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Eco-friendly highly efficient solvent free synthesis of benzimidazole derivatives over sulfonic acid functionalized graphene oxide in ambient condition

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Abstract Sulfonated graphene oxide (GO-HSO_3) heterogeneous catalyst was prepared at molecular level and characterized by using various modern analytic and spectroscopic methods. Using prepared heterogeneous catalyst GO-HSO_3, benzimidazole synthesis was carried out by means of reacting diamine and aldehyde at room temperature in solvent free condition. The catalyst GO-HSO_3 showed tremendous catalytic activity in selective synthesis of benzimidazole, as a result 100 % conversion of reactants and up to 89.0 % yield of respective benzimidazole was achieved using 0.1 mg of catalyst in very short reaction duration. The GO-HSO_3 catalyst was separated from the reaction mixture by simple filtration process at the end of reaction and reused for six successive cycles without noteworthy loss of catalytic activity and selectivity. Key advantageous of this protocol is high yield, low cost, and easy work-up procedure as well as short reaction time and solvent free condition. The present method is found eco-friendly, highly efficient, solvent free, high yielding, and clean method for the synthesis benzimidazole derivatives at room temperature.

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Introduction

Benzimidazole derivatives have acknowledged much attention in the field of medicinal chemistry as well as used as essential intermediates for the synthesis of wide pharmaceutical compounds [1–4]. Derivatives of benzimidazole have been related with wide range of biological activities together with anti-cancer, anti-glycation, anti-inflammatory, anti-urease, anti-fungals, anti-bacterial, anthelmintic, proton pump inhibitors, anti-viral, anti-oxidants [5–14]. Furthermore, with their biological consequence, benzimidazoles form unvarying complexes with diverse metals in transition group [13–15]. Metal chelations of 2-substituted imidazole and benzimidazole based structures with various ligands have been published with mono, bi and tri dentate co-ordination structures [15]. As a result, the preparation and synthesis of benzimidazoles have gained significant consideration in recent years.

Several methods have been resulted for the synthesis of benzimidazole as well as their derivatives. The condensation reaction of different organic functionalized carboxylic acids with 1,2-phenylenediamines or their similar derivatives is a common place technique but it needs harsh reaction conditions and high reaction temperature like at in the range of 150–200 °C [16]. Another option came up with the condensation of aldehyde with 1, 2 phenylene diamine in attendance of different catalysts like Ceric ammonium nitrate, silica supported sulfuric acid, $In(OTf)_3$, iodine, $SiO_2/ZnCl_2$, PEG, silica supported sodium hydrogen sulphate, $H_2O_2/Fe(NO_3)_3$ [17–24]. Benzimidazole derivatives have also been prepared from the oxidative condensation of 1,2-arylenediamines with aldehydes using different oxidative and catalytic reagents such as oxygen [25] 1,4-benzoquinone [26] nitrobenzene (high boiling oxidant/solvent) [27] 2,3-dichloro-5, benzofuroxan [28]. In recent time, without solvent synthesis of benzimidazoles in presence of MW irradiation using metal halide supported alumina, KSF clay, silica supported halides, and solid $Yb(OTf)_3$ as catalyst have also been reported [17–21]. However, many of these approaches suffer from one or more drawbacks such as requirement of low yields, strong acidic conditions, long reaction times, tedious workup procedures, requirement of excess amounts of catalyst and use of toxic reagents, catalysts or solvent. Therefore, much development has been made in the synthesis of benzimidazoles but it is still motivating to develop green and simple routes, which is of significance from a point of view of green chemistry and sustainable development.

Solid acids have the great potential to replace liquid acids as eco-friendly benign heterogeneous acid catalysts [29–32]. Acidic carbons and materials based on the impression of green chemistry were investigated as constant and highly active protonic solid acid catalysts for several acid catalyzed transformations [33]. Graphene and its derivatives (graphene oxide as well as reduced graphene oxide) have attracted a great attention and have been widely used in the field of catalysis

and engineering science [34]. Because of its physical as well as chemical properties such as high surface area, and admirable mechanical properties, GO has come forward as a capable support material for heterogeneous catalysis [33, 34]. In particular, unlike other common catalyst supports, graphene has a two-dimensional structure that allows reactive species on it to be readily accessed with limited mass-transfer resistance [33]. Graphene oxide (GO) includes high density of hydrophilic organic functional groups including hydroxyl, carboxyl, and epoxy functional groups [34]. However, these hydrophilic organic functionality can be applied for further alteration of GO and such kind of modified GO is a capable candidate as heterogeneous acid catalyst for organic transformation as well as industrial applications [33, 34]. Recently, it is confirmed that, the efficiency of GO as a solid acid catalyst for organic transformation such as esterification of organic acids with alcohols [35] and ring-opening of epoxides with various alcohols [36, 37]. In addition, using modified GO as catalyst for cyclization between OPD and substituted benzaldehyde to make industrially essential chemicals for other constructive chemical reactions were also determined [33, 34]. To the best of our knowledge, till date there is no report of synthesis of benzimidazole derivatives by using covalently modified GO-HSO_3 as heterogeneous catalyst at room temperature in solvent free reaction.

In the present report, we describe the successful preparation and covalent modification of GO into GO-HSO_3 as heterogeneous catalyst for the one-pot synthesis of benzimidazole derivatives in solvent free condition at room temperature. Prepared heterogeneous GO-HSO_3 catalyst was characterized by various analytical and spectroscopic techniques such as FT-IR, EDX, XRD, FE-TEM, FE-SEM, TGA, and N_2 adsorption–desorption analysis. Obtained results from these characterization methods reveal that, HSO_3 functionality covalently bonded to the graphene oxide surface. After successfully characterization of heterogeneous GO-HSO_3 catalyst, it was tested for synthesis of benzimidazole derivatives under solvent free condition. As results catalyst showed 100 % conversion of reactant and 86.0 % yield of respective benzimidazole. In addition, present protocol needs just filtration for the separation of catalyst from products, which shows unique green method impression for this protocol among other reported liquid acid catalysts. The separated catalyst after treatment can be recycled number of times (six cycles) without losing acidic functionality as well activity in benzimidazole synthesis.

