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Metal-free approach for imidazole synthesis via one-pot $N-\alpha-C(sp^3)-H$ bond functionalization of benzylamines†

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A metal-free one-pot method is established for the synthesis of tetrasubstituted imidazoles from the reaction of arylmethylamines and 1,2-dicarbonyls/benzoin. The $N-\alpha-C(sp^3)-H$ bond functionalization of arylmethylamines using a catalytic amount of AcOH afforded polysubstituted imidazoles under aerobic conditions in significant yields of up to 95%.

Introduction

The ever-growing influence of nitrogen heterocycles in pharmaceuticals has positioned these heterocycles in drug development and medicinal chemistry as key therapeutic agents.^{1–4} In particular,azole heterocycles have significant representation in different biological applications.⁵ Especially, five-membered imidazoles have a wide diversity of pharmaceutical importance.^{6–11} In addition, imidazole-based drug molecules such as apotzole, eprosartan, losartan and olmesartan have attracted the attention of chemists for designing bioactive molecules (Fig. 1).^{12–15} Furthermore, imidazole heterocycles have demonstrated various biological activities such as anti-fungal,¹⁶ antitumor,¹⁷ analgesic,¹⁸ antibacterial,¹⁹ anthelmintic,²⁰ anti-tuberculosis,²¹ and anti-inflammatory.²² Zeolite imidazole frameworks act as prominent materials and are exposed to potential applications such as host–guest chemistry, catalysis, luminescence, gas separation, gas sorption and magnetism.^{23,24} Moreover, they have anion and/or cation selectively functioning in different applications in asymmetric catalysis.^{25,26} In addition, these imidazoles have significant photophysical properties.^{27,28}

The traditional method for the synthesis of imidazoles is carried out through condensation of carbonyl molecules with ammonium salts. Different substrates such as aldehydes, nitriles, imines, amides, isocyanides, amidines, amino acids and benzylamines are used for the synthesis of trisubstituted imidazoles.^{29–34} Unfortunately, there are limited reports on tetrasubstituted imidazole synthesis. In particular, aldehyde, benzil, amine and NH_4OAc with acid catalysts were used for the synthesis of tetrasubstituted imidazole.^{35,36} Later, the

condensation of amidine and α -halo ketones was developed for tetrasubstituted imidazole synthesis using IBX as a strong oxidant.³⁷ Subsequently, Kevin Nguyen *et al.* demonstrated the synthesis of tetrasubstituted imidazoles from $CF_3CO_2NH_4$ and N -(2-oxo)-amide substrates at higher temperatures of up to 150 °C for the reaction.³⁸ Next, the sulphur-catalyzed cyclization reaction between ketones and aliphatic amines with a reaction time of up to 36 h was reported for tetrasubstituted imidazole synthesis.³⁹ Moreover, there are some methods for the synthesis of polysubstituted imidazoles constructed from benzils/benzoin and arylmethylamines using catalysts such as $Mo-ZnIn_2S_4$ photocatalysts,⁴⁰ $NiCl_2 \cdot 6H_2O/Ni(OAc)_2 \cdot 4H_2O$ ⁴¹ and Ag_2CO_3 .⁴² Earlier, 2,4,5-trisubstituted and tetrasubstituted imidazole synthesis was achieved using CuI and $FeCl_3$ catalysts.^{34,43,44} Biswadip Banerji *et al.* synthesized a series of tetrasubstituted imidazoles using excess K_2CO_3 (3.0 equiv.) as an additive and a I_2 catalyst.⁴⁵ As a result of a few shortcomings, such as the use of excess catalyst as well as the tedious process for catalyst design and product separation, the progress of a competent protocol is greatly providential for the synthesis of polysubstituted imidazoles.

In recent years, the utility of benzylic α -(sp^3)C–N bond functionalization has led to one of the most attractive strategies for the construction of complex molecules for preclinical research and discovery.⁴⁶ Moreover, amines play a crucial role in N-heterocycle design as a key building block.^{43,44,47–52} Herein, the AcOH-catalysed synthesis of tetrasubstituted imidazoles from benzylamines and 1,2-dicarbonyl/benzoin substrates using molecular oxygen as an oxidant was developed.

