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# Nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub>: a magnetic reusable nano-catalyst for the synthesis of pyrimido[2,1-*b*]benzothiazoles†

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Herein, nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> as a new magnetic nano-catalyst was synthesized, and its structural properties were characterized using various techniques such as Fourier transform infrared (FTIR) spectroscopy, field emission scanning electron microscopy (FE-SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), a vibrating sample magnetometer (VSM), thermogravimetric analysis (TGA) and energy-dispersive X-ray spectroscopy (EDX). This catalyst was used for the synthesis of pyrimido[2,1-*b*]benzothiazoles *via* the one-pot condensation of 2-aminobenzothiazole, an aldehyde and  $\beta$ -keto ester under solvent-free conditions at 100 °C. This simple protocol has many advantages such as easy workup, high product yields, short reaction times and reusability of the catalyst.

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## Introduction

Pyrimido[2,1-*b*]benzothiazoles are an important category of fused heterocycles, with the benzothiazole ring having diverse pharmaceutical and industrial properties.<sup>1</sup> These compounds have shown various biological activities such as anti-bacterial,<sup>2</sup> anti-tumor,<sup>3,4</sup> anti-inflammatory,<sup>5,6</sup> anti-viral,<sup>7</sup> anticonvulsant,<sup>8</sup> anti-cancer<sup>9</sup> and antifungal activities.<sup>10</sup> These compounds have been synthesized *via* the condensation reaction of 2-amino benzothiazole,  $\beta$ -keto ester and aldehydes. Previously, various catalysts, such as thiamine hydrochloride (VB1),<sup>11</sup> Fe<sub>3</sub>O<sub>4</sub>@nano-cellulose-TiCl<sub>3</sub>,<sup>12</sup> nano-TiCl<sub>2</sub>/cellulose,<sup>13</sup> nanocellulose/BF<sub>3</sub>/Fe<sub>3</sub>O<sub>4</sub>,<sup>14</sup> nano-Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>-TiCl<sub>3</sub>,<sup>15</sup> kaolin,<sup>16</sup> and tetrabutylammonium hydrogen sulfate (TBAHS),<sup>17</sup> have been applied for the preparation of these compounds. However, the drawback of these protocols is the high cost of the catalyst.

Kaolin or hydrated aluminum silicate (Al<sub>2</sub>O<sub>3</sub> · 2SiO<sub>2</sub> · 2H<sub>2</sub>O)<sup>18</sup> has been used in numerous fields such as in the medicine, paint, ceramic, rubber, paper, petroleum and glass industries.<sup>19</sup> Moreover, one of the most valuable application of kaolin is as promoter in chemical industry;<sup>20</sup> in recent years, magnetic nanoparticles (Fe<sub>3</sub>O<sub>4</sub>) have been used due to their advantages such as high stability, low toxicity and easy separation from reaction media.<sup>21–23</sup> On the other hand, single atoms,<sup>24–27</sup> such as transition metal atoms and their ions,<sup>28,29</sup> have been widely studied and used for the promotion of organic reactions. In this study, we report the

synthesis and characterization of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> for the synthesis of 4*H*-pyrimido[2,1-*b*]benzothiazoles *via* the condensation reaction of ethyl acetoacetate, aromatic aldehydes, and 2-amino benzothiazole.

## Results and discussion

Herein, nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> was prepared as a new catalyst in two-steps. At first, TiCl<sub>4</sub> was added to the mixture of nano-kaolin and CH<sub>2</sub>Cl<sub>2</sub>. The resulting white powder (nano-kaolin/Ti<sup>4+</sup>) was added to the suspension of nano Fe<sub>3</sub>O<sub>4</sub> in CH<sub>2</sub>Cl<sub>2</sub> under the ultrasonic condition for the formation of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> as a brown magnetic powder (Scheme 1). The morphology and structure of kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> were studied by various techniques such as FTIR, FE-SEM, TEM, XRD, VSM, TGA and EDX. The FTIR spectra of kaolin, Fe<sub>3</sub>O<sub>4</sub>, nano-kaolin/Ti<sup>4+</sup> and nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> are shown in Fig. 1. The absorption bands at 3342 and 3620 cm<sup>−1</sup> correspond to the stretching vibrations of the O–H bond. The band at 538 cm<sup>−1</sup> is attributed to Fe/O in the Fe<sub>3</sub>O<sub>4</sub> nanoparticles. The Al–O and Si–O stretching vibration bands are visible at 420–550 and 1050–1100 cm<sup>−1</sup>, respectively, in the FTIR spectrum of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub>.