Experimental

Materials

For the synthesis of graphene oxide, graphite flake (natural, 325 mesh) with a purity of 99.8 % was purchased from Alfa Aesar. $NaNO_3$ (95.0 %) and $KMnO_4$ (99.0 %) were obtained from Sigma Aldrich (Germany). H_2SO_4 (95–98 %) and H_2O_2 (30 %) were obtained from commercial sources. All crucial preliminary materials for benzimidazole derivatives and necessary reagents were acquired from Sigma-

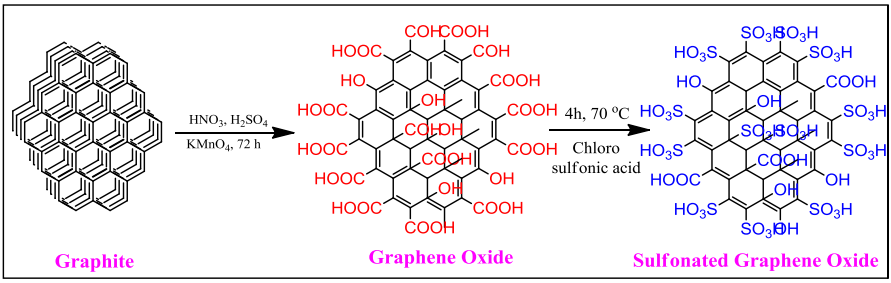
Aldrich and used without additional distillation. All solvents were purified and dried by typical methods earlier to use.

Catalyst preparation

To prepare the sulfonated graphene oxide (GO-SO_3H) in this study, pure GO was obtained by using reported method described in the literature [36]. After getting the pure graphene oxide followed the sulfonation process described below in Scheme 1. The heterogeneous GO-SO_3H catalyst was obtained by the sulfonation reaction of GO in chloroform with chlorosulfonic acid. In a representative process, in 50 ml of chloroform, 1.0 g of GO was mixed properly and for 1.5 h sonicated at room temperature. After sonication process, a black very well dispersed GO suspension was obtained. After that, carefully addition of 0.5 g of chlorosulfonic acid was done drop wise to the dispersed GO solution in a two necked round-bottomed flask. The prepared solution was then instantly refluxed with magnetic stirrer. In addition the round-bottomed flask equipped with a cold-water condenser and stirred the reaction mixture for 4 h at 70 °C. It should be well-known that the catalyst GO-SO_3H preparation steps were performed in a vacuum hood and some careful protection were taken during the addition of chlorosulfonic acid and its proper assimilation into the GO suspension. After 4 h of sulfonation reaction, the resulting brown suspension solution was cooled at room temperature naturally. Later on, filtered and washed with excess ethanol and water to remove organic moieties on the surface until the pH of the filtrate became neutral. The catalyst sample was then dried at 110 °C for 12 h in a vacuum oven, and further this material was used for the catalytic activity.

Catalyst characterization methods

XRD patterns (Powder X-ray diffraction) of the GO-SO_3H catalyst and precursors were recorded on Rigaku Miniflex X-ray diffractometer (Rigaku Corporation, Japan) with a 4° min^{-1} scan speed and a scan range of 5–90° at 30 kV and 15 mA using Ni filtered Cu Kα radiation ($\lambda = 1.5406$ Å). Thermogravimetric analyses



Scheme 1 Schematic representation of preparation of sulfonated graphene oxide from initial source graphite

(TGA) were performed on Scinco TGA *N*-100 device with ramp rate of 10 °C/min in nitrogen condition. FT-IR spectra of prepared catalysts were taken on a Varian 2000 IR spectrometer (Scimitar series) by using the KBr disc method. The Brunauer–Emmett–Teller (BET) surface areas of the nanostructures were obtained from N_2 sorption isotherms, acquired using a BEL Japan (Belsorp-II) instrument. The surface analysis as well as morphology of prepared catalysts was considered by scanning electron microscopy (SEM) by using a Hitachi, S-3500 N SEM apparatus.

The illustrations for TEM analysis were prepared by dropping about 10 µl of sonicated dilute solution of nanostructures in ethanol onto carbon-coated copper grids and gradually drying at atmospheric condition. Energy dispersive X-ray spectrometry (EDX) or elemental mappings were performed on SEM apparatus united with an INCA instrument for EDS with scanning electron electrode at 20 kV. The benzimidazole products were characterized by NMR spectra recorded on Bruker VRMS-400 MHz NMR spectrometer using $CDCl_3$ as a solvent. The described chemical shifts were in contrast to TMS as reference for ^{1}H and ^{13}C NMR. All obtained benzimidazole products have been formerly reported and all known obtained products gave reasonable analytical data analogous to the reported literature values.

General reaction procedure for synthesis of benzimidazole derivatives using sulfonated graphene oxide catalyst

To a mixture of diamine (1 mmol) and aldehyde (1 mmol) was added in 50 ml round bottom flask. A known catalytic amount of sulfonated graphene oxide was also added in the reaction mixture. There is no any addition of solvent as well as co-catalysts were done. Then, the obtained mixture was magnetically stirred under open atmosphere at room temperature for appropriate time. After the completion of the reaction (checked by TLC), ethyl acetate was added in the reaction mixture and filter by using Whatman filter paper. Washed the catalyst by ethyl acetate thrice and collect the washings and were combined and evaporated under vacuum on rotary evaporator. The crude solid product, nevertheless pure enough on TLC (70:30 %), was then passed through a short column of silica gel to afford pure benzimidazole products and further characterized by ^{1}H and ^{13}C NMR spectroscopy.

2-Phenyl-1H-benzo[d]imidazole (Table 3, Entry 1)

Yield 88 %; ^{1}H NMR (400 MHz, DMSO): δ 12.91 (s, H), 7.26 (m, 2H), 7.46 (m, H), 7.53 (m, 2H); 7.62 (m, 2H), 8.18 (m, 2H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 115.6, 123.2, 127.6, 129.7, 131.2, 133.9, 142.1, 152.7 ppm.

6-Methyl-2-phenyl-1H-benzo[d]imidazole (Table 3, Entry 2)

Yield 74 %; ^{1}H NMR (400 MHz, DMSO): δ: 2.31 (s, 3H), 7.13 (d, H), 7.42 (m, H), 7.41 (s, H), 7.51 (m, 2H); 7.56 (d, H), 8.21 (m, 2H), 12.76 (s, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 21.6, 116.1, 116.4, 125.9, 127.7, 129.3, 130.9, 131.1, 132.8, 134.6, 135.8, 152.7 ppm.

2-(p-Tolyl)-1H-benzo[d]imidazole (Table 3, Entry 3)

Yield 81 %; ^{1}H NMR (400 MHz, DMSO): δ: 2.34 (s, 3H), 7.24 (m, 2H), 7.26 (d, 2H), 7.58 (d, 2H); 8.54 (d, 2H), 12.86 (s, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 21.3, 114.9, 122.8, 128.7, 129.4, 132.1, 141.7, 151.9 ppm.

6-Methyl-2-(p-tolyl)-1H-benzo[d]imidazole (Table 3, Entry 4)

Yield 69 %; ^{1}H NMR (400 MHz, DMSO): δ: 2.31 (s, 3H), 7.12 (d, H), 7.31 (d, 2H), 7.47 (d, 1H); 7.49 (d, 1H); 8.49 (d, 2H), 12.92 (s, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 20.98, 115.3, 124.96, 127.87, 129.00, 131.89, 132.17, 134.75, 152.61 ppm.

