Green synthesis of benzimidazole derivatives by using zinc boron nitride catalyst and their application from DFT (B3LYP) study

Sureshkumar Mahalingam a, Arul Murugesan a,⁎, Thangaraj Thiruppathiraja b, Senthilkumar Lakshmipathi b, Talent Raymond Makanya a, Robert M. Gengan a,⁎⁎

a Department of Chemistry, Durban University of Technology, Durban, 4001, South Africa
b Department of Physics, Bharathiar University, Coimbatore, 641 046, TN, India

Keywords:
Zinc-boron nitride
Benzimidazole
DSC-TGA
DFT

A new zinc-based boron nitride (Zn-BNT) material was synthesized from boron nitride and zinc acetate in 95% yield. The morphological and spectroscopic properties of Zn-BNT were elucidated by SEM, XRD, BET, DSC-TGA, and FT-IR. Zn-BNT catalyzed the synthesis of benzimidazoles (3a–3h) through a reaction between o-phenylenediamine and different aromatic aldehydes under microwave conditions for 15 min. The compounds were purified by silica-gel chromatography. The synthesized compounds were characterized by FT-IR, 1H-NMR, 13C-NMR, and elemental analysis. Zn-BNT was reused eight times with only a 5% loss of catalytic activity. Furthermore, 2-(4-fluorophenyl)-1H-benzo[d]imidazole (3f) was selected for a computational study of the IR and NMR spectrum, which matched the experimentally generated spectra. The HOMO-LUMO gap was 4.48, and the Fukui function analysis showed high activity in the reactive sites.

1. Introduction

Heterogeneous catalysis plays a significant role in synthesizing organic compounds for agrochemicals, pharmaceuticals, and fine chemicals for a sustainable future. These catalysts have contributed to developing technology to produce green chemicals from biomass-derived platform chemicals under environmentally benign processes and avoid using toxic or hazardous materials [1]. However, the design and development of novel eco-friendly solid catalysts require appropriate techniques and strategies for improved recoverability, recyclability, and eco-friendliness [2]. In addition, there is an urgent need to acquire new organic compounds which might find possible applications in diverse areas of study.

⁎ Corresponding author.
⁎⁎ Corresponding author.
E-mail addresses: chemarul91@gmail.com, organicarul91@gmail.com (A. Murugesan), genganrm@dut.ac.za (R.M. Gengan).

https://doi.org/10.1016/j.heliyon.2022.e11480
Received 25 May 2022; Received in revised form 1 September 2022; Accepted 3 November 2022
2405-8440/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
Hence more environmentally and eco-friendly heterogeneous catalysts are being sought to expedite the synthesis of nitrogen-based heterocycles because of their enhanced biological activities [3].

Porous hexagonal boron nitride (h-BN) is a material that demonstrates unique physical and chemical properties, including low density, high specific surface area, high thermal conductivity, oxidation resistance, and chemical durability [4, 5]. These features make h-BN a promising catalyst for their application in various research areas, especially those related to adsorption, like gaseous uptake and pollutant adsorption. Furthermore, h-BN is excellent catalyst support [6] since they possess a hexagonally shaped crystal structure composed of continuous boron-nitrogen bonds, wherein lone pair of electrons on the nitrogen atoms can coordinate with certain metals. The hBN/metal substrates functions as supports for metal clusters with Cr(110), Molybdenum(110), Rhenium(0001), Iron(110), Iridium(111), Copper(111), Gold(111), Silver(111), Nickel(111), and Platinum(111), metal-organic complexes, and organic molecules [7]. Water-soluble and porous boron nitride is usually biocompatible and can effectively employ as a nanocarrier for loading anti-cancer drug doxorubicin [8]. Moreover, several studies supported the use of interactions of h-BN through calcium coordination bonding towards reduced graphene oxide yielded nanocomposites to enhance the mechanical, electrical and thermal properties substantially [9, 10, 11]. Therefore, we aimed to investigate a metal and concoct a novel zinc boron nitride (Zn-BNT) material to synthesize new benzimidazoles through a simple condensation reaction.

2. Experimental

2.1. Materials and methods

All the reagents were purchased from commercial sources and used as received. The reactions’ progress and the compounds’ purity were...
monitored by thin-layer chromatography (TLC) on pre-coated silica gel plates procured from E. Merck and Co. (Darmstadt, Germany). TLC spots were visualized by UV light and using an iodine-vapor chamber. The melting points of the synthesized compounds were determined using a Stuart SMP 10 melting point apparatus and are uncorrected. The IR spectra were recorded on Varian Scimitar 1000 FT-IR using KBr pellets, and the absorption frequencies are expressed in reciprocal centimeters (cm⁻¹). In addition, ¹H and ¹³C NMR were recorded on either a Bruker or a Varian FT-NMR spectrometer. FT-IR spectra were recorded on a PerkinElmer spectrophotometer. The experimental data is presented below:

2.2. Synthesis and characterization of Zn-BNT

To a solution of ZnO(C₂H₅)₂ (24.9 mg), in acetonitrile (50 ml), was added boron nitride (2.50 mg, 0.1 mmol), and the suspension was stirred at room temperature for seven days under an inert atmosphere. The resulting suspension was filtered, and the solid was washed with aqueous methanol and dried under reduced pressure to give Zn-BNT as a white powder in 95% yield.