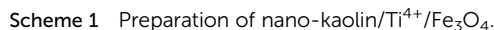
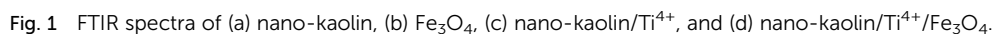
The particle size of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> was studied using field emission scanning electron microscopy (FE-SEM) and transmission electron microscopy (TEM) and found to be less than 100 nm (Fig. 2).

Energy-dispersive X-ray spectroscopy (EDS) was used to determine the percentage of elements in nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> (Fig. 3). The percentage of Fe, Si, Al, Ti, Cl, O and K in nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> was 37.4, 25.5, 12.6, 11.0, 8.2, 4.2 and 1.2, respectively.

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The X-ray diffraction (XRD) pattern of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> is shown in Fig. 6. According to the XRD pattern, the signals at  $2\theta = 13^\circ, 20^\circ, 25^\circ, 41^\circ, 46^\circ, 61^\circ$  and  $68^\circ$  indicate the



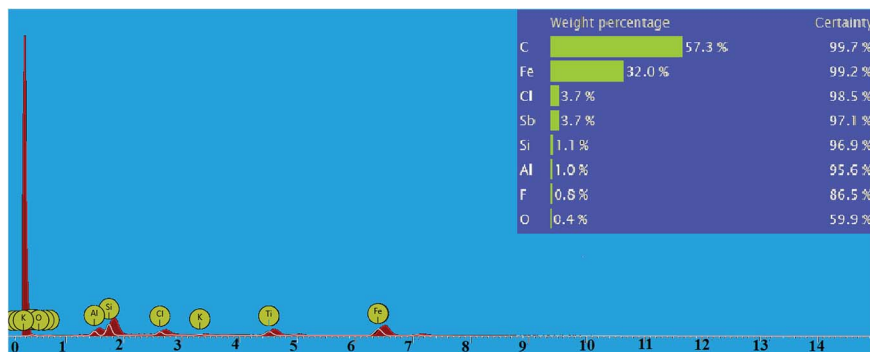


Fig. 3 The EDX spectra of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub>.

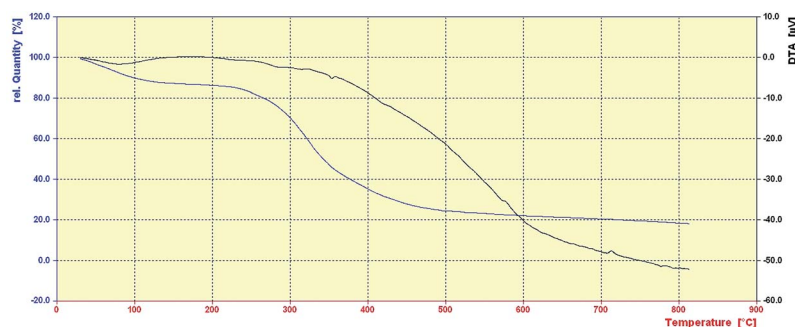


Fig. 4 Thermal gravimetric analysis of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub>.

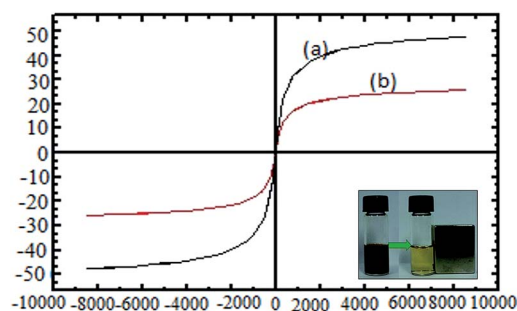


Fig. 5 Magnetization loops of (a) Fe<sub>3</sub>O<sub>4</sub> and (b) nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub>.

presence of kaolin. The four signals at  $2\theta = 21^\circ$ ,  $27^\circ$ ,  $39^\circ$  and  $50^\circ$  indicate the existence of SiO<sub>2</sub>. Moreover, the signals at  $2\theta = 31^\circ$ ,  $36^\circ$ ,  $44^\circ$ ,  $58^\circ$  and  $63^\circ$  are related to Fe<sub>3</sub>O<sub>4</sub>. Presumably, three other peaks at the  $2\theta$  value of  $37^\circ$ ,  $43^\circ$  and  $55^\circ$  revealed that Ti was bonded to kaolin and Fe<sub>3</sub>O<sub>4</sub>.