6-Methyl-2-(p-tolyl)-1H-benzo[d]imidazole (Table 3, Entry 5)

Yield 61 %; ^{1}H NMR (400 MHz, DMSO): δ: 2.36 (s, 3H), 3.87 (s, 3H), 6.93 (d, H), 7.17 (s, H); 7.26 (d, 2H); 7.91 (s, H), 8.59 (d, 2H), 12.82 (s, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 20.82, 54.9, 104.6, 112.7, 117.1, 128.6, 130.1, 131.9, 134.2, 156.3 ppm.

6-Methoxy-2-phenyl-1H-benzo[d]imidazole (Table 3, Entry 6)

Yield 78 %; ^{1}H NMR (400 MHz, DMSO): δ: 3.87 (s, 3H), 6.87 (d, H), 7.17 (s, H); 7.43 (m, H); 7.47 (d, H), 8.26 (m, 2H), 12.79 (s, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 55.7, 102.1, 111.1, 116.3, 127.3, 129.6, 134.2, 134.7, 139.3. 155.7 ppm.

6-Methoxy-2-(4-methoxyphenyl)-1H-benzo[d]imidazole (Table 3, Entry 7)

Yield 83 %; ^{1}H NMR (400 MHz, DMSO): δ: 3.91 (s, 3H), 3.96 (s, 3H) 6.91 (d, H), 7.07 (d, H), 7.12 (s, H); 7.46 (d, H); 7.92 (d, H), 12.91 (s, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 55.8, 103.2, 110.9, 113.6, 114.6, 116.3, 131.1, 134.3, 138.7, 156.1 ppm.

6-Chloro-2-phenyl-1H-benzo[d]imidazole (Table 3, Entry 8)

Yield 81 %; ^{1}H NMR (400 MHz, DMSO): δ: 7.16 (d, H), 7.43 (m, H), 7.51 (d, H) 7.56 (q, 2H), 8.26 (m, 2H); 8.34 (s, H), 12.82 (s, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 115.7, 116.3, 124.1, 127.3, 129.1, 129.7, 130.7, 131.3, 132.5, 134.6, 152.6 ppm.

6-Chloro-2-(4-chlorophenyl)-1H-benzo[d]imidazole (Table 3, Entry 9)

Yield 83 %; ^{1}H NMR (400 MHz, DMSO): δ: 7.06 (d, H), 7.32 (d, H), 7.47 (d, 2H), 8.17 (d, 2H); 8.39 (s, H), 12.91 (s, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 115.7, 116.3, 124.6, 128.5, 129.4, 129.9, 131.2, 132.7, 132.9, 134.3, 153.1 ppm.

2-Phenyl-1H-benzo[d]imidazole-6-carbaldehyde (Table 3, Entry 10)

Yield 78 %; ^{1}H NMR (400 MHz, DMSO): δ: 13.26 (s, H), 9.78 (S, H) 8.28 (m, 2H), 7.92 (s, H), 7.53 (d, H), 7.59 (t, 2H); 7.39 (m, H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 115.2, 118.5, 125.1, 127.2, 129.7, 131.3, 131.7, 134.6, 139.3, 147.6, 152.4 ppm.

6-Nitro-2-phenyl-1H-benzo[d]imidazole (Table 3, Entry 11)

Yield 81 %; ^{1}H NMR (400 MHz, DMSO): δ: 12.11 (s, H), 7.39 (m, H), 7.56 (t, 2H), 7.69 (d, H), 7.93 (s, H); 8.13 (d, H), 8.29 (d, 2H) ppm; ^{13}C NMR (100 MHz, DMSO): δ: 112.8, 116.1, 118.7, 127.6, 129.3, 131.1, 134.3, 139.7, 144.5, 147.9, 152.7 ppm.

Results and discussion

Catalyst characterization

FT-IR analysis of prepared materials

The reaction results of the chemical modification of GO are shown in Fig. 1. To determine the complete modification of GO into GO-HSO_3, comparative study of pure GO and pure graphite were also performed by FTIR spectroscopy. In all analyzed samples a wide signal situated at 3600–2800 cm^{-1} recognized due to the stretching vibration of hydroxyl (–OH) groups present in the catalysts. In pure GO

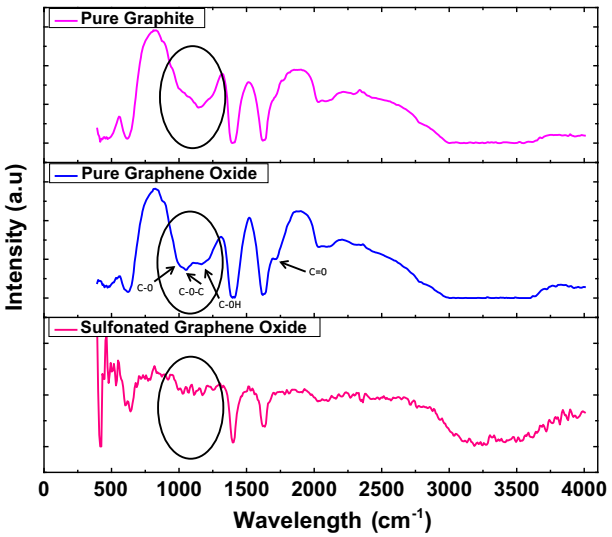


Fig. 1 FT-IR analysis of prepared sulfonated graphene oxide catalyst, graphene oxide and graphite

before sulfonation signal at 1710–1705 cm^{-1} attributed due to the carboxylic groups and strong signal at 1350 cm^{-1} is due to deformation of vibration in C–OH. In addition a peak at 1040–1023 cm^{-1} represented by functional C–O groups and a peak located at around 950 cm^{-1} from epoxy groups present in the pure GO. The spectrum of pure GO indicates the presence of O–H stretching broad peak at 3430 cm^{-1}, C=C stretching at 1590 cm^{-1}, C–O stretching at 1050 cm^{-1}, and C–OH stretching at 1220 cm^{-1}, respectively. These all representative peaks of FT-IR analysis were showed that graphite is entirely oxidized into GO. In the IR spectrum of GO-SO_3H, including all these parent peaks which belongs to GO some other peaks also observed belong to the HSO_3 group. The presence of vibrational bands at 1040, 1080, and 1171 cm^{-1} (arising from O–S–O stretching) and at 1125, 1277, and 1320 cm^{-1} (from the SO_3H stretching) in the FT-IR spectrum was showed clear indication of the presence of SO_3H in GO-SO_3H [37]. The above-mentioned FT-IR bands for O–S–O and SO_3H stretching vibrations were observed throughout sample and results indicates that, the SO_3H group is strongly covalently bonded on the GO surface.