2.3. Synthesis and characterization of 2-aryl benzimidazole derivatives (3a–h)

Equimolar quantities (1 mmol) of o-phenylenediamine (1) and aromatic aldehydes (2a–h) in acetonitrile (6 ml) were transferred to a 50 ml round bottom flask, and Zn-BNT (10 mol%) was added. The mixture was heated under reflux for 12 h, and TLC was used to monitor the progress of the reaction mixture. Upon completion of the reaction, the mixture was filtered to recover the catalyst. The solid was washed with chloroform followed by methanol and dried at 120 °C while the filtrate was purified by silica-gel column chromatography using ethyl acetate and petroleum ether 10:90 (v, v 10%) as an eluent to yield the 2-arylbenzimidazoles 3a–h, quantitatively.

The spectra data is presented below:

2.3.1. 2-phenyl-1H-benzo[d]imidazole (3a)

White solid; Yield: 97%; mp: 132–134 °C; FT-IR (ATR, νmax cm⁻¹): 3321 cm⁻¹ (N–H stretching), 3177 cm⁻¹ (–CH), 1625 (C=N), 1551, 1467, 1422 (Ar–C=C); ¹H-NMR (400 MHz, DMSO-d₆): δ = 12.91 (1H, s, N–H), 7.30–7.82 (2H, m, Ar–H), 7.39–7.82 (5H, m, Ar–H), 7.10–7.86 (1H, m, Ar–H) ppm. Found: C, 78.93; H, 5.19; N, 14.42%. Anal. Calc. for C₁₁H₈N₂O: C, 71.73; H, 4.79; N, 14.23%.

2.3.2. 2-(furan-2-yl)-1H-benzo[d]imidazole (3b)

Brown solid; Yield: 95%; mp: 296–298 °C; ¹H-NMR (400 MHz, DMSO-d₆): δ = 12.98 (1H, s, N–H), 7.93 (1H, m, Ar–H), 7.60–7.62 (1H, d, J = 8 Hz, 1H, Ar–H), 7.47–7.49 (1H, d, J = 8 Hz, Ar–H), 7.22–7.17 (3H, m, Ar–H), 6.71 (1H, m, Ar–H) ppm. Found: C, 71.75; H, 4.38; N, 15.2%. Anal. Calc. for C₁₁H₈N₂O: C, 71.73; H, 4.38; N, 15.23%.

2.3.3. 2-(2-nitrophenyl)-1H-benzo[d]imidazole (3c)

Yellow solid; Yield: 90%; mp: 294–296 °C; ¹H-NMR (400 MHz, DMSO-d₆): δ = 12.82 (1H, s, N–H), 7.96–8.03 (2H, m, Ar–H), 7.86–7.88 (1H, m, Ar–H), 7.73–7.77 (1H, m, Ar–H), 7.59–7.67 (2H, m, Ar–H), 7.23–7.25 (2H, m, Ar–H) ppm. Found: C, 75.27; H, 3.79; N, 17.56%. Anal. Calc. for C₁₁H₈N₂O₂: C, 75.27; H, 3.81; N, 17.58%.

2.3.4. 2-(4-nitrophenyl)-1H-benzo[d]imidazole (3d)

Yellow solid; Yield: 88%; mp: 306–308 °C; FT-IR (ATR, νmax cm⁻¹): 3321 cm⁻¹ (N–H stretching), 3177 cm⁻¹ (–CH), 1625 (C=N), 1551, 1467, 1422 (Ar–C=C); ¹H-NMR (400 MHz, DMSO-d₆): δ = 13.60 (1H, s, N–H), 8.39 (1H, d, Ar–H), 8.15 (1H, d, 1H, Ar–H), 8.00 (1H, d, 1H, Ar–H), 7.64–7.66 (1H, dd, Ar–H), 7.25–7.27 (1H, dd, Ar–H) ppm. Anal. Calc. for C₁₃H₁₁N₂O₂: C, 65.27; H, 3.79; N, 17.56%. Found: C, 65.29; H, 3.81; N, 17.57%.

2.3.5. 2-(4-chlorophenyl)-1H-benzo[d]imidazole (3e)

Brown solid; Yield: 89%; mp: 280–282 °C; ¹H-NMR (400 MHz, DMSO-d₆): δ = 12.76 (1H, s, N–H), 8.17 (2H, m, Ar–H), 7.58–7.63 (4H, m, Ar–H), 7.20–7.22 (2H, m, Ar–H) ppm. Anal. Calc. for C₁₃H₁₁ClN₂: C, 68.28; H, 3.97; N, 12.25%. Found: C, 68.30; H, 3.98; N, 12.27%.