Results and discussion

At the outset, the reaction optimization commenced with benzylamine **1** (2.1 mmol) and benzil **2a** (1.0 mmol) substrates in the presence of AcOH (30 mol%) under air oxygen (O_2) (Table 1). Initially, different polar solvents such as BuOH, EtOH and

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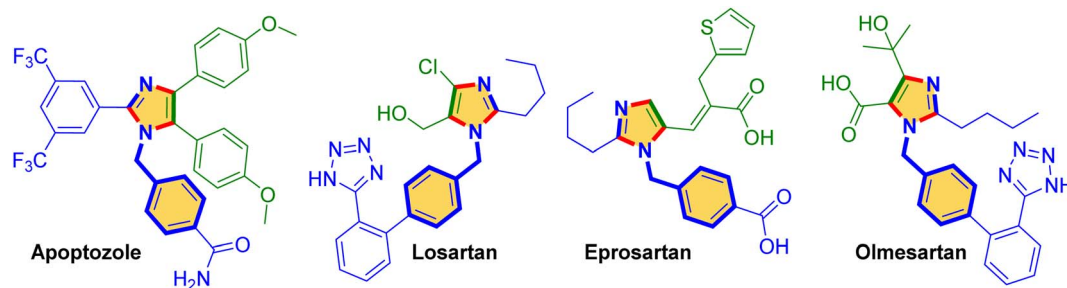


Fig. 1 Imidazole containing drug molecules.

Table 1 Optimization of reaction conditions^a

Entry	Solvent	Temp (°C)	Time (h)	Yield ^b (%)
1	BuOH	100	8	78
2	EtOH	80	8	65
3	MeOH	60	8	55
4	CH ₃ CN	80	8	60
5	1,4-Dioxane	100	8	62
6	Ethyl acetate	78	8	15
7	DMF	140	8	75
8	DMSO	140	8	72
9	Toluene	110	8	30
10	<i>o</i> -Xylene	130	8	56
11	Chlorobenzene	130	8	52
12	1,2-Dichlorobenzene	140	8	35
13	Neat	140	3	91
14	Neat	120	4	80
15	Neat	100	4	69
16 ^c	Neat	140	4	88
17 ^d	Neat	140	4	85
18 ^e	Neat	140	4	69
19 ^f	Neat	140	4	Trace

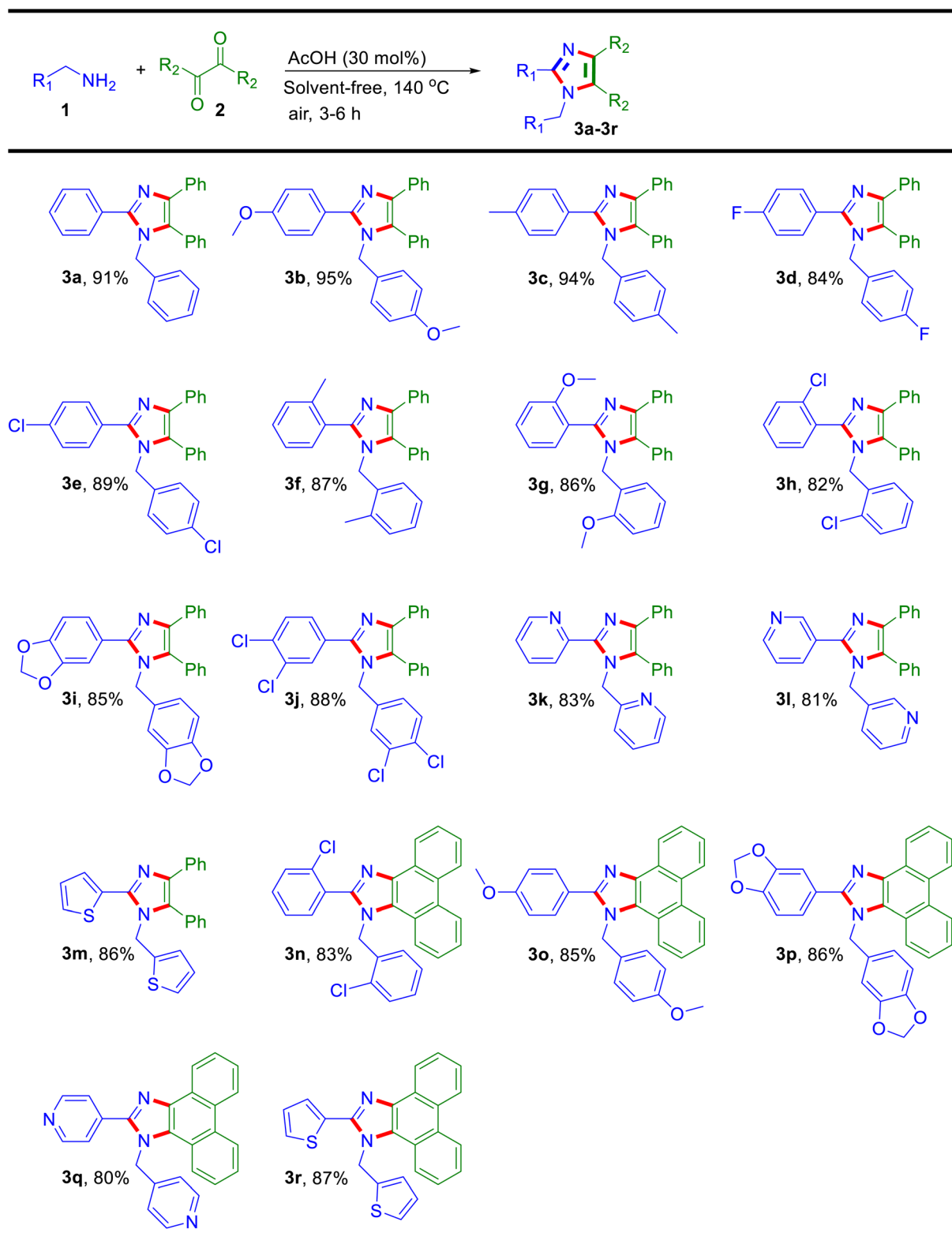
^a Reaction conditions: **1a** (2.1 mmol), **2a** (1.0 mmol), AcOH (30 mol%), and solvent (1 mL) in air O₂. ^b Isolated yield. ^c Reaction was carried out at 20 mol%. ^d Reaction was carried out at 15 mol%. ^e Reaction was carried out without air. ^f Under an N₂ atmosphere.