XRD analysis of catalysts

The X-ray diffraction pattern (XRD) characterization results of pure graphite, pure GO and sulfonated GO are shown in Fig. 2. For the pure graphite sample, the (002) sharp peak appears at 27°, indicating an interlayer spacing of 0.34 nm. After completion of oxidation process induced expansion of the (002) peak shifts to 11°, theta value in pure GO which suggested that complete oxidation process occurred and the interlayer space distance enlarged to 0.51 nm by the oxidation method. These results are consistent with the data reported in the literature. After modification of sulfonation process, the resulting graphene sulfonated GO nano-sheets from pure GO showed similar parental peak pattern as GO but the intensity of

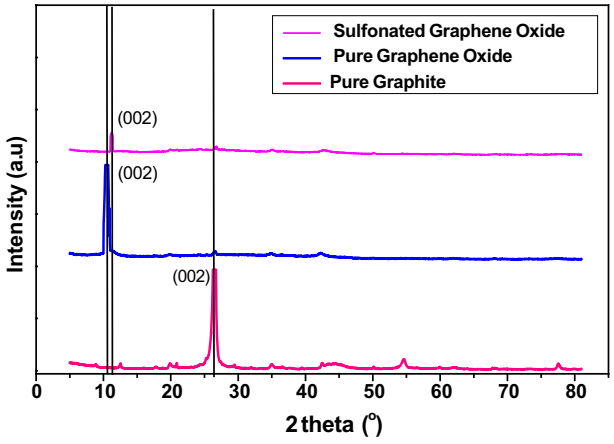


Fig. 2 XRD analysis of sulfonated graphene oxide as well as graphene oxide and graphite

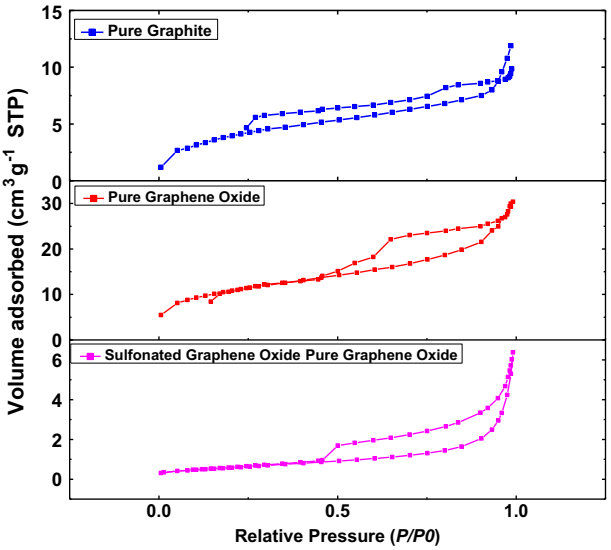


Fig. 3 Adsorption–desorption isotherms of sulfonated graphene oxide as well as graphene oxide and pure graphite

peaks is very weak and broad at approximately near at 25°. This may stem from the change of the chemically covalently bonded the sulfonated group over the GO and these kinds of results are reported previously [34–36]. In addition, the interlayer spacing (d-spacing) value for GO was 0.51 nm, while the interlayer spacing of GO-HSO_3 was calculated to be 0.79 nm, which revealed the increase of distance between GO-HSO_3 nano-sheets by sulfonation [33, 34].

Adsorption/desorption isotherms and surface area analysis of prepared heterogeneous catalysts

The adsorption/desorption isotherms and BET test results are shown in Fig. 3. The corresponding specific surface area of pure graphite, pure graphene oxide and sulfonated graphene oxide are 8.0, 89.0, and 73.0 m^2/g, respectively. The increased specific surface area in pure graphene oxide could be attributed due to exfoliation of graphite into graphene oxide. This result reveals that complete modification of graphite into graphene oxide occurred in the oxidation process [33–35]. However, when the modification of pure graphene oxide into sulfonated graphene oxide occurred, surface area of GO-HSO_3 was reduced. Result showed that sulfonated graphene oxide showed 73.00 m^2/g surface areas. Reported literature showed that, reduction in the surface area of GO-HSO_3 due to the HSO_3 acidic moiety chemically grafted on the surface of graphene oxide [36]. However, obtained surface area for GO-HSO_3 is 73.00 m^2/g r is highly efficient for any organic transformation [34]. Hence from these results it is reveals that, successfully modification of GO into the GO-HSO_3 occurred.

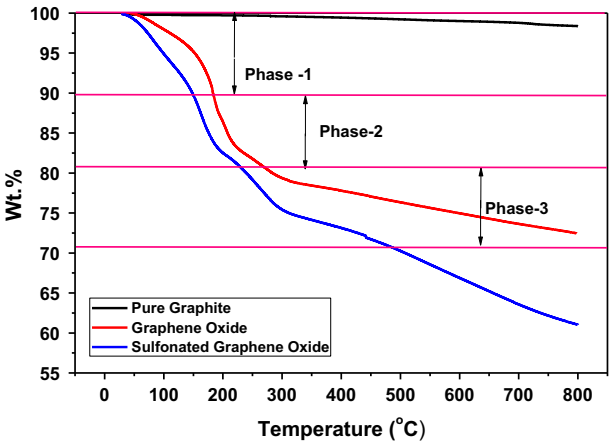


Fig. 4 TGA analysis of prepared sulfonated graphene oxide, pure graphene oxide and pure graphite

Thermogravimetric analysis of sulfonated graphene oxide

Figure 4 displays the TGA curves of pure graphite, pure graphene oxide and sulfonated graphene oxide samples. As seen in the figure, graphite did show any weight loss in the determined temperature phase of TGA analysis. In the TGA analyses of pure GO, the overall weight loss of 27 % for GO occurs in three successive steps. The primary step is a stable weight loss of 3–5 % recognized due to the vaporization of physically adsorbed water molecules and take place at approximately 100 °C [33]. Then a second speedy weight loss of 8–10 % observed due to the breakdown of the oxygen-containing organic functional groups such as COOH (carboxyl), OH (hydroxyl), C=O (carbonyl) and epoxy groups in the temperature phase of 120–208 °C. Furthermore, third weight loss of 14–15 % accredited due to successive breakdown of carbon skeleton in the temperature phase range of 210–800 °C is observed and finally total residual weight of GO obtained at 800 °C was around 75 %. Later on there is no weight loss after this designated temperature and finally sample approximately reserved constant weight throughout the analysis. On the other side, in the sulfonated GO total weight loss observed approximately 45 %, in which initially 6.0 % weight loss observed due to the vaporization of absorbed moisture at 100–110 °C. There is successive rapid decrease in the weight loss 8–12 % observed at 120–210 °C due to the decomposition of unreacted oxygen functional groups. In the next step, the 20–25 % weight loss in the temperature range can be attributed to decomposition of sulfonated groups which is. Later on again sudden decreases in weight loss was observed due to the sulfonated group functionality at approximately at 400–550 °C, which shows 20–25 % weight loss belong to the sulfonated functionality covalently bonded on GO [33, 34]. These obtained results are quite similar with the previously reported methods.