2.3.6. 2-(4-fluorophenyl)-1H-benzo[d]imidazole (3f)

White solid; Yield: 93%; mp: 186–188 °C; ¹H-NMR (400 MHz, DMSO-d₆): δ = 12.91 (1H, s, N–H), 8.20–8.24 (1H, q, Ar–H), 7.74–7.78 (1H, q, Ar–H), 7.72 (1H, t, Ar–H), 7.49 (1H, t, Ar–H), 7.34–7.42 (1H, m, Ar–H), 7.25 (1H, t, Ar–H), 7.10 (1H, t, Ar–H), 7.00–7.07 (1H, q, Ar–H) ppm. Anal. Calc. for C₁₃H₁₁FNO₂: C, 73.57; H, 4.27; N, 13.20%. Found: C, 73.59; H, 4.29; N, 13.21%.

2.3.7. 2-(p-tolyl)-1H-benzo[d]imidazole (3g)

Greyish solid; Yield: 82%; mp: 178–180 °C; ¹H-NMR (400 MHz, DMSO-d₆): δ = 12.82 (1H, s, N–H), 8.04 (2H, m, Ar–H), 7.54–7.65 (2H, m, Ar–H), 7.34–7.36 (2H, m, Ar–H), 7.16–7.20 (2H, m, Ar–H), 2.34 (3H, s, CH₃), ppm. Anal. Calc. for C₁₃H₁₃N₂: C, 80.74; H, 5.81; N, 13.45%. Found: C, 80.76; H, 5.83; N, 13.47%.

2.3.8. 2-(1H-benzo[d]imidazole-2-yl)phenol (3h)

White solid; Yield: 94%; mp: 222–224 °C; ¹H-NMR (400 MHz, DMSO-d₆): δ = 12.72 (1H, s, N–H), 9.61 (1H, s, Ar–OH), 8.03–8.06 (1H, m, Ar–H), 7.70–7.72 (2H, m, Ar–H), 7.27–7.36 (2H, m, Ar–H), 6.88 (2H, m, Ar–H), 6.60 (1H, m, Ar–H) ppm. Anal. Calc. for C₁₃H₁₁N₂O: C, 74.27; H, 4.79; N, 13.33%. Found: C, 74.29; H, 4.81; N, 13.35%.

3. Results and discussion

3.1. Synthesis and characterisation of Zn-BNT

The new catalyst Zn-BNT (Figure 2) was synthesized through a simple reaction between boron nitride, zinc acetate in acetonitrile under an inert
Figure 3. XRD pattern of (a) Zn-BNT (b) BNT exhibiting the facets of Zn and BN.

Figure 4. SEM image of 1, 2 and 4% Zn-BNT (a, b, c, d).
atmosphere by stirring at room temperature for seven days. The novel catalyst was characterized using FT-IR, XRD, SEM, SEM-EDX, SEM-mapping, BET, and DSC-TGA.

3.2. FT-IR spectrum of Zn-BNT

The FT-IR spectrum of Zn-BNT is presented in Figure S1 (Supporting Information). The FT-IR revealed the presence of functional bond stretching frequencies N–B–N at 1738 cm\(^{-1}\), B–N at 1365 cm\(^{-1}\), and B–N–B at 920 cm\(^{-1}\), with other additional bands for Zn–N at 1365 cm\(^{-1}\) and 1217 cm\(^{-1}\) assigned as asymmetric and symmetric stretching frequencies, respectively.

3.3. Powder XRD pattern of Zn-BNT

The powder XRD diffraction analysis [5] showed the crystal-like Zn-BNT. The characteristic Bragg’s XRD peaks at 20 boron nitride peaks are observed at 26.67\(^{\circ}\), 41.62\(^{\circ}\), 55.02\(^{\circ}\) and 75.91\(^{\circ}\) are indexed to the (002), (100), (004), (220) while the Zn peaks 43.81\(^{\circ}\) and 50.15\(^{\circ}\) were indexed to (111), (012), respectively (Figure 3a and 3b).

3.4. Scanning electron microscope image of Zn-BNT

Zn-BNT was analyzed by scanning electron microscopy (SEM) for morphological characteristics. The particles appeared to be randomly distributed, as shown in Figure 5. SEM-Mapping of Zn-BNT a, b, c, and d. The SEM-EDX spectrum further confirmed the elemental composition of the catalyst, with B, N, Zn, and O detected (Figure 6). SEM-EDX spectrum of Zn-BNT.

Figure 5. SEM-Mapping of Zn-BNT a, b, c, and d.

Figure 6. SEM-EDX spectrum of Zn-BNT.
The particles were observed as small and had a high surface area with a smaller number of active sites compared to 2% Zn-BNT. Similarly, the particles appeared larger and therefore had a smaller surface area in 4% Zn-BNT compared with 2% Zn-BNT. The SEM-EDX spectrum of Zn-BNT material was further confirmed by SEM-EDX analysis.

