Check for updates

Synthesis, Characterization, and Catalytic Properties of Magnetic Fe₃O₄@FU: A Heterogeneous Nanostructured Mesoporous Bio-Based Catalyst for the Synthesis of Imidazole Derivatives

Maryam Banazadeh, Sara Amirnejat and Shahrzad Javanshir*

Heterocyclic Chemistry Research Laboratory, Chemistry Department, Iran University of Science and Technology, Tehran, Iran

In this protocol, Fucoidan (FU), a fucose-rich sulfated polysaccharide extracted from brown algae Fucus vesiculosus was used for *in situ* preparation of magnetic Fe₃O₄@FU. Nanoco magnetic properties of Fe₃O₄@FU were investigated by energy dispersive X-ray (EDX) spectroscopy, X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FT-IR), field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), Brunauer–Emmett–Teller (BET) adsorption method, and vibrating sample magnetometer (VSM). The catalytic activity of Fe₃O₄@FU was employed for the synthesis of tri- and tetra-substituted imidazoles through three- and four-component reactions respectively, between benzyl, aldehydes, NH₄OAc and benzyl, aldehydes, NH₄OAc, and amine under reflux in ethanol. It is worth nothing that excellent yields, short reaction times, chromatography-free purification, and environmental friendliness are highlighted features of this protocol.

Keywords: fucoidan, heterogeneous catalyst, imidazoles, superparamagnetic iron oxide nanoparticles, sulfated polysaccharides

INTRODUCTION

Through extensive applications and potential in the chemical industry and preservation of the environment, the recently supported solid nanocatalysis has been faced with various attentions in catalysis science and technology (Amirnejat et al., 2013; Fereshteh and Shahrzad, 2020). To overcome the difficulty of catalyst separation, some magnetic heterogeneous catalysts with unique features and advanced functionalities suitable for a range of applications, including biological and environmental applications have been made (Pourian et al., 2018; Zaheri et al., 2018). The magnetic materials have gained more attention due to their combined physicochemical characteristics such as high surface area, high thermal and chemical stability, excellent biocompatibility and biodegradability, and efficient super magnetic behavior (Dolatkah et al., 2018; Piri et al., 2019).

Natural biopolymers as an effective tool have given rise to a new method of producing degradable materials. Meanwhile, marine polysaccharides exhibit a vast variety of structures and could be considered as a novel natural source (Dekamin et al., 2016; Alipour et al., 2018; Dolatkhah et al., 2019). Nanomaterials based on marine polysaccharides have been considered as one of

the most important topics of research in recent years, especially in chemical and bio-based research, due to biocompatibility and biodegradability, cheapness, non-toxicity, and abundance (Hemmati et al., 2016; Amirnejat et al., 2020a,b,c). Fucoidan refers to a type of polysaccharide which contains substantial percentages of L-fucose and sulfated ester groups, mainly derived from brown seaweed which has been extensively studied due to its numerous interesting biological activities (Gomez-Zavaglia et al., 2019; Zayed and Ulber, 2019, 2020).

In recent decades, it has been extensively represented that multi-component reaction (MCR) is an ideal tool for creating molecular diversity and complexity (Graebin et al., 2019). Meanwhile imidazoles, polar in nature and with a five-member ring structure, are one of the most important compounds showing a wealthy source of biologically important features such as inhibitors, fungicides, herbicides plant, anti-inflammatory, anticancer, antimicrobial, analgesic, and anti-tubercular activity (Shalini et al., 2010; Varzi and Maleki, 2019). Numerous approaches have been developed for the synthesis of 1,2,4,5-tetrasubstituted imidazoles, which can be prepared by a four-component cyclo condensation consisting of aldehyde, benzil, a primary amine and ammonium acetate in the presence of different catalysts such as $BF_3 \cdot SiO_2$ (Sadeghi et al., 2008), and silica gel/$NaHSO_4$ (Karimi et al., 2006), while other main components are achieved by synthesis of tri-substituted imidazoles by the condensation of benzil derivatives, aryl aldehydes, and ammonium acetate catalyzed by different catalysts such as $ZrCl_4$ (Shitole et al., 2015), sulfanilic acid (Gadekar et al., 2009), and chitosan (Zheng et al., 2019). However, some of these methodologies have

some drawbacks, such as low yields, long reaction times, severe reaction conditions, and work up procedure. Herein, we report the *in situ* synthesis of a novel eco-friendly magnetic heterogeneous catalyst Fe_3O_4@FU for the synthesis of tri- and tetra-substituted imidazoles under reflux condition in ethanol (**Scheme 1**). Easy work up and separation, high product yields and short reaction times made this method effective and advantageous.

EXPERIMENTAL

Materials and Methods

All solvents and chemicals were purchased from Merck and Aldrich. All reactions and the purity of the products were monitored by thin-layer chromatography (TLC) using aluminum plates coated with silica gel F254 plates (Merck) using ethyl acetate and n-hexane as eluents. UV light with a wavelength of 254 nm was used for the detection of products. By using an Electro thermal 9100, melting points were determined in open capillaries. IR spectra were run on a 400s Shimadzu FTIR Spectrophotometer (as KBr pellets). ^{1}H and ^{13}C NMR spectra were recorded on a 500 MHz Bruker Avance DRX Spectrometer instrument using TMS as an internal standard and $CDCl_3$, DMSO-*d6* as a solvent. The XRD patterns were obtained on an X-ray diffractometer (Holland, Philips Xpert, Co K, radiation, λ = 0.178897 nm). A Field Emission Scanning Electron Microscope (FE-SEM) with 15 KV, Mira3, Tescan), Thermal Gravimetric Analysis (TGA D-32609 from Hullhorst), and Transmission electron microscope (TEM, Philips –CM120, 100 KV) were used. An ultrasonic probe watt ultrasonic homogenizer 400 from

SCHEME 1 | The synthesis of 2,4,5-triaryl-1*H*-imidazoles **5a-k** and 1,2,4,5- tetraaryl-1*H*-imidazoles **6l-p** *via* catalytic application of Fe_3O_4@FU.
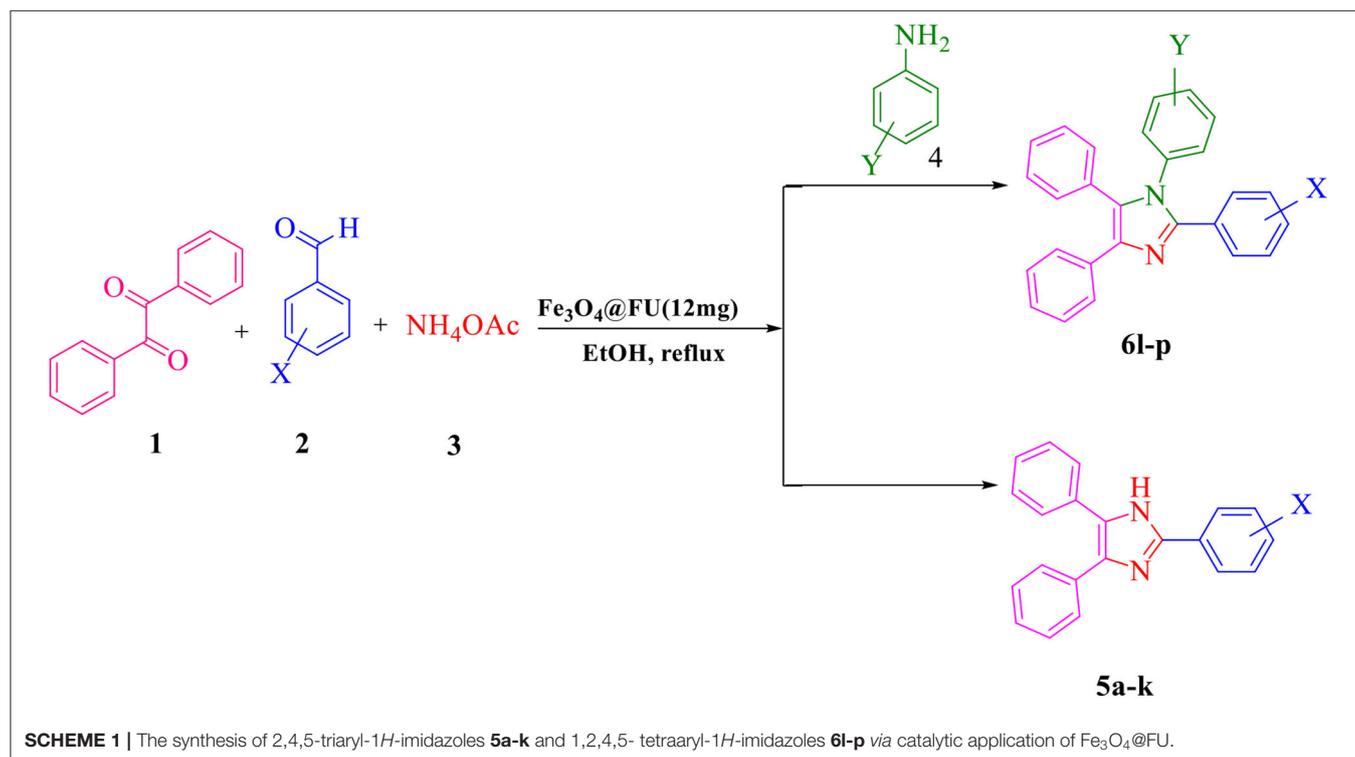
Topsonics Co was used in room temperature for optimization of the reaction.