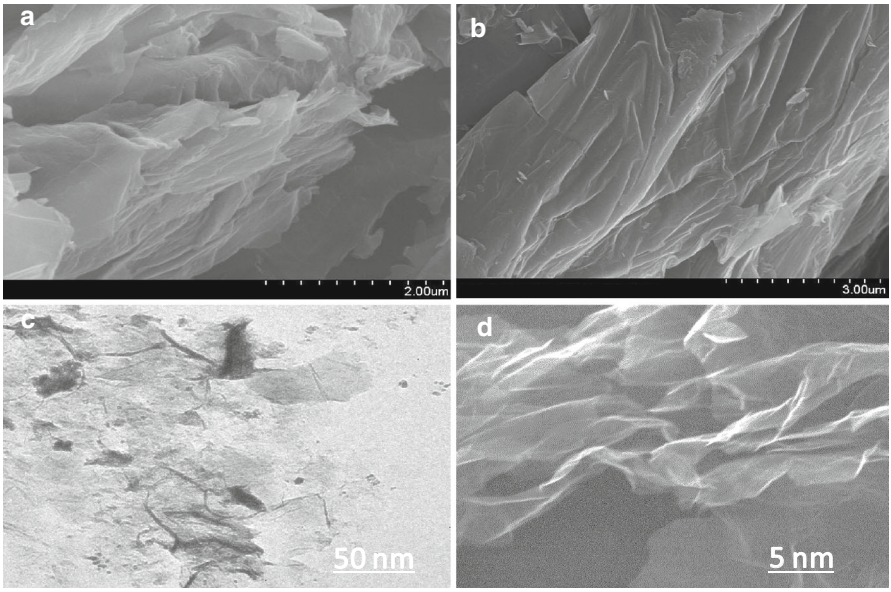


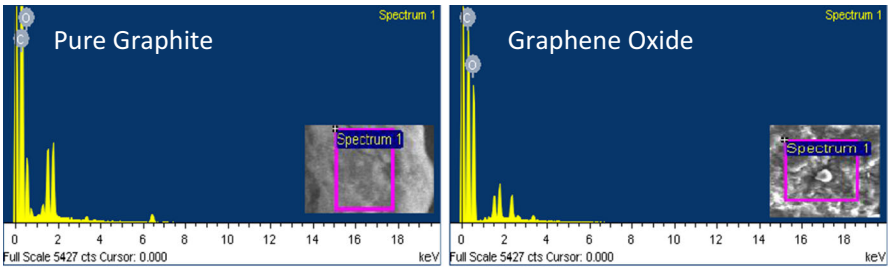
Fig. 5 FE-SEM and TEM analysis of pure graphene oxide (**a**, **c**) and sulfonated graphene oxide (**b**, **d**) respectively

FE-SEM and FE-TEM analysis of prepared heterogeneous catalyst

Scanning electron microscopy (SEM) and TEM analysis of prepared catalysts GO-HSO_3 and pure graphene oxide were performed for investigating the morphology and effect of sulfonyl functionality groups on the obtained GO-HSO_3. As shown in Fig. 5, pure GO showed nano sheets like structure in SEM image (Fig. 5a) in addition similarity structures consistent was also observed with TEM images of pure GO (Fig. 5b). Modified GO-HSO_3 reveals the sulfonation of GO led to further exfoliation of the clusters of sheets into a random pile. Similar to the SEM images, the TEM image of GO-HSO_3 showed that the sheets were randomly oriented and crumpled sheets (Fig. 5c, d). Obtained FE-SEM and TEM images reveals that, successfully modification of GO into GO-HSO_3 was occurred without damaging the spinal nano structure of Graphene oxide.

Elemental analysis (EDX) of sulfonated graphene oxide

Quantitative energy dispersive X-ray spectroscopy (EDS) mapping of pure graphite, pure GO and GO-HSO_3 were performed to investigating the successful oxidation and distribution of sulfonated functionality on the obtained modified GO–HSO_3 (Fig. 6). In the pure graphite and pure GO, distributions of carbon and oxygen elements were determined. Before the oxidation, pure graphite showed homogenous distribution of 51 % of carbon and 47 % oxygen respectively. Whereas after



Catalyst	% of C		% of O		% of S	
	Wt. %	Atm. %	Wt. %	Atm. %	Wt. %	Atm. %
Graphite	51.0	58.64	46.8	404	-	-
Graphene Oxide	43.4	50.6	56.5	49.4	-	-
GO-HSO3	50.5	57.4	45.9	39.6	3.89	1.96

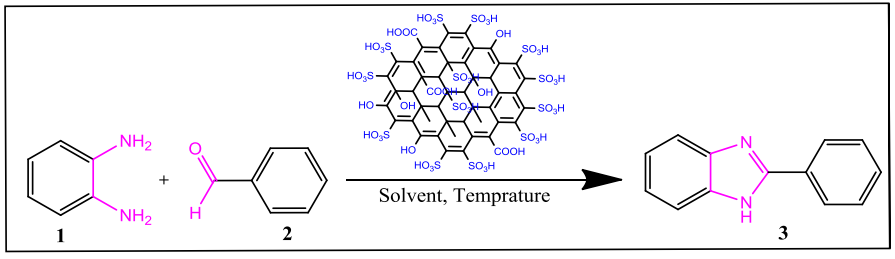
Fig. 6 Elemental analysis of prepared heterogeneous catalysts sulfonated graphene oxide and pure graphene oxide as well as graphite

oxidation in pure GO the percentage of carbon and oxygen changed due to the oxidation process. In this case pure GO showed 43 % of carbon and 57 % oxygen percentage homogenously distributed. This increased percentage of oxygen and decreased percentage of carbon reveals that oxidation occurred on pure graphite and installation of oxygen functionality such as carboxylic acid, epoxy, and ketone. On the other side, we have also analyzed GO-SO_3H sample, which showed 50 % carbon, 45 % of oxygen and 4 % of sulfur. The presence of 4 % of sulfur and 45 % of oxygen in GO-SO_3H reveals that covalently functionalization occurred on GO by sulfonation functionality. In addition, this functionality is homogenously scattered throughout the sample which conclude homogeneously attachment of HSO_3 functionality on GO-HSO_3. These characteristics should be facilitate its catalytic performance, because reactants and products can easily access the active sulfonyl groups on both sides of the two-dimensional GO-HSO_3 with limited mass allocation resistance.

