol Biotechnol*, 2007, 34: 787
- [31] Chimenti F, Bizzarri B, Bolasco A, Secci D, Chimenti P, Carradori S, Granese A, Rivanera D, Lilli D, Zicari A, Scaltrito M M, Sisto F. *Bioorg Med Chem Lett*, 2007, 17: 3065
- [32] Kostova I. *Mini-Rev Med Chem*, 2006, 6: 365
- [33] Nayyar A, Jain R. *Curr Med Chem*, 2005, 12: 1873
- [34] Fylaktakidou K C, Hadjipavlou-Litina D J, Litinas K E, Nicolaides D N. *Curr Pharm Des*, 2004, 10: 3813
- [35] Asres K, Seyoum A, Veeresham C, Bucar F, Gibbons S. *Phytother Res*, 2005, 19: 557
- [36] Wang X S, Zhou J X, Zeng Z S, Li Y L, Shi D Q, Tu S J. *Arkivoc*, 2006, xi: 107
- [37] Stoyanov E V, Ivanov I C, Heber D. *Molecules*, 2000, 5: 19
- [38] Rajguru D, Keshwal B S, Jain S. *Med Chem Res*, 2013, 22: 5934
- [39] Mosaddegh E, Hassankhani A. *Tetrahedron Lett*, 2011, 52: 488
- [40] Mosaddegh E. *Ultrasonics Sonochem*, 2013, 2: 1436