Preparations of Fucoidan Powder

2.5 gr of algae Fucus vesiculosus was finely ground by a ball mill for 5 min and was placed in a round bottom 200 ml flask containing 100 ml of 96% ethanol, and was stirred for 12 h. Then,

the suspension was centrifuged at 4,000 rpm for 15 min and the resulting powder was dried at 50°C for 1 h.

Synthesis of Magnetic Fe_3O_4@FU Nanocomposite

For the preparation of the Fe_3O_4@FU, 0.2 g of fucoidan powder, $FeCl_2.4H_2O$ (2 g, 0.01 mol) and (5.5 g, 0.02 mol) of $FeCl_3$ were

SCHEME 2 | Preparation of Fe_3O_4@FU magnetic nanocomposite.

FIGURE 1 | The FT-IR spectra for **(a)** FU, **(b)** Fe_3O_4@FU NPs.
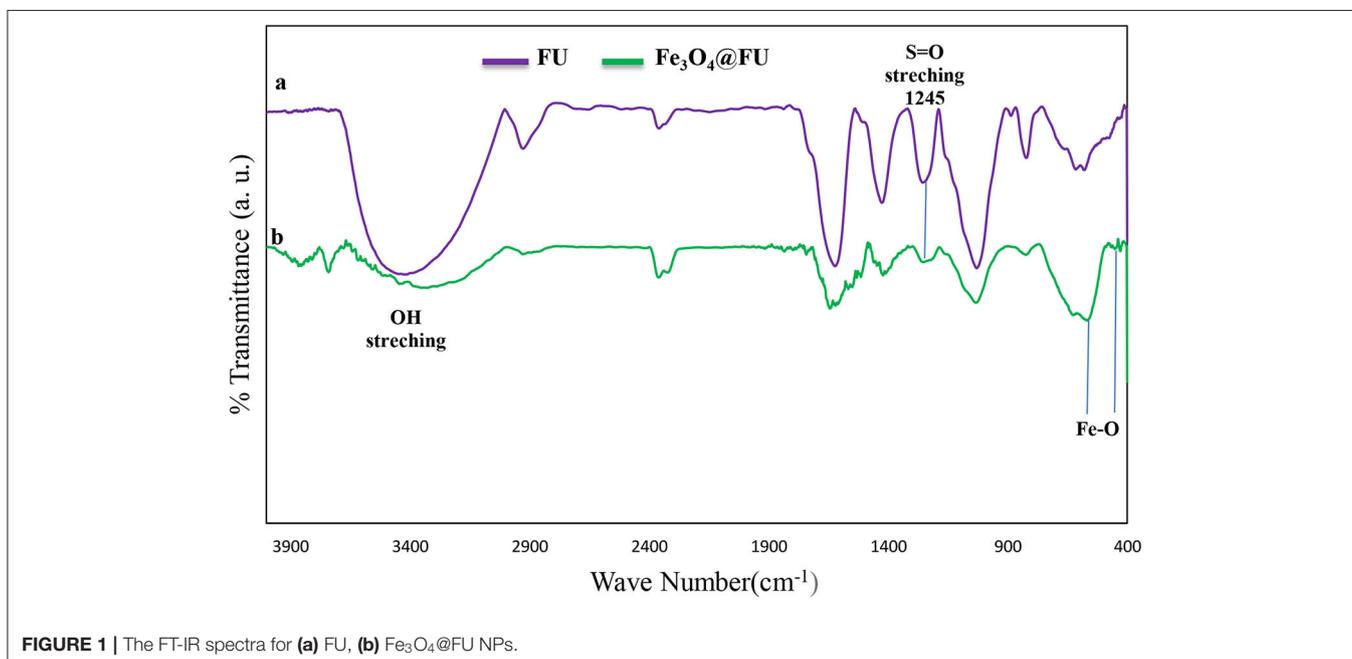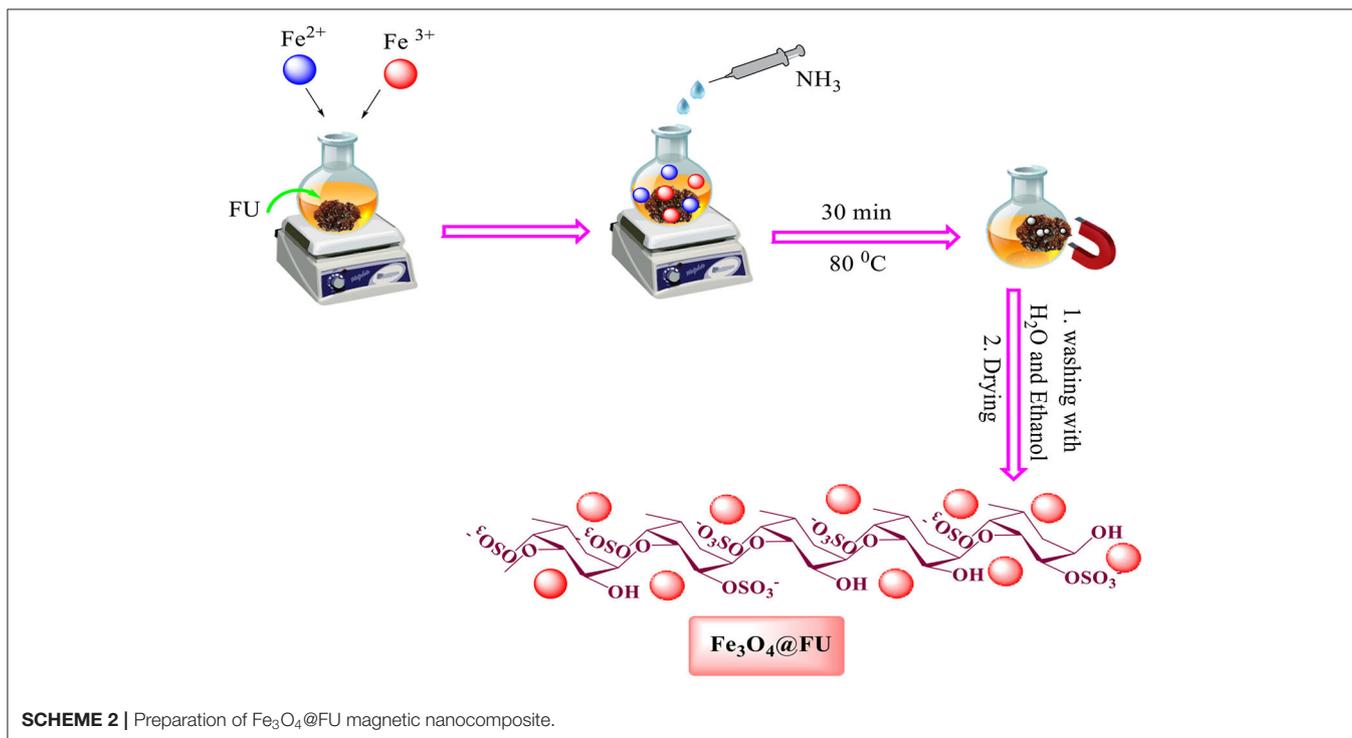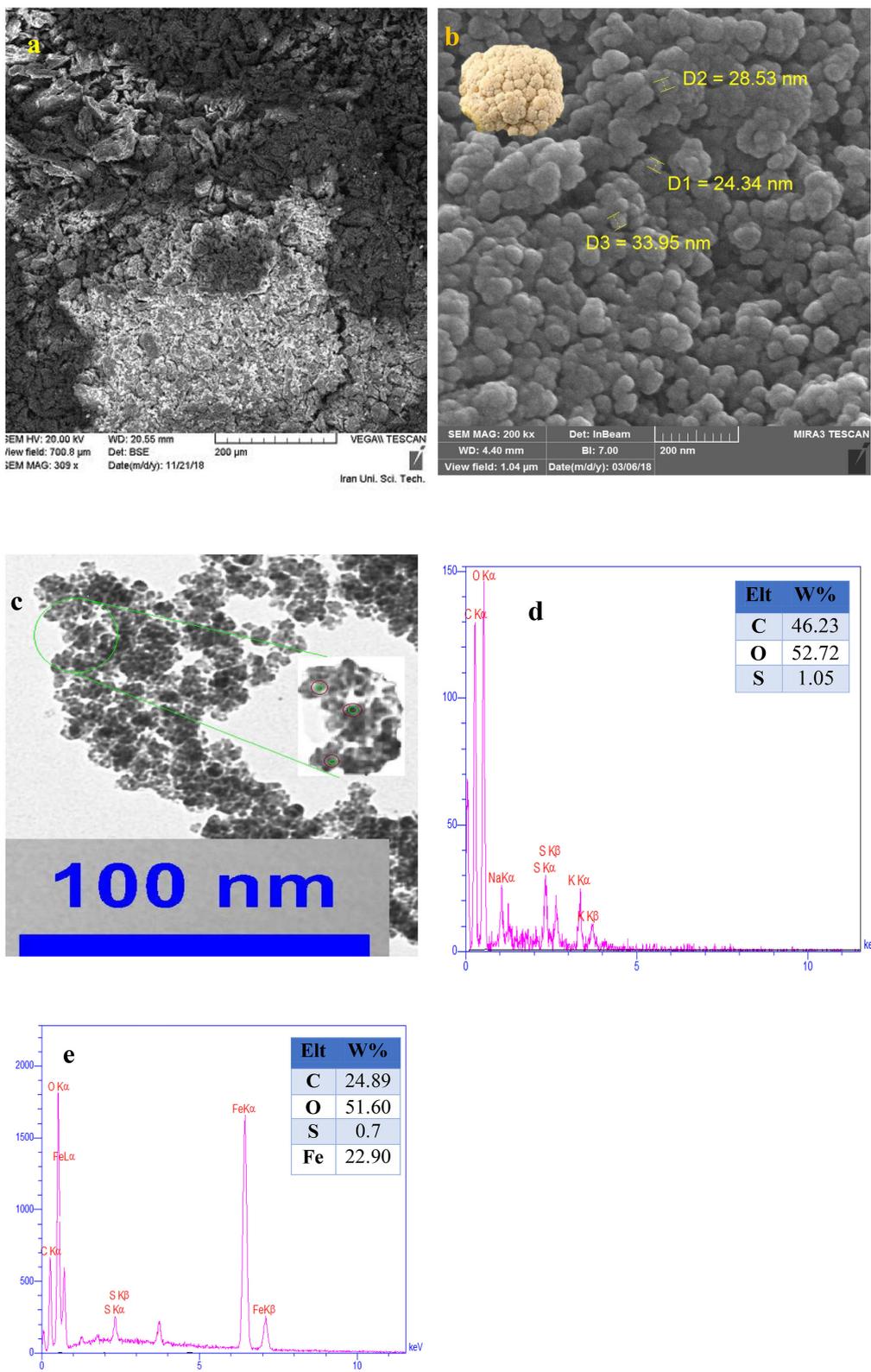
FIGURE 2 | SEM images of **(a)** FU, **(b)** Fe$_3$O$_4$@FU, and **(c)** TEM images of Fe$_3$O$_4$@FU NPs. EDX analysis of **(d)** FU, and **(e)** Fe$_3$O$_4$@FU NPs.
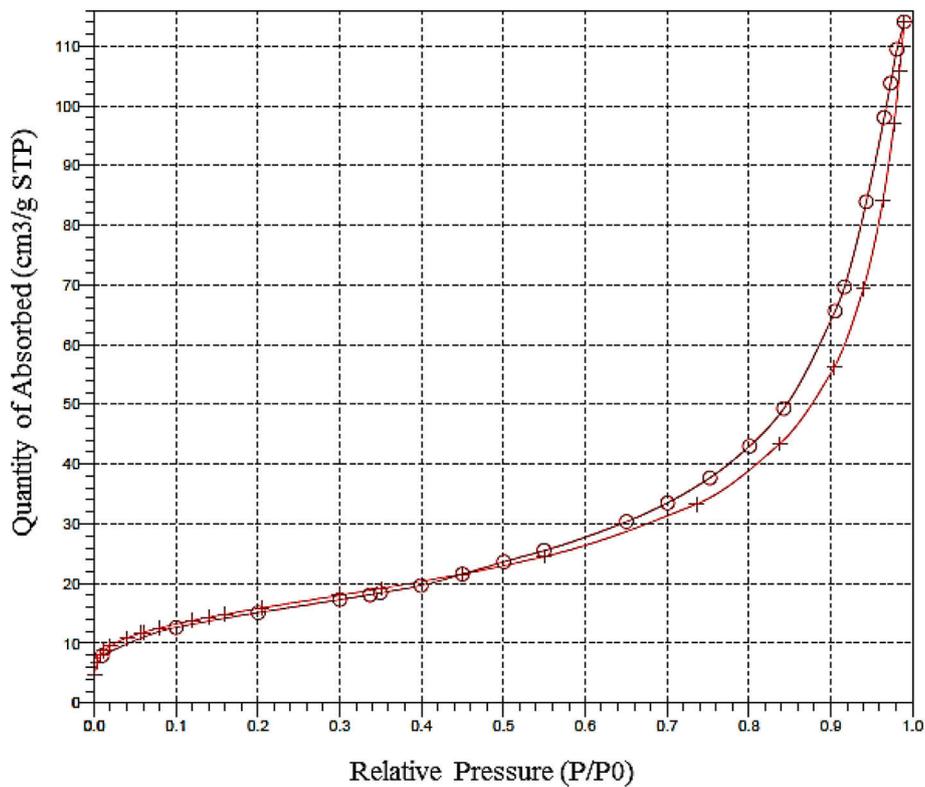
FIGURE 3 | BET curve of Fe_3O_4@FU NPs.
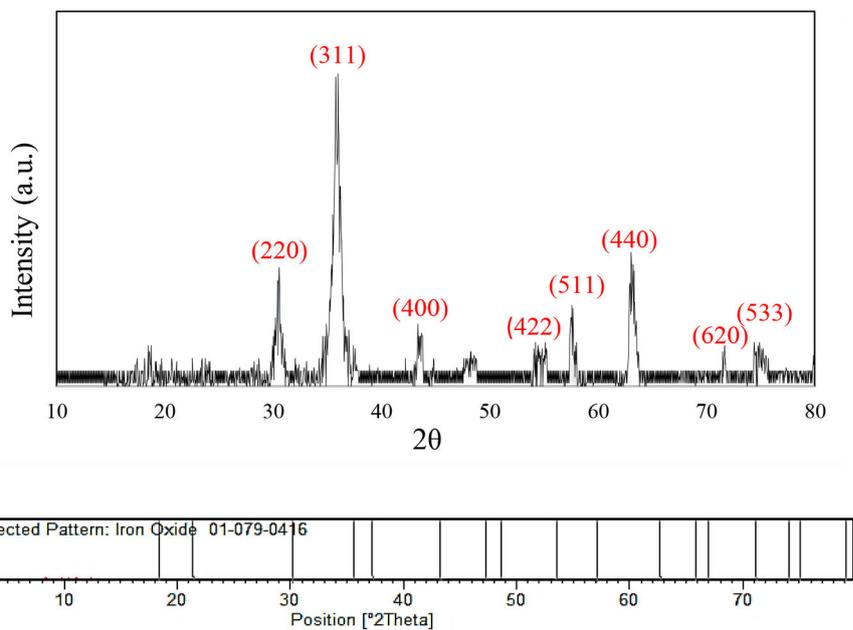
FIGURE 4 | XRD patterns of Fe_3O_4@FU NPs.