Catalyst activity

With the sulfonated heterogeneous catalyst GO-HSO_3 in hand, one-pot reaction of benzimidazole synthesis (**3**) reaction was performed by using Benzene-1,2-diamine and benzaldehyde representation compounds and optimize the reaction condition. The results of these studies are summarized in Table 1. First, neat reaction without catalyst and solvent was performed to determine the reactivity of components. Negative results were obtained for this reaction up to 24 h stirring (Entry 1). Later on same reaction was conducted at 90 °C to determine the effect of temperature and this reaction also resulted in zero yields without any product (Entry 2). However, in

Table 1 Optimization of reaction condition for the synthesis of benzimidazole using sulfonated graphene oxide



Sr. no.	Catalyst	Cata. amount (mg)	Solvent	Temp. (°C)	Time (h)	Conv. (%)	Yield (%)[a]
1	–		–	RT	24	0	0
2	–		–	90	24	0	0
3	Pure graphite	0.5	–	RT	24	18	5
4	Pure GO	0.5	–	RT	12	41	16
5	Pure GO	0.5	–	RT	24	67	21
6	GO-HSO_3	0.5	–	RT	2	100	91
7	GO-HSO_3	0.3	–	RT	4	100	90
8	GO-HSO_3	0.1	–	RT	7	100	89
9	GO-HSO_3	0.1	Methanol	RT	12	100	57
10	GO-HSO_3	0.1	DCM	RT	8	100	61
11	GO-HSO_3	0.1	Acetonitrile	RT	12	100	38

All reactions were carried out on 1.0 mmol of diamine and 1.0 mmol of aldehyde using catalytic amount of catalyst in solvent free condition

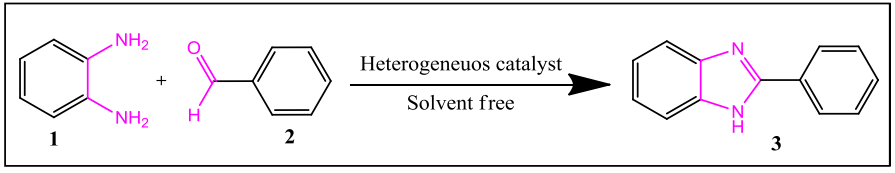
[a] Yield refers to the isolated product, characterized by ^{1}H and ^{13}C NMR, and FT-IR

next step for the same reaction at room temperature, pure graphite was used as catalyst to determine the catalytic ability of pure graphite. This reaction showed 18 % conversion and only 5 % selective yield of benzimidazole in 24 h reaction time (Entry 3). Moreover, reactions were conducted by using catalytic amount of pure graphene oxide at room temperature in solvent free condition for 12 and 24 h reaction times. These reactions were also fails to give the efficient yield of respective products and showed 41 and 67 % conversion with 16 and 21 % yield respectively (Entries 4, 5). These obtained results demonstrate that pure graphite and graphene oxide is not sufficient as catalyst for the development of benzimidazole at room temperature in solvent free condition. In subsequent step, we tested 0.5 equiv. of GO-HSO_3 for the same reaction under solvent free condition at room temperature. This reaction showed marvelous production of benzimidazole in very short reaction time. 100 % conversion with 91 % selective formation of benzimidazole was obtained in 2 h reaction time in solvent free condition at room temperature (Entry 6). Then we tried to reduce the amount of the catalyst, the reactions required the little longer time with reduction of catalyst amount. 0.3 equiv. catalysts showed 100 % in 4 h reaction time and obtained 90 % yield (Entry 7).

Moreover 0.1 equiv. catalysts showed approximately same yield (89 %) in 7 h reaction time (Entry 8). Therefore for further application of this prepared GO-HSO_3 catalyst 0.1 equiv. of catalytic amount was applied. However the present protocol is highly efficient in solvent free condition, but determination of solvent effect is still necessary for the catalytic application at large scale production of benzimidazole. Therefore, we have tested many solvents for this protocol at room temperature. Initially methanol was tested which showed 100 % conversion but gave only 57 % yield in 12 h reaction duration (Entry 9). In addition to that DCM and acetonitrile as solvent, these solvent also fails to give efficient yield. Results showed that, these solvent acquired 100 % conversion but showed only 61 and 38 % yield of respective benzimidazole (Entries 10, 11). However, when reactions were conducted in all above reactions number of side products were detected, due to this reason they fail to give efficient selective yield of benzimidazole.

To compare the remarkable catalytic activity of GO-HSO_3 catalyst with other reported heterogeneous catalyst, we conducted model benzimidazole synthesis reaction using optimized reaction condition and the results are shown in Table 2. Entries 1 and 2 show benzimidazole synthesis using heterogeneous $AlCl_3$ and $FeCl_3$ in solvent free condition. These reactions were preceded very sluggishly and provide only 66 and 41 % of respective benzimidazole product respectively after 8 h. However, it is very hard to separate the catalyst and obtained products with these metal chlorides. Next, we carried out same reaction using $CuCl_2{\cdot}2H_2O$ in solvent free condition to demonstrate the catalytic role of $CuCl_2{\cdot}2H_2O$ in this protocol. We observed that catalyst $CuCl_2{\cdot}2H_2O$ (0.1 equiv) was unable to give selective yield of benzimidazole in optimized condition and resulted 31 % yield with 82 % conversion (entry 3). While, $NiCl_2$ and $CoCl_2{\cdot}6H_2O$ were produced 47 and 51 % yield of benzimidazole with 100 % conversion (entries 4 and 5). In addition, we have also carried out reactions with heterogeneous catalyst $Co(NO_3)_2{\cdot}6H_2O$ and $Ni(NO_3)_2{\cdot}6H_2O$ in optimized reaction condition in solvent free conditions. Both these catalysts were fails to give efficient yield of product in

Table 2 Synthesis of benzimidazole using different heterogeneous catalysts and comparison of sulfonated graphene oxide with other heterogeneous catalysts in optimized reaction condition



Sr. no.	Catalyst	Time (h)	Conversion (%)	Yield (%)[a]
1	$AlCl_3$	8	100	66
2	$FeCl_3$	8	100	41
3	$CuCl_2{\cdot}2H_2O$	12	82	31
4	$NiCl_2$	18	100	47
5	$COCl_2{\cdot}6H_2O$	8	100	51
6	$CO(NO_3)_2{\cdot}6H_2O$	24	88	38
7	$Ni(NO_3)_2{\cdot}6H_2O$	24	61	42
8	$Al(NO_3)_3$	18	57	28
9	GO-HSO_3	7	100	89

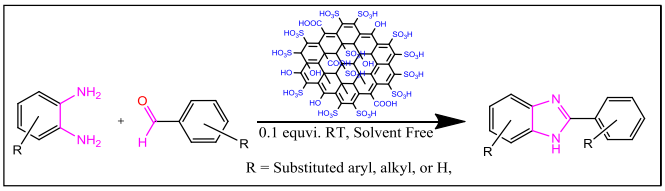
All reactions were carried out on 1.0 mmol of diamine and 1.0 mmol of aldehyde using catalytic amount of heterogeneous catalyst in solvent free condition