The catalytic activity of the catalyst was investigated for the synthesis of 4*H*-pyrimido[2,1-*b*]benzothiazole using the three-component reaction of  $\beta$ -keto ester, aromatic aldehydes and 2-aminobenzothiazole. To select optimum conditions, the reaction of ethyl acetoacetate, benzaldehyde and 2-amino benzothiazole was studied as a model reaction under different conditions. According to Table 1, the best

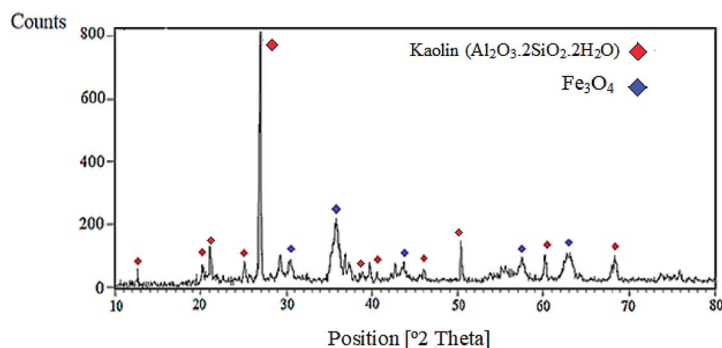
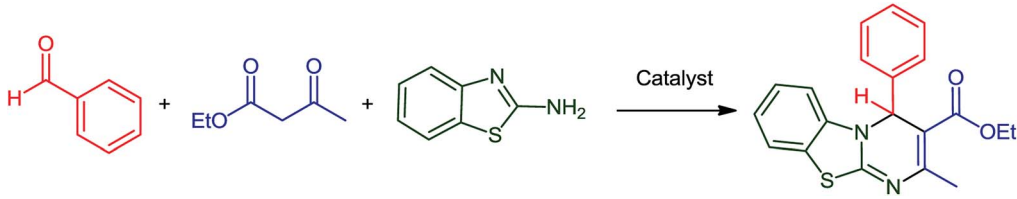


Fig. 6 XRD pattern of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub>.



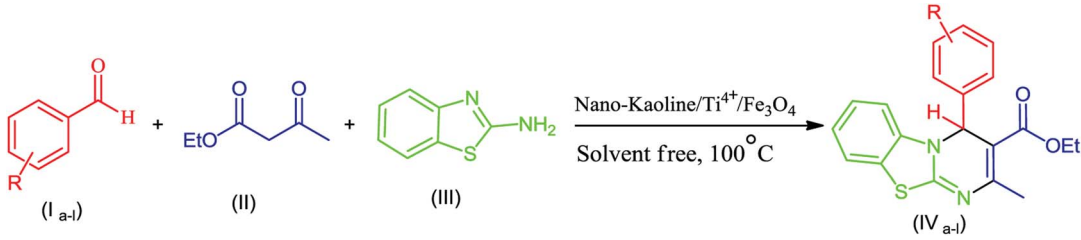
**Table 1** The reaction of 2-aminobenzothiazole, benzaldehyde and ethyl acetoacetate in the presence of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> under various conditions<sup>a</sup>