used. $6H_2O$ was dissolved in 100 ml of distilled water. Then the mixture was vigorously stirred under a nitrogen atmosphere at 80°C for 15 min to reach a uniform solution. The pH of the solution was then adjusted to 12 by the dropwise addition of an aqueous ammonia solution (25%). The mixture was stirred at 80°C for 45 min. The prepared magnetic nanoparticles were separated by an external magnet, finally washed with ethanol and DI, and dried for 6 h at 60°C (**Scheme 2**).

General Procedure for the Preparation of 2, 4, 5-Trisubstituted Imidazoles Derivatives

A mixture of benzil (210 mg, 1 mmol), aldehydes (1 mmol), NH_4OAc (154 mg, 2 mmol), and $Fe_3O_4@$ FU NPs (12 mg) in 3 ml EtOH was stirred under reflux conditions for the appropriate

times. The progress of the reactions was monitored by TLC (eluent: EtOAc / n-hexane, 1: 3). After completion of the reaction, the catalyst was easily separated by an external magnet and then reused as such for the following experiment after being washed with EtOH and dried. The pure products were obtained by recrystallization from hot EtOH and then dried at 60°C for 1 h.

General Procedure for the Preparation of 1, 2, 4, 5-Tetrasubstituted Imidazoles Derivatives

Benzil (210 mg, 1 mmol), aldehydes (1 mmol), NH_4OAc (77 mg, 1 mmol), amine (1 mmol), and $Fe_3O_4@FU$ NPs (12 mg) in ethanol (3 mL) was stirred under reflux conditions until completion of the reaction which was monitored by TLC (eluent: EtOAc/n-hexane, 1:3). The catalyst was separated from the mixture by an external magnet, washed and dried for use in the next run. The crude products were filtered and recrystallized from ethanol.

RESULTS AND DISCUSSION

$Fe_3O_4@FU$ magnetic nanoparticles as a heterogeneous catalyst were characterized by Fourier transform infrared (FT-IR) spectral analysis. One strong broad band at 3,500 cm^{-1} was attributed to the stretching vibration due to the O-H of fucoidan and water. The appearance of the peak at 1,624 cm^{-1}, attributed to significant polysaccharide chains (**Figure 1a**), is stronger than magnetic fucoidan (**Figure 1b**). The absorption band at 1,029 cm^{-1} indicated hemiacetal vibration at alcohol and ether functional groups in fucoidan structure. Furthermore, the peak at 1,240–1,255 cm^{-1} was related to the stretching vibration of S=O from the SO_3H group. The presence of the metal oxide peaks of 570 and 455 cm^{-1} also exhibited in FT-IR of $Fe_3O_4@FU$

FIGURE 5 | Magnetization curves for Fe_3O_4 and the $Fe_3O_4@FU$ at room temperature.

FIGURE 6 | TGA curves of (a) FU (b) $Fe_3O_4@FU$ NPs.
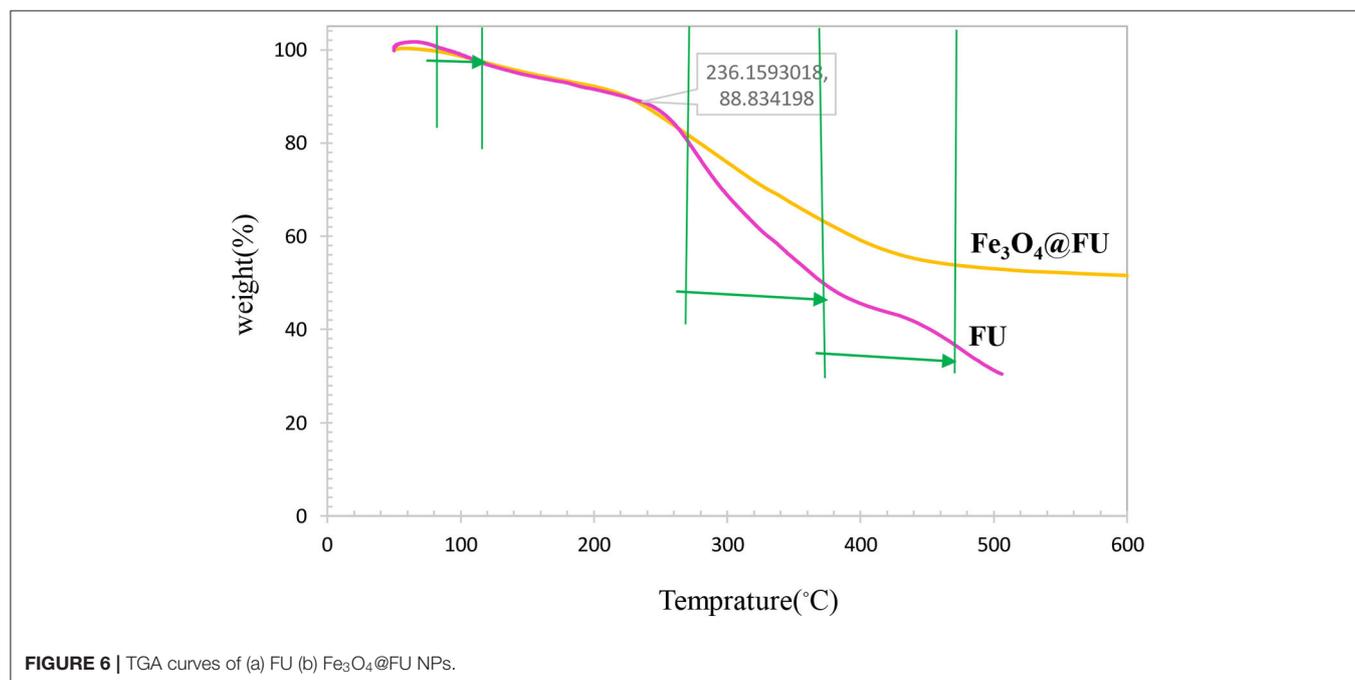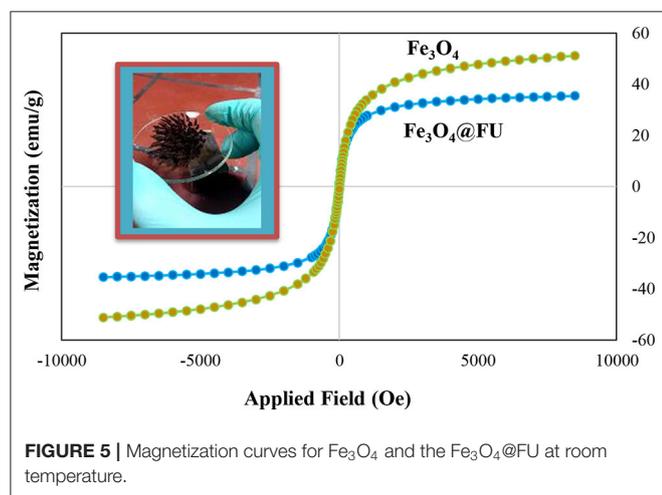
TABLE 1 | Condition optimization for the synthesis of 2,4,5-trisubstituted imidazole (5k)[a].