3.5. SEM-mapping of Zn-BNT

The particles were observed as small and had a high surface area with a smaller number of active sites. Furthermore, the SEM mapping indicated the elements of Zn-BNT (Figure 5a, b, c, and d). Zn-BNT, boron, nitrogen, and zinc. The morphology of Zn-BNT material was further confirmed by SEM-EDX analysis.

3.6. SEM-EDX spectrum of Zn-BNT

The SEM-EDX spectrum of Zn-BNT (Figure 6) displayed elements B, N, O, and Zn of weight (%) 20.11, 9.13, 70.72, and 0.04, respectively. Au peaks were due to the sample being coated with Au in the sampling process.

3.7. BET analysis of Zn-BNT

Brunauer-Emmett-Teller (BET) specific surface was determined from the nitrogen adsorption data at the relative pressure using a multipoint method. Figure 7(a) and (b) shows the isotherms of a 2 and 4% Zn-BNT in N2 adsorption-desorption. The sample exhibited type-III isotherms. The type-III isotherm is closely related to the mesoporous structure of the catalyst and therefore no identifiable monolayer formation; the adsorbent-adsorbate interactions are now relatively weak and the adsorbed molecules are clustered around the most favorable sites on the surface of the solid. 2% Zn-BNT material showed a surface area of 25.42 m² g⁻¹ with a pore volume of 0.119 cm³ g⁻¹ and 4% Zn-BNT material showed a surface area of 23.58 m² g⁻¹ with a pore volume of 0.114 cm³ g⁻¹ and a pore size 188.74 Å thereby indicating a mesoporous structure and effective as a catalyst for organic reactions.

3.8. Thermal analysis of Zn-BNT

Zn-BNT was analysed for its thermal properties from room temperature to 800 °C. Figure 8 presents the DSC-TGA profile of the Zn-BNT material. The DSC curve of the sample indicated a broad exothermic peak. The weight loss occurred in stages; about 1.2% loss up to 200 °C due to moisture and other volatile materials, whereas a loss of about 1.8% occurred until 800 °C. These results demonstrated that Zn-BNT has good thermal stability; hence, it can be used effectively as suitable for the catalyst for several organic reactions.

3.9. Synthesis and characterization of 2-aryl benzimidazole derivatives (3a–h)

Briefly, equimolar quantities of o-phenylenediamine (1) and differently substituted aromatic aldehydes (2a–h) were added in acetonitrile. Zn-BNT was added, and the mixture was subjected to microwave irradiation for 15 min. The crude product was purified by silica-gel column chromatography using ethyl acetate and petroleum ether (10:90) to yield the pure 2-arylbenzimidazoles (3a–h) quantitatively. The recovered catalyst was reused for other reactions. The facile, one-step synthetic route is shown in Scheme 1. Notably, various aromatic aldehydes containing both electron-withdrawing and electron-donating groups underwent condensation to afford the target compounds. The results show that aromatic aldehydes bearing electron-donating groups such as hydroxyl and methyl afforded corresponding 2-arylbenzimidazole derivatives in better yields than the aldehydes having electron-withdrawing groups.

3.10. Solvent optimization methodology

The effect of different solvents, such as protic and aprotic, with different polarities were investigated (Table 1) on the model reaction to synthesize 3a. An initial reaction of ortho-phenylenediamine (1) and benzaldehyde, in acetonitrile under reflux for 12 h produced a 75% yield of 3a. Protic solvents such as methanol and ethanol and aprotic solvents such as toluene, dichloromethane, tetrahydrofuran, and dioxane were investigated. The yield of 3a varied with the nature of the solvents used in the reaction. Since dioxane and acetonitrile gave the highest yield of 3a, we selected these two solvents and used microwave irradiation to decrease the reaction time and increase the yield of 3a. For a reaction time of 15 min, the yield of 3a was 55% and 97% for dioxane and acetonitrile, respectively (Table 1, entry 9). Published data on benzimidazole synthesis was analyzed and presented in Table 2. It was obvious that Zn-BNT outclassed published data; however, further work should be undertaken with named catalysts and under similar reaction conditions. Although the synthesis of the Zn-BNT material was recorded as seven days, the catalyst showed excellent catalytic activity, is
environmentally friendly, non-toxic, and produces a high product yield (Table 2).