| Entry | Catalyst (g)                          | Solvent/condition                       | Time (h) | Yield <sup>b</sup> (%) |
|-------|---------------------------------------|-----------------------------------------|----------|------------------------|
| 1     | Fe <sub>3</sub> O <sub>4</sub> (0.03) | —/100 °C                                | 1.5      | 52                     |
| 2     | Kaolin (0.03)                         | —/100 °C                                | 1.5      | 72                     |
| 3     | Nano-kaolin/Ti <sup>4+</sup> (0.03)   | —/100 °C                                | 1.5      | 78                     |
| 4     | Catalyst <sup>c</sup> (0.03)          | H <sub>2</sub> O/reflux                 | 3        | 50                     |
| 5     | Catalyst <sup>c</sup> (0.03)          | C <sub>2</sub> H <sub>5</sub> OH/reflux | 4        | 30                     |
| 6     | Catalyst <sup>c</sup> (0.03)          | —/80 °C                                 | 2        | 82                     |
| 7     | Catalyst <sup>c</sup> (0.03)          | —/90 °C                                 | 2        | 75                     |
| 8     | Catalyst <sup>c</sup> (0.03)          | —/110 °C                                | 1.5      | 95                     |
| 9     | Catalyst <sup>c</sup> (0.025)         | —/100 °C                                | 1.5      | 65                     |
| 10    | Catalyst <sup>c</sup> (0.03)          | —/100 °C                                | 1.5      | 95                     |
| 11    | Catalyst <sup>c</sup> (0.04)          | —/100 °C                                | 1.5      | 78                     |

<sup>a</sup> The amount ratios of 2-aminobenzothiazole (mmol), benzaldehyde (mmol) and ethyl acetoacetate (mmol) equals to 1 : 1 : 1. <sup>b</sup> Isolated yield.<sup>c</sup> Nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub>.

conditions for the synthesis of 4*H*-pyrimido[2,1-*b*]benzothiazole under solvent-free conditions correspond to the utilization of 0.03 g of catalyst at 100 °C.

According to the conditions optimized for the model reaction, 4*H*-pyrimido[2,1-*b*]benzothiazole derivatives were synthesized by the reaction of various aromatic aldehydes,

**Table 2** The synthesis of 4*H*-pyrimido[2,1-*b*]benzothiazole derivatives<sup>a</sup>


| Entry | R                     | Product         | Time (h) | Yield <sup>b</sup> (%) | Melting point |          | Ref. |
|-------|-----------------------|-----------------|----------|------------------------|---------------|----------|------|
|       |                       |                 |          |                        | Observed      | Reported |      |
| 1     | H                     | IV <sub>a</sub> | 1.5      | 95                     | 178–180       | 178–180  | 23   |
| 2     | 4-NO <sub>2</sub>     | IV <sub>b</sub> | 0.5      | 98                     | 172–173       | 170–172  | 30   |
| 3     | 4-Cl                  | IV <sub>c</sub> | 2.2      | 95                     | 141–143       | 140–142  | 15   |
| 4     | 4-Br                  | IV <sub>d</sub> | 1.6      | 92                     | 111–113       | 110–114  | 31   |
| 5     | 4-OH                  | IV <sub>e</sub> | 3        | 90                     | 210–214       | 110–112  | 30   |
| 6     | 2-NO <sub>2</sub>     | IV <sub>f</sub> | 1        | 50                     | 120–124       | 123–125  | 14   |
| 7     | 2-Cl                  | IV <sub>g</sub> | 2.2      | 78                     | 131–133       | 130–132  | 17   |
| 8     | 3-NO <sub>2</sub>     | IV <sub>h</sub> | 0.5      | 80                     | 222–224       | 222–224  | 23   |
| 9     | 3-OH                  | IV <sub>i</sub> | 1.25     | 94                     | 259–261       | 260–263  | 12   |
| 10    | 2,4-(Cl) <sub>2</sub> | IV <sub>j</sub> | 1.4      | 70                     | 133–135       | 133–135  | 13   |
| 11    | 2-OEt                 | IV <sub>k</sub> | 1.1      | 85                     | 170–172       | 171–173  | 12   |
| 12    | 3,4-(OH) <sub>2</sub> | IV <sub>l</sub> | 0.9      | 60                     | 227–229       | 225–227  | 15   |

<sup>a</sup> One mmol of 2-aminobenzothiazole, aldehyde and ethyl acetoacetate was used. <sup>b</sup> Isolated yield.

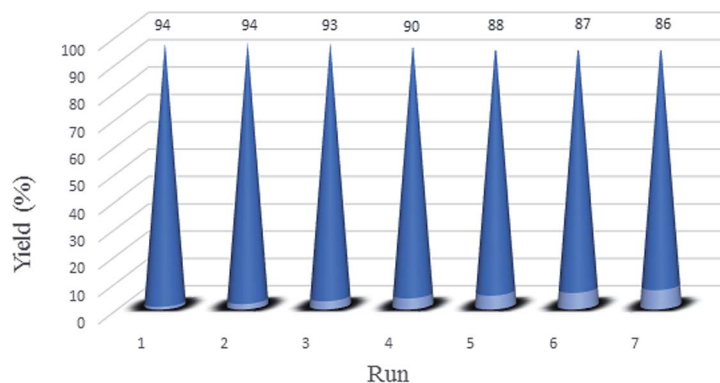


Fig. 7 The reusability experiment data of the catalyst.