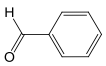
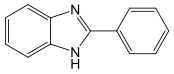
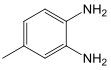
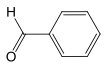
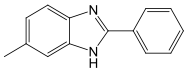
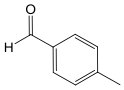
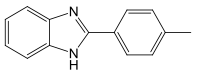
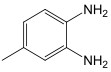
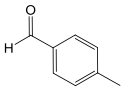
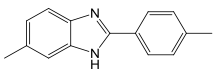
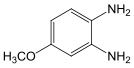
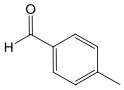
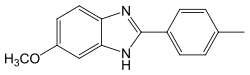
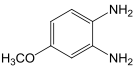
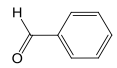
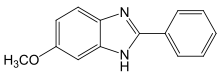
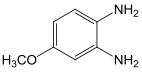
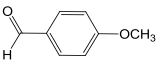
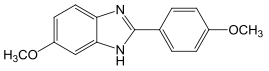
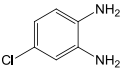
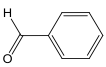
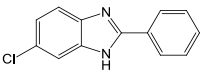
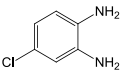
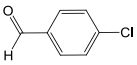
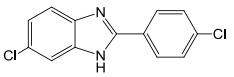
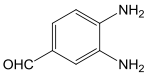
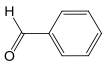
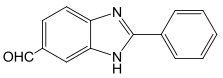
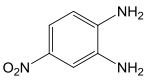
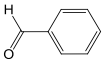
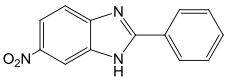
[a] Yield refers to the isolated product, characterized by ^{1}H and ^{13}C NMR, and FT-IR

24 h reaction time. As a results these catalyst showed 32 and 48 % yield with 88 and 61 % conversion respectively (Entries 6 and 7). Finally, to confirm the catalytic role of Al $(NO_3)_3$ in optimized condition, we carried out same reaction in solvent free condition and this reaction was unable to produce high yield of benzimidazole even after 18 h. This reaction produced 28 % yield with 57 % conversion (Entry 8). These reactions results clearly indicate that prepared GO-HSO_3 catalyst in solvent free condition having high selective catalytic ability for the preparation of benzimidazole in high yield by consuming di-amine and aldehyde (Entry 9).

With effectively preparation and compared catalytic activity in replica compound benzimidazole **3** preparations by using different heterogeneous catalysts, we decided to investigate the possibility and simplification of this GO-HSO_3 catalyst reaction in the synthesis of other different benzimidazole with various substituents on the aromatic rings. Consequently, a diversity of commercially accessible substituted various 1,2 di-amines and different structurally substituted aldehydes were treated underneath the optimized reaction conditions for benzimidazole synthesis and results are summarized in Table 3. As marked from Table 3, all substituted 1,2 di-amines and aldehydes participated well in this cyclization reaction and affording the desired products of benzimidazole in good to efficient yields. In addition these reactions were completed in short reaction time and small amount of catalyst offered high to efficient yield. Initially without substituted diamine benzimidazole benzene-1,2-diamine was reacted with benzaldehyde in presence of 0.1 equiv. of catalyst which showed 89 % selective yield of respective benzimidazole in 7 h reaction time (Entry 1). Soon after, reactions were performed using electron donating organic group substituted diamine 4-methyl-benzene-1,2-diamine with unsubstituted benzaldehyde moiety which gave 74 % competent yield of particular benzimidazole in 3 h (Entry 2). In addition, reaction was also preceded very well with electro donating present on the while using the aldehyde which also resulted respective efficient yield of benzimidazole (Entry 3). Electro donating substituted diamine as well as aldehyde was reacted smoothly and obtained 69 % yield (Entry 4). Electro donating groups such as methoxy group functionalized substituted di-amine as well as aldehydes were also showed outstanding results with sulfonated graphene. As a results electro donating group substituted diamines showed 67 and 78 % yield of respective benzimidazole (Entries 5, 6 and 7). In further step chloro substituted electron withdrawing group substituted diamines were showed 81 and 83 % yield of respective benzimidazole in short reaction time using 0.1 equiv. sulfonated graphene oxide as catalyst (Entries 8 and 9). In addition, with aldehyde and nitro group substituted diamine were also performed reaction efficiently and obtained quantitative yield (Entries 10 and 11). However, from these results it can conclude that, sulfonated functionalized graphene oxide is highly suitable catalyst for the synthesis of benzimidazole with any functional substitution on the aromatic rings. In addition, these substituted functionalities were preserved throughout the course of reaction in presence of prepared catalyst in optimized reaction condition.

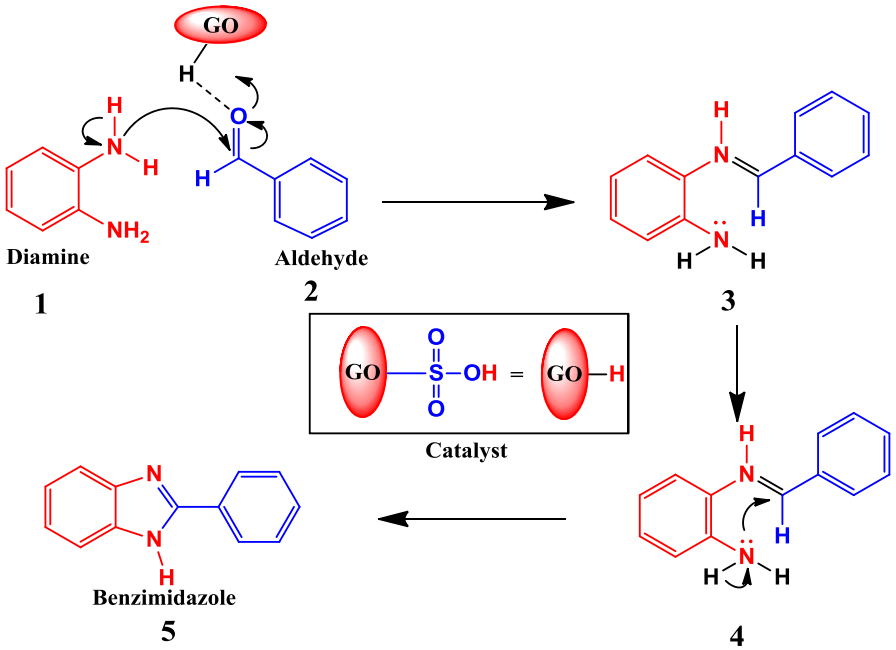
Table 3 Synthesis of different substituted benzimidazole derivatives using sulfonated graphene oxide in optimized reaction condition