After optimizing the reaction, 3a–h were synthesized using acetonitrile and Zn-BNT under MW conditions at 140 °C for 15 min. Appropriate ortho-phenylenediamine 1 and different aldehyde (2a–h) were used. The yield of the products (Table 3) ranged from 82 to 97%. The products 3a–h were characterized by spectroscopic techniques FT-IR, 1H-NMR, 13C-NMR, and elemental analysis. The spectral confirmation of 3a is discussed as a template analysis. The FT-IR spectrum displayed the characteristic vibrational band as a single sharp peak at 3321 cm⁻¹, which indicated the formation of new aromatic secondary amino-N-H stretch, while there was no shoulder peak in the region of 3500–3400 cm⁻¹, which would strongly indicate the NH₂. A strong peak at 1625 cm⁻¹ demonstrated the C¼N stretch. Also, there was no signal for the C¼O stretch in the region of 1680–1715 cm⁻¹, indicating the absence of the aromatic aldehyde, one of the starting materials. Thus, the new C¼N bond and N–H bond confirmed the main functional groups of 3a.

Moreover, the characteristic peaks at 1551 cm⁻¹, 1467 cm⁻¹ and 1422 cm⁻¹ indicated the Ar–C¼C stretch and a sharp peak at 3177 cm⁻¹ represented the =CH stretch. The 1H-NMR spectrum of 3a showed a distinctive N-H proton broad singlet at δ 12.91, and no broad singlets were observed in the region of δ 5–7 ppm corresponding to the starting compound. The 13C-NMR displayed the N–C–N signal at δ 151.18 while the remaining 10 aromatic carbons appeared in the range δ 130.07–122.09 ppm. Elemental analysis revealed Anal. Calc. for C13H10N2: C, 80.39; H, 5.19; N, 14.42%. Found: C, 80.40; H, 5.21; N, 14.44%.

After optimizing the reaction, 3b–h was synthesized using acetonitrile and Zn-BNT under MW conditions at 140 °C for 15 min. Appropriate

| Entry | Catalyst | Solvent | Temp (°C) | Time(h/minutes) | Isolated Yield (%) |
|-------|----------|---------|-----------|-----------------|-------------------|
| 1     | Zn-BNT   | EtOH    | r.t       | 12 h            | 55                |
| 2     | Zn-BNT   | MeOH    | r.t       | 22 h            | 45                |
| 3     | Zn-BNT   | CH₃CN   | reflux    | 12 h            | 75                |
| 4     | Zn-BNT   | EtOH    | reflux    | 10 h            | 60                |
| 5     | Zn-BNT   | MeOH    | reflux    | 8 h             | 50                |
| 6     | Zn-BNT   | Toluene | reflux    | 7 h             | 65                |
| 7     | Zn-BNT   | DCM     | reflux    | 8 h             | 60                |
| 8     | Zn-BNT   | THF     | reflux    | 6 h             | 70                |
| 9     | Zn-BNT   | Dioxane | reflux    | 5 h             | 75                |
| 10    | Zn-BNT   | Dioxane | 140 (MW)  | 15 (minutes)    | 55                |
| 11    | Zn-BNT   | CH₃CN   | 140 (MW)  | 15 (minutes)    | 97                |
The condensation reaction was conducted using acetonitrile as the solvent at 140 °C and different amounts of 2% Zn-BNT catalyst in the range of 0.05–1 g. The best yield of product 3a was obtained with 0.07 g of the catalyst. Higher amounts of the catalyst did not improve the yield. The catalyst could be quickly recovered by simple filtration of the reaction mixture, followed by washing with chloroform and then methanol; the solid was dried at 105 °C and then used for subsequent reactions. The reusability potential of Zn-BNT was also investigated in the model reaction to synthesize 3a. Recovery of the catalytic activity of Zn-BNT was better than other catalysts. Zn-BNT could be reused up to 8 times with only 5% loss of catalytic activity (Table 4), indicating good potential if undertaken on an industrial scale for synthesizing any benzimidazole derivatives.

3.11. Reusability of the Zn-BNT catalyst

The condensation reaction was conducted using acetonitrile as the solvent at 140 °C and different amounts of 2% Zn-BNT catalyst in the range of 0.05–1 g. The best yield of product 3a was obtained with 0.07 g of the catalyst. Higher amounts of the catalyst did not improve the yield. The catalyst could be quickly recovered by simple filtration of the reaction mixture, followed by washing with chloroform and then methanol; the solid was dried at 105 °C and then used for subsequent reactions. The reusability potential of Zn-BNT was also investigated in the model reaction to synthesize 3a. Recovery of the catalytic activity of Zn-BNT was better than other catalysts. Zn-BNT could be reused up to 8 times with only 5% loss of catalytic activity (Table 4), indicating good potential if undertaken on an industrial scale for synthesizing any benzimidazole derivatives.

4. Density functional theory study

4.1. Computational details

The ground state (DFT) optimization energy calculations were performed using the hybrid exchange-correlation functional B3LYP [40] with the basis set for the 6-311++G(d,p) [41]. The various possible conformers for compound 3f were optimized in the gas phase. The conformer with the lowest energy with the fundamental frequencies in the ground state was considered and shown in Table S1 and Figure S13 (Supplementary Information). The total energy and Cartesian coordinates for the optimized minimum energy structure are given in Table S2. The infra-red (IR) spectrum and frequency values of 3f from DFT calculations are shown in Figure S15 and Table S3. Further, the NMR shielding tensors computed from DFT calculations are shown in Figure S16 and Table S4. All the calculations were carried out with the Gaussian09 program package [42].