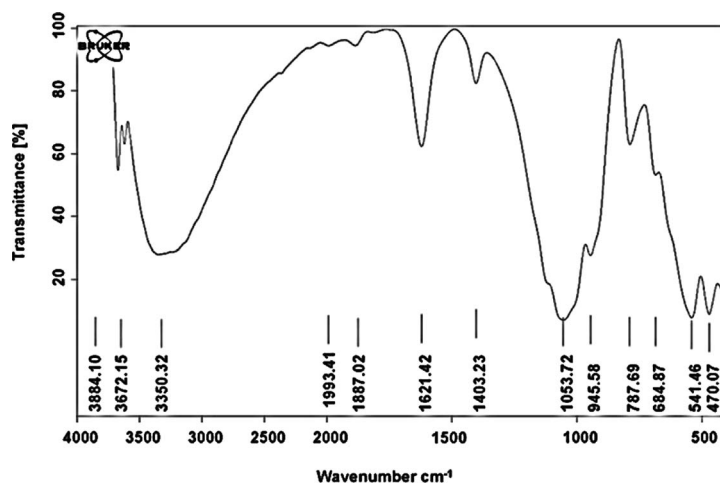


Fig. 8 The FTIR spectrum of the reused catalyst.

2-aminobenzothiazole and ethylacetoacetate in the presence of the nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> catalyst. Based on the results tabulated in Table 2, the effects of the electron and the nature of the substituent on aldehyde significantly affected the time and yield of the reaction. The presence of electron-withdrawing groups in aryl aldehyde rings increased the activity of the aldehyde group and their yields were compared with that of electron-donating groups; the structure of the product was identified using melting point, FTIR, and <sup>1</sup>H-NMR spectral results.

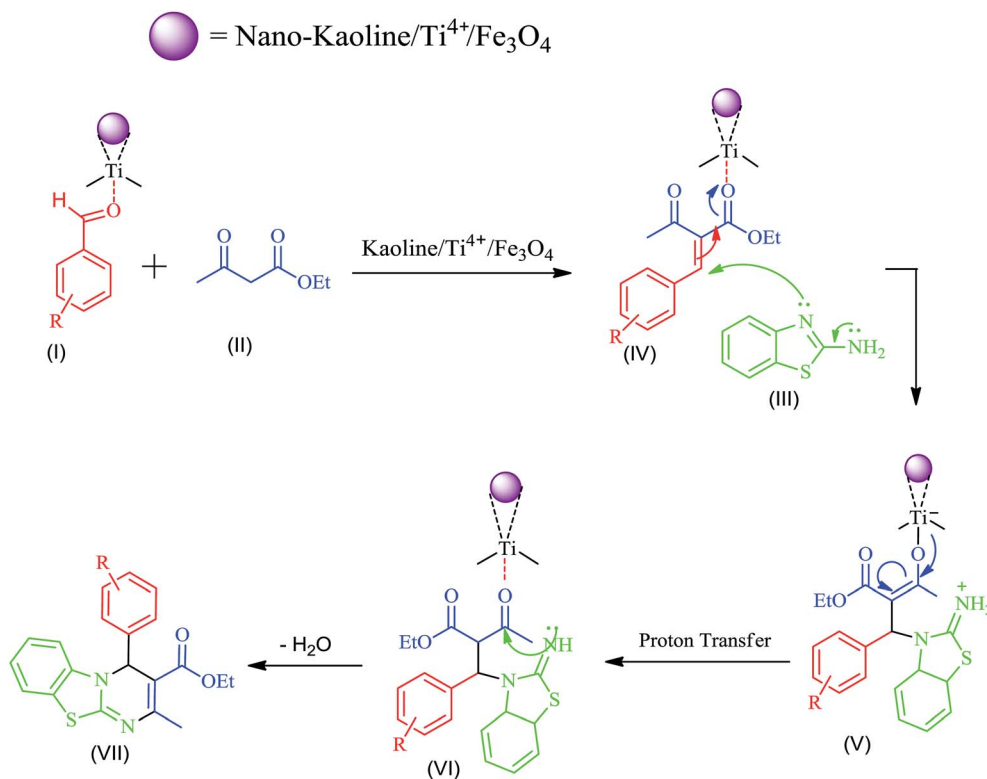
To investigate the recovery and reuse function of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub>, the catalyst was used for seven times in the model reaction under identical conditions. After using the catalyst in the model reaction, it was isolated by an external magnet, washed with ethanol and then dried at room temperature. The results indicate that the catalyst nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> can be reused without any significant loss of its catalytic activity (Fig. 7). The FTIR spectrum of the reused catalyst shows that there is no change in the catalyst structure during the recovery process (Fig. 8).