Entry	Catalyst	Temp. (°C)	Solvent	Catalyst (mg)	Time (min)	Yield (%)
1	-	r.t.	Solvent free	-	24 h	-
2	-	Reflux	Ethanol	-	250	Trace
3	FU	Reflux	Ethanol	12	40	70
4	Fe_3O_4	Reflux	Ethanol	12	40	55
5	Fe_3O_4@FU	Reflux	Ethanol	12	20	96
6	Fe_3O_4@FU	Reflux	Ethanol/ Water	12	30	80
7	Fe_3O_4@FU	r.t.	Ethanol	12	35	75
8	Fe_3O_4@FU	Reflux	Water	12	40	60
9	Fe_3O_4@FU	Reflux	CH_3CN	12	70	48
10	Fe_3O_4@FU	Reflux	THF	12	90	40
11	Fe_3O_4@FU	Reflux	Toluene	12	60	45
12	Fe_3O_4@FU	Reflux	Ethanol	15	20	96
13	Fe_3O_4@FU	Reflux	Ethanol	10	30	90
14	Fe_3O_4@FU	Reflux	Ethanol	5	50	60

[a]Reaction conditions: benzaldehyde (1 mmol), benzil (1 mmol), ammonium acetate (2 mmol), solvent (3 ml).

TABLE 2 | Synthesis of 2,4,5-triaryl **(5a-k)**[a] and 1,2,4,5- tetraaryl−1H-imidazoles **(6l-p)**[b] catalyzed by Fe_3O_4@FU nanocomposite.
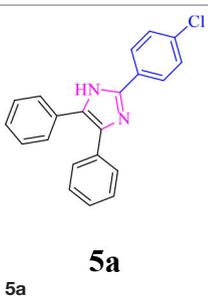
Entry	R^1-ArCHO	R^2-ArNH$_2$	Product[d]	Time (min)	Yield[c] (%)	M.p (°C) found/reported
1		-	**5a**	12	96	261–262/260–261 (Salimi et al., 2015)
2		-	**5b**	20	90	192–194/191–192 (Shaabani et al., 2017)
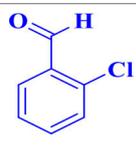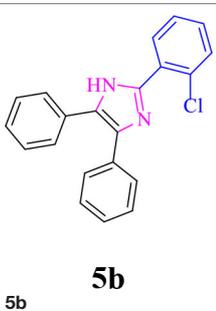
(Continued)

TABLE 2 | Continued

Entry	R^1-ArCHO	R^2-ArNH$_2$	Product^d	Time (min)	Yield^c (%)	M.p (°C) found/reported
3		-	**5c**	12	96	248–250/248–250 (Marques et al., 2012)
4		-	**5d**	15	91	170–173/171–174 (Amirnejat et al., 2020a)
5		-	**5e**	22	90	301–303/300–303 (Amirnejat et al., 2020a)
6		-	**5f**	25	88	229–231/230–233 (Momahed Heravi et al., 2019)
7		-	**5g**	15	95	195–197/196–198 (Shaabani et al., 2016)
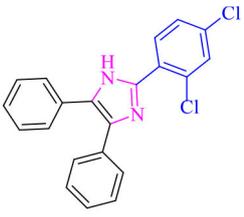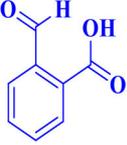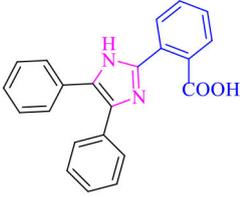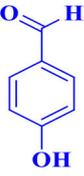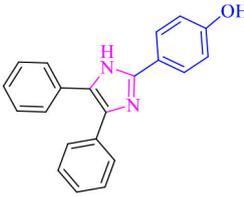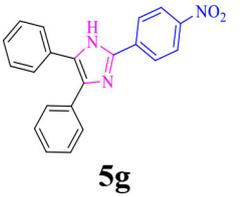
(Continued)

TABLE 2 | Continued

Entry	R^1-ArCHO	R^2-ArNH$_2$	Product^d	Time (min)	Yield^c (%)	M.p (°C) found/reported
8		-	5h	20	86	314–316/313–315 (Momahed Heravi et al., 2019)
9		-	5i	25	80	257–259/256–259 (Salimi et al., 2015)
10		-	5j	30	80	230–232/230–232 (Mirsafaei et al., 2016)
11		-	5k	20	90	268–270/270 (Shaterian and Ranjbar, 2011)
12		NH$_2$	6l	20	94	157–159/156–158 (Salimi et al., 2015)
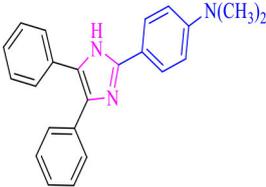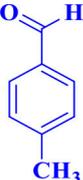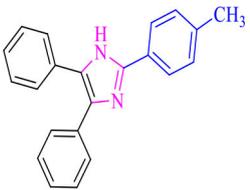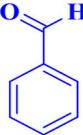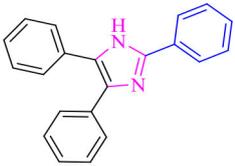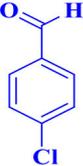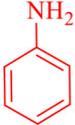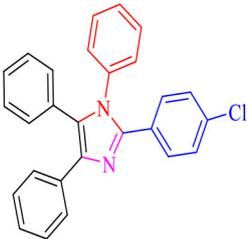
(Continued)

TABLE 2 | Continued

Entry	R[1]-ArCHO	R[2]-ArNH₂	Product[d]	Time (min)	Yield[c] (%)	M.p (°C) found/reported
13			 **6m**	30	85	175–177/176–178 (Ray et al., 2013)
14			 **6n**	30	90	230–234/232–236 (Salimi et al., 2015)
15			 **6o**	35	83	260–262/257–259 (Mohammadi et al., 2012)
16			 **6p**	30	87	150–152/150–152 (Salimi et al., 2015)
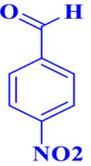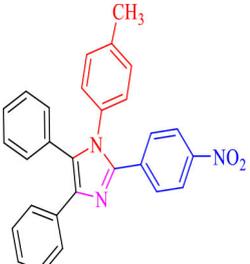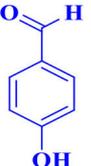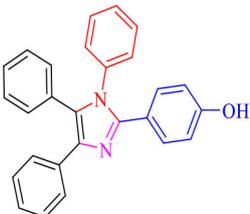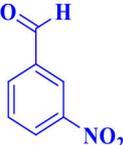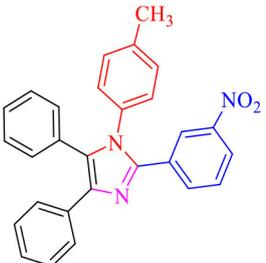
[a]Reaction conditions: benzil (1 mmol), aldehydes (1 mmol), ammonium acetate (2 mmol), EtOH (3 ml), and Fe₃O₄@FU nanocomposite (12 mg) **(5a-k)**.

[b]Reaction conditions: benzil (1 mmol), aldehydes (1 mmol), ammonium acetate (2 mmol), aniline (1 mmol), EtOH (3 ml), and Fe₃O₄@FU nanocomposite (12 mg) **(6l-p)**.

[c]Isolated yields.

[d]The ¹HNMR spectra for products 5a and 5c have been provided in supplementary file.

acknowledged that the chemical structure of the magnetic nanoparticles have been preserved after the functionalization.

Primarily, the size, structure, and morphology of FU, and the as prepared nanocomposite were investigated by SEM analyses (**Figures 2a,b**). As can be seen, Fe₃O₄@FU nanocomposites have a cauliflower-shaped morphology in which the average size distribution was around 24–33 nm. TEM analysis of the as-synthesized Fe₃O₄@FU showed that the Fe₃O₄@FU NPs have a

core–shell structure (**Figure 2c**). Simultaneously, the elemental composition of Fe_3O_4@FU and FU were studied by EDX analysis (**Figures 2d,e**) which confirmed the presence of O, C, Fe, and S elements constituted in the nanocomposite.