4.2. Molecular orbitals, Mulliken charge analysis, and electrostatic potential map

The energy level of the highest-occupied molecular orbital (E_HOMO) and lowest-unoccupied molecular orbital (E_LUMO) energies, along with the E_HOMO-LUMO gap is an important parameter [43] to evaluate the reactivity of 3f. The HOMO-LUMO plot is given in Figure 9. The energy gap value of 3f was E_{HOMO-LUMO} = 4.48 eV. The large E_{HOMO-LUMO} energy gap denotes the compound’s high stability and lower reactivity.

The atomic charge distribution of 3f is obtained using Mulliken charge analysis [44] in Figure S14. The nitrogen and fluorine atoms show negative charge distribution due to electronegative properties. Consistently, the hydrogen zones represent a positive charge distribution in compound 3f.

The electrostatic potential surface (ESP) [45] ranges an isosurface from −0.02 a.u. to 0.02 a.u., as shown in Figure 10. The ESP map showed the high electron density for the blue region, which is due to higher electronegativity (nitrogen zones). In contrast, the red region denoted low electron density (hydrogen zones). The results mentioned above indicated that the C-N bond is an active site.

4.3. Fukui function

Fukui function predicts the most probable sites of the nucleophilic, electrophilic, and radical attack selectivity and chemical reactivity using DFT calculation shown in Figure S17 [46]. The Fukui function indices on

---

**Table 2. The Zn-BNT catalyst compared with other catalysts.**

| Entry | Substrate (2a–h) | Product (3a–h) | Time (minutes) | Isolated Yield (%) | Reference |
|-------|------------------|----------------|----------------|-------------------|-----------|
| 1     | C_6H_4CHO        | 2a             | 15             | 97                | 15        |
| 2     | MnZnO_2·450      | 2b             | 10             | 94                | 28        |
| 3     | Ni(OAc)_2        | 2c             | 1              | 95                | 30        |
| 4     | LaCl_3           | 2d             | 20             | 96                | 35        |
| 5     | In(OTf)_3        | 2e             | 6              | 97                | Present work |
| 6     | P-benzoquinone   | 2f             | 0.5            | 93                | 31        |
| 7     | Zn-BNT           | 2g             | 0.5            | 96                | 35        |

**Table 3. The synthesis of benzo[d]imidazole derivatives in the presence of Zn-BNT in solvent acetonitrile under microwave irradiation conditions.**

| Entry | Substrate (2a–h) | Product (3a–h) | Time (minutes) | Isolated Yield (%) | M.p. (°C) |
|-------|------------------|----------------|----------------|-------------------|-----------|
| 1     | C_6H_4CHO        | 3a             | 15             | 97                | 152–154   |
| 2     | 2- C_6H_4CHO     | 3b             | 15             | 95                | 296–298   |
| 3     | 2-C_6H_4NO_2CHO  | 3c             | 15             | 90                | 294–296   |
| 4     | 4-C_6H_4NO_2CHO  | 3d             | 15             | 88                | <300      |
| 5     | 4-C_6H_4CHO      | 3e             | 15             | 89                | 280–282   |
| 6     | 4-FC_6H_4CHO     | 3f             | 15             | 93                | 186–188   |
| 7     | 2-CH_3C_6H_4CHO  | 3g             | 15             | 82                | 178–180   |
| 8     | 2-OHCH_2CHO      | 3h             | 15             | 94                | 222–224   |

ortho-phenylenediamine 1 and different aldehyde (2a–h) were used. The yield of the products (Table 3) ranged from 82 to 97%. The products 3a–h were characterized by spectroscopic techniques FT-IR, 1H-NMR, 13C-NMR, and elemental analysis.
Figure 9. The HOMO-LUMO plot for compound 3f.

- $E_{\text{HOMO}} = -6.15 \text{ eV}$
- $E_{\text{H-L gap}} = 4.48 \text{ eV}$
- $E_{\text{LUMO}} = -1.67 \text{ eV}$
- $E_{\text{A}} = 1.67 \text{ eV}$
- $E_{\text{P}} = 6.15 \text{ eV}$

Figure 10. The molecular electrostatic potential surface of the compound 3f.
of the nucleophilic reactivity particular site with positive/negative values. The dual descriptor values clear distinction between nucleophilic and electrophilic attacks at a

the ith atomic site, for nucleophilic (fi), electrophilic (f1), and free radical (f0) are following equations,

$$f_i^0 = q_i(N + 1) - q_i(N)$$

$$f_i^1 = q_i(N) - q_i(N - 1)$$

$$f_i^f = \frac{1}{2}[q_i(N + 1) - q_i(N - 1)]$$

The f^0, f^1 and f^f represent the nucleophilic, electrophilic, and free radical attack on the reference compound 3f. From Eqs. (1), (2), and (3), q_i denotes the atomic charge at the ith atomic sites of the chemical species are anionic (N + 1), cationic (N − 1), and neutral (N), respectively. Here, the Fukui function for f^0, f^1 and f^f attack is calculated using Mulliken charge analysis.