The proposed mechanism for the synthesis of 4*H*-pyrimido[2,1-*b*]benzothiazoles is shown in Scheme 2. In this reaction, the Ti<sup>4+</sup> cation in the catalyst acts as a Lewis acid and activates the carbonyl groups in the substrates. At first, the aldehyde (I) as an electrophile and β-keto esters (II) as active methylene compounds produce the alkene (IV) *via* the Knoevenagel reaction. Then, the 2-aminobenzothiazole (III) reacts with the alkene (IV) *via* a Michael addition reaction, and an iminium ion (V) is formed. Subsequently, using proton transfer and intramolecular cyclization, the 4*H*-pyrimido[2,1-*b*]benzothiazole derivative(VII) is formed.

To investigate the performance of the nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> catalyst in synthesis of 4*H*-pyrimido[2,1-*b*]benzothiazole derivatives, condensation of benzaldehydes, 2-aminobenzothiazole and ethyl acetoacetate was employed as the model reaction, and the results were compared with those obtained using other reported catalysts. The results of this study are shown in Table 3. According to the obtained results, the nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> is one of the best catalyst for this purpose.







Scheme 2 A proposed mechanism for the preparation of 4H-pyrimido[2,1-b]benzothiazole derivatives.

**Table 3** Comparison of the nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> catalyst with other reported catalysts for the synthesis of ethyl-2-methyl-4-(phenyl)-4H-pyrimido[2,1-b][1,3]benzothiazole-3-carboxylate<sup>a</sup>

| Entry | Catalyst                                                                | Solvent/condition      | Time (h) | Yield <sup>b</sup> (%) (ref.) |
|-------|-------------------------------------------------------------------------|------------------------|----------|-------------------------------|
| 1     | TMGT <sup>c</sup> (0.08 g)                                              | —/100 °C               | 5        | 66 (31)                       |
| 2     | TBAHS <sup>d</sup> (10 mol%)                                            | Ethylene glycol/120 °C | 2        | 83 (17)                       |
| 3     | Acetic acid (10 mol%)                                                   | Methanol/reflux        | 12       | 65 (32)                       |
| 4     | AlCl <sub>3</sub> (10 mol%)                                             | —/60 °C                | 1.2      | 79 (30)                       |
| 5     | FeF <sub>3</sub> (10 mol%)                                              | —/80 °C                | 2        | 85 (33)                       |
| 6     | Nano-cellulose/BF <sub>3</sub> /Fe <sub>3</sub> O <sub>4</sub> (0.06 g) | —/100 °C               | 1        | 80 (14)                       |
| 7     | Nano-kaolin/TiCl <sub>4</sub> /Fe <sub>3</sub> O <sub>4</sub> (0.03 g)  | —/100 °C               | 1.5      | 95 (this work)                |

<sup>a</sup> One mmol of any substrate (2-aminobenzothiazole, benzaldehyde and ethyl acetoacetate) was used. <sup>b</sup> Isolated yield. <sup>c</sup> 1,1,3,3-*N,N,N',N'*-Tetramethylguanidinium trifluoroacetate. <sup>d</sup> Tetrabutylammonium hydrogen sulfate.