The surface area and pore size distributions of the Fe_3O_4@FU were analyzed by N_2 adsorption-desorption analysis. As shown in **Figure 3**, Fe_3O_4@FU NPs have type IV isotherms and type H_3 hysteresis loops. The BET surface area, average pore diameter and the total pore volume were calculated to be 55.65 m^2/g, 11 nm, and 1.749 cm^3/g, respectively.

The XRD patterns of Fe_3O_4@FU NPs are presented in **Figure 4**. As can be seen, diffraction peaks at 2θ values = 30.4°, 35.8°, 43.7°, 55.3°, 57.8°, and 63.3° could be indexed to the presence of all the crystal planes such as (220), (311), (400), (422), (511), and (440) attributed to the cubic inverse spinel structure of Fe_3O_4 which

TABLE 3 | Comparison of the activity of the catalysts in synthesis **5k** with some of the other catalysts reported in the literature.

Entry	Catalyst	Reaction condition	Reaction time (min)	Yield (%)	References
1	[Et_3NH][HSO_4](10 mol %)	Solvent-free/ 130°C	40	89	Deng et al., 2013
2	COPAPSC(20 mg)	Solvent-free/ 110°C	4h	77	Salimi et al., 2015
3	(CTA)3PMo-MMT nanocomposite (50 mg)	Solvent-free/ 100°C	60	85	Masteri-Farahani et al., 2020
4	Fe_3O_4@FU (12 mg)	EtOH, Reflux	20	90	This work

SCHEME 3 | The proposed mechanism for the synthesis of 2,4,5-trisubstituted imidazoles by using Fe_3O_4@FU nanocomposite.
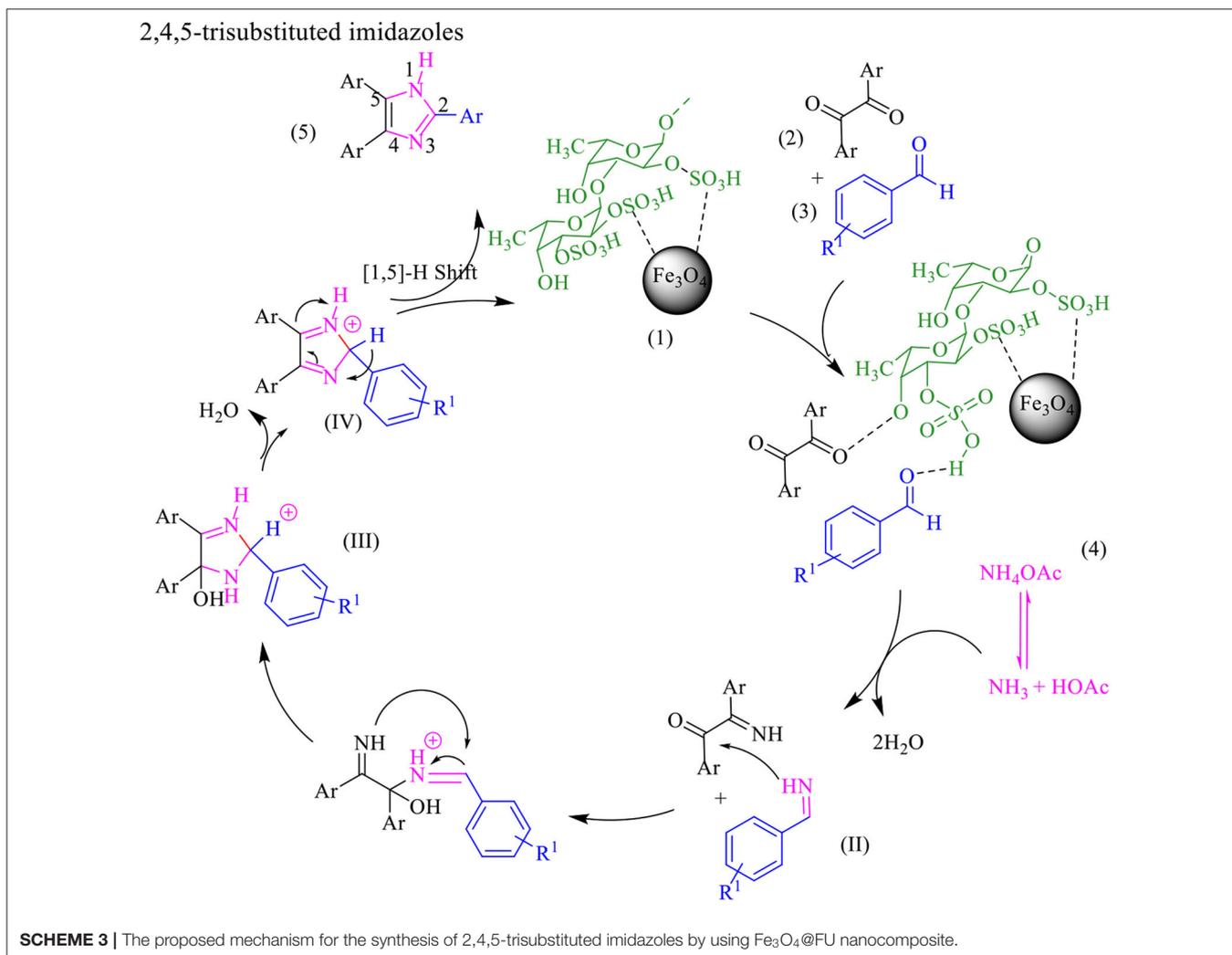
matched with the standard pattern (JCPDS-PDF, No. 01-087-2334). These results proved that the crystalline structure of Fe_3O_4 was maintained after its decoration with fucoidan polysaccharide.

The magnetization curves of Fe_3O_4 and Fe_3O_4@FU NPs measured at room temperature with a vibrating sample magnetometer (VSM) were shown in **Figure 5**. The hysteresis loops of Fe_3O_4@FU NPs showed the superparamagnetic behavior of Fe_3O_4@FU NPs. The saturation magnetization (Ms) values for the Fe_3O_4 and the Fe_3O_4@FU NPs were 51, 35 emu/g, respectively. It is important to note that the saturation magnetization remains sufficient after covering by FU.

The thermogravimetric analysis (TGA) curve of FU and Fe_3O_4@FU NPs showed three-stage weight loss in the temperature range from 100 to 500°C (**Figure 6**). The first weight loss of around 2 wt% ensues at 100°C indicating the evaporation of water or solvent. The next weight loss of about

12 wt% occurs at 240°C and the third weight loss about 42 wt% at 440°C for the decomposition of polysaccharide. Accordingly, the TGA studies showed improved stability for Fe_3O_4@FU NPs.

Catalytic Activity of Magnetic Fe_3O_4@FU NPs

The catalytic efficacy of Fe_3O_4@FU NPs as a proficient heterogeneous catalyst was investigated in the one-pot reaction between benzil (1 mmol), benzaldehyde (1 mmol), and ammonium acetate (2 mmol) as a model reaction for the synthesis of imidazole derivatives. To determine the role of the catalyst, the model reaction was performed in the absence of the catalyst. The anticipated product was not shown after a long reaction time. The results reveal that the presence of the catalyst has a considerable effect on the formation of these compounds. The model reactions were carried out in the presence of different

SCHEME 4 | The proposed mechanism for the synthesis of1, 2,4,5-tetra-substituted imidazoles by using Fe_3O_4@FU nanocomposite.

FIGURE 7 | Reusability of Fe_3O_4@FU for the synthesis of tri-substituted **(5a)** and tetra-substituted **(6l)** imidazoles.

FIGURE 8 | FT-IR spectra of Fe_3O_4@FU (a) before being used in the reaction, (b) after being used six times in the reaction.