The dual descriptor ΔF(r), the difference between the nucleophilic (f^0) and the electrophilic (f^1) Fukui function as the given equation is [47],

$$\Delta F(r) = f_i^0 - f_i^1$$

Eq. (4) represents the nucleophilic and electrophilic (electron added and removed from the LUMO and HOMO) sites given in Figure 9. The nucleophilic and electrophilic attack sites are favored, whereas dual descriptor ΔF(r) > 0 and ΔF(r) < 0. Here, the dual descriptor ΔF(r), is the clear distinction between nucleophilic and electrophilic attacks at a particular site with positive/negative values. The dual descriptor values are presented in Table 5 which indicated that the nucleophilic reactivity of 3f was in the following order N7 > H12 > C1 > H13 > C5 > F24 > H10 > H11 > C23 > H22 > H21 > C4 > C19 > H18 > H25 > C8 > H17 > C14 > N9 > C20 > C3 > C16 > C6 > C2 and electrophilic reactivity in the order C16 > C15 > C1 > C23 > N7 > C4 > H22 > H21 > C8 > H12 > H13 > F24 > H10 > H11 > H18 > H17 > C5 > H25 > C19 > N9 > C20 > C6 > C3 > C2 > C14 while the free radical attack reactivity order was C1 > N7 > C16 > H12 > C23 > H13 > F24 > H10 > H22 > H11 > H21 > C4 > C5 > C8 > C15 > H18 > C17 > C19 > C25 > N9 > C20 > C6 > C3 > C14. Furthermore, the condition of dual descriptor, the positive values denoted nucleophilic site (F(r) > 0) for C2, C3, C5, C6, N7, N9, H10, H11, H12, H13, C14, C19, C20, and F24. Similarly, the electrophilic site was negative values (F(r) < 0) are C1, C4, C8, C15, C16, H17, H18, H21, H22, C23, and H25. Finally, behavior for the nucleophilic, electrophilic, and free radical attack indicated the highly reactive sites were N26 (0.096), C8 (1.611), and C8 (0.801).

5. Conclusion

In this work, we developed a facile, one-pot synthesis of 2-substituted benzimidazole derivatives through a reaction between o-phenylenediamine and different aromatic aldehydes in the presence of a novel zinc-boron nitride catalyst. The advantages of the developed method include the environmental-friendly reaction conditions, simple operation, broad substrate scope, satisfying yields, easy isolation of the product, and reusability of the catalyst. Furthermore, 2-(4-fluorophenyl)-1H-benzo[d]imidazole (3f) was selected for a computational study of the IR and NMR spectrum, which matched the experimentally generated spectra. The HOMO-LUMO gap was calculated as 4.48 eV. Moreover, the novel catalyst could be employed to synthesize other heterocyclic compounds, and their biological activity can be evaluated.

Declarations

Author contribution statement

Sureshkumar Mahalingam, Arul Murugesan: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Thangaraj Thiruppathiraja, Senthilkumar Lakshmiopathi: Performed the experiments; Wrote the paper.

Talent Raymond Makhanya: Performed the experiments; Analyzed and interpreted the data.

Robert Moonsamy Gengan: Conceived and designed the experiments; Analyzed and interpreted data.

Funding statement

SureshKumar Mahalingam was supported by National Research Foundation (NRF) of South Africa (Grant No. 98725).

Data availability statement

The data that has been used is confidential.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2022.e11480.

References

[1] B. Mallesham, D. Raikwar, D. Shee, Chapter 1 - the role of catalysis in green synthesis of chemicals for sustainable future, in: C. Mustansar Hussain, P. Sudarsanan (Eds.), Advanced Functional Solid Catalysts for Biomass Valorization, Elsevier, 2020, pp. 1–37.

[2] P. Gupta, A. Mahajan, Green chemistry approaches as sustainable alternatives to conventional strategies in the pharmaceutical industry, RSC Adv. 5 (34) (2015) 26686–26705.

[3] M. Butters, et al., Critical assessment of pharmaceutical ProcessesA rationale for changing the synthetic route, Chem. Rev. 106 (7) (2006) 3002–3027.

[4] S. Marchesini, X. Wang, C. Petit, Porous Boron Nitride Materials: In Valorization, Elsevier, 2020, pp. 1–18.

[5] A. Rehbe, R.S. Jagtap, S.S. Ubhane, One pot synthesis of substituted benzimidazole derivatives and their characterization, Rasayan J. Chem. 8 (2015) 213–217.