## Conclusion

Due to the importance of green chemistry, we have introduced the preparation and characterization of nano-kaolin/Ti<sup>4+</sup>/Fe<sub>3</sub>O<sub>4</sub> as a novel, eco-friendly and magnetically recyclable heterogeneous catalyst. This catalyst was used to synthesize 4H-pyrimido[2,1-b]benzothiazole derivatives *via* the one-pot three-component reaction of 2-aminobenzothiazole, aldehydes and ethyl acetoacetate under solvent-free conditions at 100 °C. Some of the important advantages of this protocol include short reaction times, high yields, easy work-up procedure and easy separation of the catalyst with reusability.

## Experimental

### General remarks

A Bruker (DRX-400 Avance) NMR spectrometer was used to obtain the NMR spectra. FTIR spectra were obtained using the Bruker, Equinox 55 spectrometer. Melting points were determined by the Buchi melting point B-540 B.V.CHI apparatus. Field emission scanning electron microscopy (FE-SEM) was carried out *via* Mira 3-XMU, and transmission electron microscopy (TEM) was conducted using Philips CM120 with the LaB<sub>6</sub> cathode and the accelerating voltage of 120 kV. The X-ray diffraction (XRD) pattern was obtained by the Philips X'pert MPD diffractometer equipped with a Cu K $\alpha$  anode ( $k =$



1.54 Å) in the  $2\theta$  range from  $10^\circ$  to  $80^\circ$ . The VSM measurements were performed using a vibrating sample magnetometer (Meghnatis Daghigh Kavir Co. Kashan, Iran). The thermogravimetric analysis (TGA) was conducted by NETZSCH TG 209 F1 Iris. Energy-dispersive X-ray spectroscopy (EDS) of the catalyst was conducted by the EDS instrument Phenom pro X.

### Preparation of the $\text{Fe}_3\text{O}_4$ NPs

A mixture of  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  (2.7 g, 10 mmol) and  $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$  (1 g, 5 mmol) in deionized water (25 ml) was heated until  $80^\circ\text{C}$ . Then, 17 ml of  $\text{NH}_3$  (30%) was added slowly. The mixture was stirred using a mechanical stirrer for 30 minutes. Then, black magnetic nanoparticles were deposited using an external magnet and washed three times with deionized water. Finally, the  $\text{Fe}_3\text{O}_4$  NPs were dried at  $80^\circ\text{C}$  for 4 hours.

### Preparation of nano-kaolin/ $\text{Ti}^{4+}$

In a beaker, 1 ml of  $\text{TiCl}_4$  was added dropwise to a mixture of nano-kaolin (2 g) in 10 ml of dichloromethane and stirred using a mechanical stirrer for 1 h at room temperature. The obtained suspension was filtered, washed with dichloromethane and dried at room temperature.

### Preparation of nano-kaolin/ $\text{Ti}^{4+}/\text{Fe}_3\text{O}_4$

At first, a mixture of nano-kaolin/ $\text{Ti}^{4+}$  (2 g) and dichloromethane (10 mL) was placed in an ultrasonic bath for 30 minutes. Then, nano- $\text{Fe}_3\text{O}_4$  (1 g) was added to the mixture and placed in the ultrasonic bath for 40 minutes to disperse the particles. The resulting suspension was obtained by an external magnet, washed with dichloromethane, and dried at room temperature.

### General procedure for the synthesis of 4H-pyrimido[2,1-b]benzothiazole derivatives

In a sand bath, a mixture of aldehyde (1 mmol), ethyl acetoacetate (1 mmol), 2-aminobenzothiazole (1 mmol) and nano-kaolin/ $\text{Ti}^{4+}/\text{Fe}_3\text{O}_4$  (0.03 g) was heated to  $100^\circ\text{C}$ . The right time for the completion of the reactions is shown in Table 2. After completion of the reaction, the reaction mixture was dissolved in ethanol, and the catalyst was separated by an external magnet. Finally, water was added to the residue, and the product appeared as a pure solid. For the recovery of the catalyst, the magnetically resolved catalyst was washed with ethanol at least three times and then dried at room temperature.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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## References