FIGURE 9 | The EDX analysis of recycled Fe_3O_4@FU after recycling of Fe_3O_4@FU NPs.

solvents such as EtOH, H_2O, THF, and Toluene, CH_3CN and solvent-free conditions. As the results show, Ethanol (3 ml) was found to be the most effective solvent. To evaluate the optimum catalyst concentration, the model reaction was carried out in the presence of various amounts of catalyst (5, 10, 12, and 15 mg). Consequently, the best yield is accessible in the presence of just 12 mg catalyst, and use of extra amounts of the catalyst (15 mg) did not increase the result to a significant level (**Table 1**). The model reaction was carried out with FU, Fe_3O_4, and Fe_3O_4@FU. These results endorsed that Fe_3O_4@FU was more suitable for this reaction. Overall, the most significant conditions for the desired products were achieved at reflux under ethanol in the presence of 12 mg magnetic nanocomposite.

For total assessment of the synthesis of 2,4,5-trisubstituted and 1,2,4,5-tetrasubstituted imidazoles after the mentioned optimized conditions, various aromatic aldehydes and anilines were evaluated which can be seen in **Table 2**, including both electron-donating and electron-withdrawing substitutions which

were studied in these reactions. While the presence of electron-donating groups resulted in the corresponding products being prepared with lower reaction yields, in addition, electron-withdrawing functionalities led to the higher yields with shorter reaction times. Most of the products directly crystallized from the mixture of reaction with high purity with good to excellent yields (80–96%). It should be mentioned that all the products were confirmed by melting points, and some of the products were characterized by NMR spectral data.

To evaluate the generality of this catalyst in comparison to previously reported results in the literature, Fe_3O_4@FU acts as

an appropriate green biocatalyst due to the yields of products, reaction time and temperature (**Table 3**).

The proposed mechanism for the synthesis of tri-substituted imidazoles was shown in **Scheme 3**. In the first step, the aldehyde and benzil group were activated by the formation of a hydrogen bond with the functional group of fucoidan, followed by the nucleophilic attack of ammonia, coming from the ammonium acetate, the intermediate imine (II) is formed after the removal of H_2O. Intermediate (II) is then added to benzil forming intermediate (III). Dehydration of intermediate (III) afforded the intermediate (IV), which rearranges via 1,5 H-shift which, followed by deprotonation, gives tri substituted imidazole (5).

The proposed mechanism for the preparation of four one-pot reactions of benzil, aldehyde, and ammonium acetate and amine is shown in **Scheme 4**. Aldehyde and 1, 2-diketone were first activated by $Fe_3O_4@FU$, then amine was added to the aldehydes forming an imine intermediate which was attacked by ammonia (released from the ammonium acetate) to form the amine intermediate (II). On the other hand, the amine intermediate (II) reacted with the activated carbonyl groups of benzil to form the intermediate (III). Finally, the imidazole derivative was formed after dehydration, followed by a 1,5 H-shift.

The main concerns from an economic and environmental aspect, such as recyclability and the ability to reuse the catalyst, were also surveyed. In this regard, after the reaction was completed, the catalyst was collected by an external magnet and then washed with ethyl acetate, n-hexane and ethanol and dried at 50°C in an oven. The recycled catalyst was used six consecutive times in the reaction. According to the results, no appreciable reduction in the efficiency of the catalysts is observed (**Figure 7**).

The recycled catalyst was identified by EDX and FT-IR analysis. The comparison of the FT-IR spectrum of $Fe_3O_4@FU$ before and after six consecutive runs confirms that no definite change in its structure was seen, which can therefore be considered as a recyclable and stable biocatalyst in organic reactions (**Figure 8**). However, the EDX analysis of the recovered

catalyst (**Figure 9**) showed that a degree of catalyst desulfation and leaching occurred after six runs, which explains the decrease in the yield of reactions.

CONCLUSION

In summary, magnetic core-shell structured fucoidan coated Fe_3O_4 NPs were *in situ* synthesized and their structural and magnetic properties were investigated. The catalytic property of $Fe_3O_4@FU$ was studied in the synthesis of imidazoles derivatives. Outstanding catalytic activity alongside a simple synthesis method, easy processing and separation, a high product yield, and short reaction time make $Fe_3O_4@FU$ an attractive bio-based heterogeneous catalyst.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

MB and SA: investigation and writing—original draft preparation. SJ: project administration, conceptualization, resources, writing—review, and editing. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fchem.2020.596029/full#supplementary-material

REFERENCES

Alipour, A., Javanshir, S., and Peymanfar, R. (2018). Preparation, characterization and antibacterial activity investigation of hydrocolloids based Irish moss/ZnO/CuO bio-based nanocomposite films. *J. Cluster Sci.* 29, 1329–1330. doi: 10.1007/s10876-018-1449-4

Amirnejat, S., Movahedi, F., Masrouri, H., Mohadesi, M., and Kassaee, M. (2013). Silica nanoparticles immobilized benzoylthiourea ferrous complex as an efficient and reusable catalyst for one-pot synthesis of benzopyranopyrimidines. *J. Mol. Catal. A Chem.* 378, 135–141. doi: 10.1016/j.molcata.2013.05.023

Amirnejat, S., Nosrati, A., and Javanshir, S. (2020c). Superparamagnetic Fe3O4@ Alginate supported L-arginine as a powerful hybrid inorganic–organic nanocatalyst for the one-pot synthesis of pyrazole derivatives. *Appl. Organomet. Chem.* 34:e5888. doi: 10.1002/aoc.5888

Amirnejat, S., Nosrati, A., Javanshir, S., and Naimi-Jamal, M. R. (2020a). Superparamagnetic alginate-based nanocomposite modified by L-arginine: an eco-friendly bifunctional catalysts and an efficient antibacterial agent. *Int. J. Biol. Macromol.* 152, 834–845. doi: 10.1016/j.ijbiomac.2020.02.212

Amirnejat, S., Nosrati, A., Peymanfar, R., and Javanshir, S. (2020b). Synthesis and antibacterial study of 2-amino-4H-pyrans and pyrans annulated heterocycles catalyzed by sulfated polysaccharide-coated $BaFe_{12}O_{19}$ nanoparticles. *Res. Chem. Intermed.* 46, 3683–3701. doi: 10.1007/s11164-020-04168-x

Dekamin, M. G., Peyman, S. Z., Karimi, Z., Javanshir, S., Naimi-Jamal, M. R., and Barikani, M. (2016). Sodium alginate: an efficient biopolymeric catalyst for green synthesis of 2-amino-4H-pyran derivatives. *Int. J. Biol. Macromol.* 87, 172–179. doi: 10.1016/j.ijbiomac.2016.01.080

Deng, X., Zhou, Z., Zhang, A., and Xie, G. (2013). Brønsted acid ionic liquid [Et 3 NH][HSO 4] as an efficient and reusable catalyst for the synthesis of 2, 4, 5-triaryl-1H-imidazoles. *Res. Chem. Intermed.* 39, 1101–1108. doi: 10.1007/s11164-012-0669-8

Dolatkhah, Z., Javanshir, S., Bazgir, A., and Hemmati, B. (2019). Palladium on magnetic Irish moss: a new nano-biocatalyst for suzuki type cross-coupling reactions. *Appl. Organomet. Chem.* 33:e4859. doi: 10.1002/aoc.4859

Dolatkhah, Z., Javanshir, S., Bazgir, A., and Mohammadkhani, A. (2018). Magnetic isinglass a nano-bio support for copper immobilization: Cu–IG@ Fe_3O_4 a heterogeneous catalyst for triazoles synthesis. *ChemistrySelect* 3, 5486–5493. doi: 10.1002/slct.201800501

Fereshteh, N., and Shahrzad, J. (2020). Magnetic γFe_2O_3@ Sh@ Cu_2O: an efficient solid-phase catalyst for reducing agent and base-free click synthesis of 1, 4-disubstituted-1, 2, 3-triazoles. *BMC Chem.* 14:9. doi: 10.1186/s13065-019-0657-9

Gadekar, L. S., Mane, S. R., Katkar, S. S., Arbad, B. R., and Lande, M. K. (2009). Scolecite as an efficient heterogeneous catalyst for the synthesis of 2, 4, 5-triarylimidazoles. *Cent. Eur. J. Chem.* 7, 550–554. doi: 10.2478/s11532-009-0050-y