[6] M. Rekha, et al., Synthesis of 2-substituted benzimidazoles and 1,5-disubstituted benzimidazepines on alumina and zirconia catalysts, Chin. J. Catal. 33 (2) (2012) 439–446.

[7] S. Ozyeb, et al., 2-(2,4-Dichlorophenyl)-5-fluoro-6-morpholin-4-yl-1H-benzimidazole monohydrate, Acta Crystallograp. Section E-Struct. Rep. Online 58 (2002).

[8] Y. Venkateswarlu, S.R. Kumar, P. Leelavathi, Facile and efficient one-pot synthesis of benzimidazoles using lantanum chloride, Org. Chem. Lett. Mater. 3 (1) (2013) 7.

[9] R. Trivedi, S.K. De, R.A. Gibbs, A Convenient one-pot synthesis of 2-substituted benzimidazoles, J. Catal. 245 (1) (2007) 14–11.

[10] S. Park, J. Jung, E.J. Cho, Visible-light-activated synthesis of benzimidazoles, Eur. J. Org. Chem. 2014 (19) (2014) 4148–4154.

[11] V.D. Patil, K. Patil, Synthesis of benzimidazole and benzoxazole derivatives catalyzed by nickel acetate as organometallic catalyst 8, 2015, pp. 457–465.

[12] V. Ghosh, A. Mandal, Catalytic role of sodium dodecyl sulfate: selective synthesis of 1,2-disubstituted benzimidazoles in water, Catal. Commun. 12 (8) (2011) 744–747.

[13] A. Murugesan, R.M. Gengan, A. Krishnan, Sulfonic acid functionalized boron nitride nanomaterials as a microwave-assisted efficient and highly biologically active one-pot synthesis of piperazinylquinolinyl fused Benzo[c]aridine derivatives, Mater. Chem. Phys. 188 (2017) 154–167.

[14] A. Murugesan, et al., One-pot synthesis of Claisen-Schmidt reaction through (E)-chalcone derivatives: spectral studies in human serum albumin protein binding and molecular docking investigation, Synth. Commun. 47 (20) (2017) 1884–1904.

[15] A. Murugesan et al., Microwave-assisted: boron nitride nanomaterials based sulfonic acid catalyst for the synthesis of biologically active ethylpiperazinyl-1H-benzimidazolyl fused Benzo[c]aridine derivatives, Adv. Mater. 5 (2018) 785–789.

[16] P.H. Jay, W.R. Wad, Ab initio effective core potentials for molecular calculations. Potentials for the transition metal atoms Sc to Hg, J. Chem. Phys. 82 (1) (1985) 270–283.

[17] A.D. Becke, Density-functional exchange-energy approximation with correct asymptotic behavior, Phys. Rev. 38 (6) (1988) 3098–3100.

[18] T. Thiruppathiraja, et al., H, OH and COOH functionalized magnesium electrocatalysts by bioinspired design, Nat. Commun. 12 (1) (2021) 12374.

[19] S. J. Lee, W. Yang, R.G. Parr, Development of the Colle-Salvetti correlation-energy formula into a functional of the electron density, Phys. Rev. B 37 (2) (1988) 446–448.

[20] C. Lee, W. Yang, R.G. Parr, Development of the Colle-Salvetti correlation-energy formula into a functional of the electron density, Phys. Rev. B 38 (2) (1988) 785–789.

[21] T. Thiruppathiraja et al., A proposal based on quantum phenomena for the ORR mechanism on nitrogen-doped carbon-based electrocatalysts, Int. J. Energ. 44 (24) (2019) 12674–12680.

[22] A. Legarreta-Mendoza, N. Flores-Holguín, D. Lardizabal-Gutierrez, A DFT study, Int. J. Hyd. Energy 44 (2019) 12374–12380.

[23] A. Legarreta-Mendoza, et al., A proposal based on quantum phenomena for the ORR mechanism on nitrogen-doped carbon-based electrocatalysts, Int. J. Hyd. Energ. 44 (2019) 12374–12380.

[24] A. Legarreta-Mendoza, et al., A proposal based on quantum phenomena for the ORR mechanism on nitrogen-doped carbon-based electrocatalysts, Int. J. Hyd. Energ. 44 (2019) 12374–12380.

[25] A. Legarreta-Mendoza, et al., A proposal based on quantum phenomena for the ORR mechanism on nitrogen-doped carbon-based electrocatalysts, Int. J. Hyd. Energ. 44 (2019) 12374–12380.

[26] A. Legarreta-Mendoza, et al., A proposal based on quantum phenomena for the ORR mechanism on nitrogen-doped carbon-based electrocatalysts, Int. J. Hyd. Energ. 44 (2019) 12374–12380.

[27] A. Legarreta-Mendoza, et al., A proposal based on quantum phenomena for the ORR mechanism on nitrogen-doped carbon-based electrocatalysts, Int. J. Hyd. Energ. 44 (2019) 12374–12380.