- 1 Z. Y. Yu, Q. S. Fang, J. Zhou and Z. B. Song, *Res. Chem. Intermed.*, 2016, **42**, 2035.
- 2 M. S. Chaitanya, G. Nagendrappa and V. P. Vaidya, *J. Chem. Pharm. Res.*, 2010, **2**, 206.
- 3 A. Y. Hassan, *Phosphorus, Sulfur Silicon Relat. Elem.*, 2009, **184**, 2856.
- 4 M. T. Gabr, N. S. El-Gohary, E. R. El-Bendary and M. M. El-Kerdawy, *Eur. J. Med. Chem.*, 2014, **85**, 576.
- 5 D. V. Kashinath, Y. M. Rajmani and C. S. Ravindra, *J. Pharma Res.*, 2013, **6**, 574.
- 6 V. K. Deshmukh, P. Raviprasad, P. A. Kulkarni and S. V. Kuberkar, *Int. J. ChemTech Res.*, 2011, **3**, 136.
- 7 M. A. El-Sherbeny, *Arzneim.-Forsch./Drug Res.*, 2000, **50**, 848.
- 8 M. M. M. Gineinah, *Sci. Pharm.*, 2001, **69**, 53.
- 9 M. Yadav, V. K. Deshmukh and S. R. Chaudhari, *Int. J. Pharm. Sci. Rev. Res.*, 2013, **22**, 41.
- 10 S. Maddila, S. Gorle, N. Seshadri, P. Lavanya and S. B. Jonnalagadda, *Arabian J. Chem.*, 2016, **9**, 681.
- 11 S. R. Vaidya and J. J. Chamergore, *Chem. Biol. Interface*, 2016, **6**, 47.
- 12 S. Azad and B. F. Mirjalili, *RSC Adv.*, 2016, **6**, 96928.
- 13 S. Azad and B. F. Mirjalili, *Res. Chem. Intermed.*, 2017, **43**, 1723.
- 14 B. F. Mirjalili and F. Aref, *Res. Chem. Intermed.*, 2018, **44**, 4519.
- 15 S. A. Fazeli-Attar and B. F. Mirjalili, *Res. Chem. Intermed.*, 2018, **44**, 6419.
- 16 P. K. Sahu, P. K. Sahu and D. D. Agarwal, *RSC Adv.*, 2013, **3**, 9854.
- 17 L. Nagarapu, H. K. Gaikwad, J. D. Palem, R. Venkatesh, R. Bantu and B. Sridhar, *Synth. Commun.*, 2013, **43**, 93.
- 18 Q. Zhang, W. Tongamp and F. Saito, *Powder Technol.*, 2011, **212**, 354.
- 19 H. H. Murray, *Appl. Clay Sci.*, 2000, **17**, 207.
- 20 A. M. Doyle, T. M. Albayati, A. S. Abbas and Z. T. Alismaeel, *Renewable Energy*, 2016, **97**, 19.
- 21 A. H. Lu, E. E. Salabas and F. Schüth, *Angew. Chem., Int. Ed.*, 2007, **46**, 1222.
- 22 X. Batlle and A. Labarta, *J. Phys. D: Appl. Phys.*, 2002, **35**, R15.
- 23 R. Narayanan, Ch. Tabor and M. A. El-Sayed, *Top. Catal.*, 2008, **48**, 60.
- 24 L. Xu, L.-M. Yang and E. Ganz, *Theor. Chem. Acc.*, 2018, **137**, 98.
- 25 J.-H. Liu, L.-M. Yang and E. Ganz, *J. Mater. Chem. A*, 2019, **7**, 11944.
- 26 J.-H. Liu, L.-M. Yang and E. Ganz, *J. Mater. Chem. A*, 2019, **7**, 3805.
- 27 J.-H. Liu, L.-M. Yang and E. Ganz, *ACS Sustainable Chem. Eng.*, 2018, **6**, 15494.
- 28 S. Azad and B. F. Mirjalili, *Mol. Diversity*, 2019, **23**, 413.



- 29 B. F. Mirjalili, A. Bamoniri and L. Asadollah Salmanpoor, *J. Nanostruct.*, 2018, **8**, 276.
- 30 P. K. Sahu, P. K. Sahu, J. Lal, D. Thavaselvam and D. D. Agarwal, *Med. Chem. Res.*, 2012, **21**, 3826.
- 31 A. Shaabani and A. Maleki, *Appl. Catal., A*, 2007, **331**, 149.
- 32 P. K. Sahu, P. K. Sahu, Y. Sharma and D. D. Agarwal, *J. Heterocycl. Chem.*, 2014, **51**, 1193.
- 33 A. B. Atar, Y. S. Jeong and Y. T. Jeong, *Tetrahedron*, 2014, **70**, 5207.