Sr. no.	Diamine	Aldehyde	Time (h)	Product	Yield [a] (%)
1			7.0		89
2			3.0		74
3			4.0		81
4			6.0		69
5			10.0		67
6			6.0		78
7			4.5		83
8			7.0		81
9			6.0		83
10			9		78
11			8		81

All reactions were carried out on 1.0 mmol of diamine and 1.0 mmol of aldehyde using catalytic amount of catalyst in solvent free condition

[a] Yield refers to the isolated product, characterized by ^{1}H and ^{13}C NMR, and FT-IR



Scheme 2 Proposed reaction mechanism for the formation of benzimidazole using sulfonated graphene oxide as heterogeneous catalyst

Proposed reaction mechanism

In order to understand in depth reaction mechanism with GO-HSO_3 catalyst on the basis of obtained results in this study, a plausible reaction mechanism constructed for the development of benzimidazole derivatives is depicted in Scheme 2. It is proposed that initially acidic proton of sulfonic group present on surface of sulfonated graphene oxide gets interaction with the oxygen which is present in aldehyde functionality, which activates carbonyl group to generate the carbonium ion, facilitating nucleophilic attack by diamine resulting in imine [33, 34]. The resulting imine eventually undergoes ring closure by the intramolecular attack of second amino group and subsequently undergoes aromatization to afford the desired benzimidazole.

Recyclability test of sulfonated graphene oxide catalyst

It is highly significant to consider the recyclability of heterogeneous catalysts to understand its lifetime activity for particular reaction, especially for industrial, pharmaceutical and engineering applications [36–39]. Therefore, it is very essential to figure out the stability of heterogeneous catalyst under solvent free reaction conditions. To understand and study the reusability of prepared catalyst, solid GO-HSO_3 catalyst was filtered out from the reaction mixture by means of straightforward filtration procedure and catalyst rinsed three successive times with de-ionized

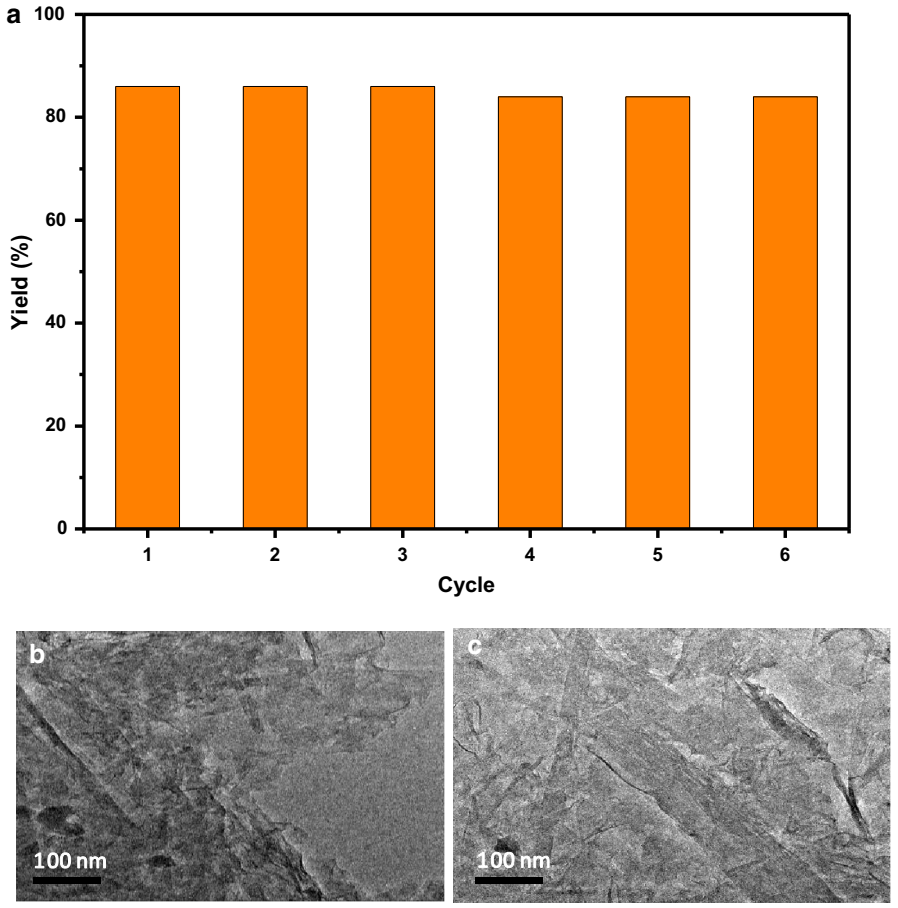


Fig. 7 Recyclability test of sulfonated graphene oxide in benzimidazole synthesis in optimized reaction condition in solvent free condition (**a**). TEM analysis of fresh catalyst (**b**) and after 6th recycled catalyst (**c**)

H_2O and after drying in vacuum oven catalyst reused in subsequent attempts of reactions. Recyclability of GO-HSO_3 catalyst was studied over six cycles for the synthesis of benzimidazole under solvent free condition at room temperature. No significant loss in the yield and selectivity of product was observed over six cycles (Fig. 7a). Furthermore, conversion of reactant was 100 % and the yield of product was maintained constant at 82.0 % during recycling tests. In addition morphology determination of fresh catalyst and after 6th recycled run catalyst did not show much variation in morphology (Fig. 7b, c) and graphene sheets morphology still remains constant even after 6th successive runs.

Therefore, the catalyst GO-HSO_3 can be competently recycled for six times without significant failure in its catalytic activity as well as selectivity in the preparation of benzimidazole by means of solvent free condition. These results

indicate that, the present methodology is highly eco-friendly and green approach for the preparation of benzimidazole derivatives.

Conclusions

In conclusion, sulfonated graphene oxide (GO-HSO_3) was utilized as a heterogeneous catalyst for the synthesis of various substituted benzimidazole at room temperature for the development of a simple and competent one-pot solvent free method. The heterogeneous catalyst GO-HSO_3 was prepared and characterized by using fancy analytical and spectroscopic methods which showed that efficient grafting of the sulfonation groups are occurred over oxidized graphene oxide by simple sulfonation methods. These grafted special sulfonation groups on prepared graphene oxide, highly improved sufficient acidity of catalyst which showed the tremendous positive effect in the yield benzimidazole at room temperature in solvent free condition. Using 0.1 equiv. amount of catalyst obtained 100 % conversion and up to 89 % yield. In addition catalyst could be recycled up to six cycles over sulfonated graphene oxide without damaging selectivity and yield of benzimidazole. Simplicity of operation, heterogeneity of catalyst, high yields, easy work-up and purification of compounds, without reaction temperature, and solvent free condition are the key advantages of this method.

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