Gomez-Zavaglia, A., Prieto Lage, M. A., Jimenez-Lopez, C., Mejuto, J. C., and Simal-Gandara, J. (2019). The potential of seaweeds as a source of functional ingredients of prebiotic and antioxidant value. *Antioxidants* 8:406. doi: 10.3390/antiox8090406

Graebin, C. S., Ribeiro, F. V., Rogério, K. R., and Kümmerle, A. E. (2019). Multicomponent reactions for the synthesis of bioactive compounds: a review. *Curr. Org. Synth.* 16, 855–899. doi: 10.2174/1570179416666190718153703

Hemmati, B., Javanshir, S., and Dolatkhah, Z. (2016). Hybrid magnetic Irish moss/Fe_3O_4 as a nano-biocatalyst for synthesis of imidazopyrimidine derivatives. *RSC Adv.* 6, 50431–50436. doi: 10.1039/C6RA08504K

Karimi, A. R., Alimohammadi, Z., Azizian, J., Mohammadi, A. A., and Mohammadizadeh, M. (2006). Solvent-free synthesis of tetrasubstituted imidazoles on silica gel/NaHSO4 support. *Catal. Commun.* 7, 728–732. doi: 10.1016/j.catcom.2006.04.004

Marques, M. V., Ruthner, M. M., Fontoura, L. A., and Russowsky, D. (2012). Metal chloride hydrates as Lewis acid catalysts in multicomponent synthesis of 2, 4, 5-triarylimidazoles or 2, 4, 5-triaryloxazoles. *J. Braz. Chem. Soc.* 23, 171–179. doi: 10.1590/S0103-50532012000100024

Masteri-Farahani, M., Ezabadi, A., Mazarei, R., Ataeinia, P., Shahsavarifar, S., and Mousavi, F. (2020). A new nanocomposite catalyst based on clay-supported heteropolyacid for the green synthesis of 2, 4, 5-trisubstituted imidazoles. *Appl. Organomet. Chem.* 34:e5727. doi: 10.1002/aoc.5727

Mirsafaei, R., Heravi, M. M., Ahmadi, S., and Hosseinnejad, T. (2016). Synthesis and properties of novel reusable nano-ordered KIT-5-N-sulfamic acid as a heterogeneous catalyst for solvent-free synthesis of 2, 4, 5-triaryl-1 H-imidazoles. *Chem Pap.* 70, 418–429. doi: 10.1515/chempap-2015-0228

Mohammadi, A., Keshvari, H., Sandaroos, R., Maleki, B., Rouhi, H., Moradi, H., et al. (2012). A highly efficient and reusable heterogeneous catalyst for the one-pot synthesis of tetrasubstituted imidazoles. *Appl. Catal. A.* 429, 73–78. doi: 10.1016/j.apcata.2012.04.011

Momahed Heravi, M., Karimi, N., and Pooremami, S. (2019). One-pot three components synthesis of 2, 4, 5-triaryl-imidazoles catalyzed by Caro's acid-silica gel under solvent–free condition. *Adv. J. Chem. A.* 2, 73–78. doi: 10.29088/SAMI/AJCA.2019.2.7378

Piri, T., Peymanfar, R., Javanshir, S., and Amirnejat, S. (2019). Magnetic BaFe$_{12}$O$_{19}$/Al$_2$O$_3$: an efficient heterogeneous lewis acid catalyst for the synthesis of α-aminophosphonates (Kabachnik–Fields Reaction). *Catal. Lett.* 149, 3384–3394. doi: 10.1007/s10562-019-02910-8

Pourian, E., Javanshir, S., Dolatkhah, Z., Molaei, S., and Maleki, A. (2018). Ultrasonic-assisted preparation, characterization, and use of novel biocompatible core/shell Fe_3O_4@ GA@ isinglass in the synthesis of 1, 4-dihydropyridine and 4 H-pyran derivatives. *ACS Omega* 3, 5012–5020. doi: 10.1021/acsomega.8b00379

Ray, S., Das, P., Bhaumik, A., Dutta, A., and Mukhopadhyay, C. (2013). Covalently anchored organic carboxylic acid on porous silica nano particle: a novel organometallic catalyst (PSNP-CA) for the chromatography-free highly product selective synthesis of tetrasubstituted imidazoles. *Appl. Catal. A.* 458, 183–195. doi: 10.1016/j.apcata.2013.03.024

Sadeghi, B., Mirjalili, B. B. F., and Hashemi, M. M. (2008). BF$_3$SiO$_2$: an efficient reagent system for the one-pot synthesis of 1, 2, 4, 5-tetrasubstituted imidazoles. *Tetrahedron Lett.* 49, 2575–2577. doi: 10.1016/j.tetlet.2008.02.100

Salimi, M., Nasseri, M. A., Chapesshloo, T. D., and Zakerinasab, B. (2015). (Carboxy-3-oxopropylamino)-3-propylsilylcellulose as a novel organocatalyst for the synthesis of substituted imidazoles under solvent-free conditions. *RSC Adv.* 5, 33974–33980. doi: 10.1039/C5RA01909E

Shaabani, A., Afshari, R., and Hooshmand, S. E. (2017). Crosslinked chitosan nanoparticle-anchored magnetic multi-wall carbon nanotubes: a bio-nanoreactor with extremely high activity toward click-multi-component reactions. *New J. Chem.* 41, 8469–8481. doi: 10.1039/C7NJ01150D

Shaabani, A., Sepahvand, H., Hooshmand, S. E., and Borjian Boroujeni, M. (2016). Design, preparation and characterization of Cu/GA/Fe_3O_4@ SiO_2 nanoparticles as a catalyst for the synthesis of benzodiazepines and imidazoles. *Appl. Organomet. Chem.* 30, 414–421. doi: 10.1002/aoc.3448

Shalini, K., Sharma, P. K., and Kumar, N. (2010). Imidazole and its biological activities: a review. *Der Chemica Sinica* 1, 36–47.

Shaterian, H. R., and Ranjbar, M. (2011). An environmental friendly approach for the synthesis of highly substituted imidazoles using Brønsted acidic ionic liquid, N-methyl-2-pyrrolidonium hydrogen sulfate, as reusable catalyst. *J. Mol. Liq.* 160, 40–49. doi: 10.1016/j.molliq.2011.02.012

Shitole, B. V., Shitole, N. V., Ade, S. B., and Kakde, G. K. (2015). Microwave-induced one-pot synthesis of 2, 4, 5-trisubstituted imidazoles using rochelle salt as a green novel catalyst. *Orbital Electron. J. Chem.* 7, 240–244. doi: 10.17807/orbital.v7i3.720

Varzi, Z., and Maleki, A. (2019). Design and preparation of ZnS-ZnFe$_2$O$_4$: a green and efficient hybrid nanocatalyst for the multicomponent synthesis of 2, 4, 5-triaryl-1H-imidazoles. *Appl. Organomet. Chem.* 33:e5008. doi: 10.1002/aoc.5008

Zaheri, H. M., Javanshir, S., Hemmati, B., Dolatkhah, Z., and Fardpour, M. (2018). Magnetic core–shell Carrageenan moss/Fe_3O_4: a polysaccharide-based metallic nanoparticles for synthesis of pyrimidinone derivatives via Biginelli reaction. *Chem. Cent. J.* 12:108. doi: 10.1186/s13065-018-0477-3

Zayed, A., and Ulber, R. (2019). Fucoidan production: approval key challenges and opportunities. *Carbohydr. Polym.* 211, 289–297. doi: 10.1016/j.carbpol.2019.01.105

Zayed, A., and Ulber, R. (2020). Fucoidans: downstream processes and recent applications. *Mar. Drugs* 18:170. doi: 10.3390/md18030170

Zheng, Y., Monty, J., and Linhardt, R. J. (2019). Polysaccharide-based nanocomposites and their applications. *Carbohydr. Res.* 405, 23–32. doi: 10.1016/j.carres.2014.07.016