MeOH were examined considering green chemistry principles in which the tetrasubstituted imidazole product **3a** was obtained in 78%, 65% and 55% yields (Table 1, entries 1–3). From these results, further study was carried out with polar aprotic solvents such as CH₃CN, 1,4-dioxane, ethyl acetate, DMF and DMSO where the anticipated product **3a** was accomplished in yields of 60%, 62%, 15%, 75% and 72%, respectively (Table 1, entries 4–8). The reaction was further performed using non-polar solvents (such as toluene, *o*-xylene, chlorobenzene and 1,2-dichlorobenzene), affording lower yields of the desired product (Table 1, entries 9–12). After screening of polar and non-polar solvents, the reaction was examined at 140 °C under

solvent-free conditions where the formation of product **3a** was observed to be significant up to 91% of yield (Table 1, entry 13). Then, the same product **3a** was furnished in lower yields when the temperature study was carried out at 120 °C and 100 °C (Table 1, entries 14–15). Furthermore, the reaction investigation was performed with catalyst loadings such as 20 mol% and 15 mol% of AcOH under solvent-free conditions, in which product **3a** was obtained in slightly lower yields of 88% and 85%, respectively (Table 1, entries 16–17). At last, the product furnished up to 69% yield under anaerobic conditions, whereas the trace amount of the product obtained under N₂ conditions recognized the role of air oxygen in the reaction for the product formation (Table 1, entries 18–19). Finally, the best-optimized conditions for the formation of product **3a** under solvent-free conditions are benzylamine **1** (2.1 mmol) and benzil **2a** (1.0 mmol), AcOH (30 mol%) under air O₂ at 140 °C.

By using the optimized conditions, the finding of the reaction scope was broadly explored with substituted benzylamines and 1,2-dicarbonyls for the synthesis of polysubstituted imidazoles (Table 2). Initially, the reaction of benzil **2a** was studied with *para*-substituted benzylamines of electron-donating and electron-withdrawing functional groups, where the products **3a**, **3b**, **3c**, **3d** and **3e** were obtained in the yields of 91%, 95%, 94%, 84% and 89%, respectively. Then, *ortho*-substituted benzylamines were examined with benzil **2a** and afforded products **3f** (87%), **3g** (86%) and **3h** (82%) in excellent yields. After that, the disubstituted arylmethylamines were used to prepare tetrasubstituted products that were achieved in yields of **3i** (85%) and **3j** (88%). Also, the optimized conditions with heteroaryl benzylamines were found feasible for the synthesis of imidazoles as **3k** (83%), **3l** (81%) and **3m** (86%). Additionally, the substrate scope was further explored with substituted arylmethylamines using 9,10-phenanthrenequinone **2b** where the analogous products formed (**3n**: 83%, **3o**: 85% and **3p**: 86%) were in excellent yields. After that, heteroaryl methylamines were screened with 9,10-phenanthrenequinone **2b** and products were obtained (**3q**: 80% and **3r**: 87%) in significant yields (Table 2). There are a number of methods available for the synthesis of imidazoles using 1,2-diketones (benzil) but not from α -hydroxy ketone. Due to this, the optimized reaction conditions were tested against α -hydroxy ketones (benzoin) with different substituted arylmethylamines for the synthesis of imidazole, achieved in good to excellent yields as illustrated in Table 3. Here, the improved method has



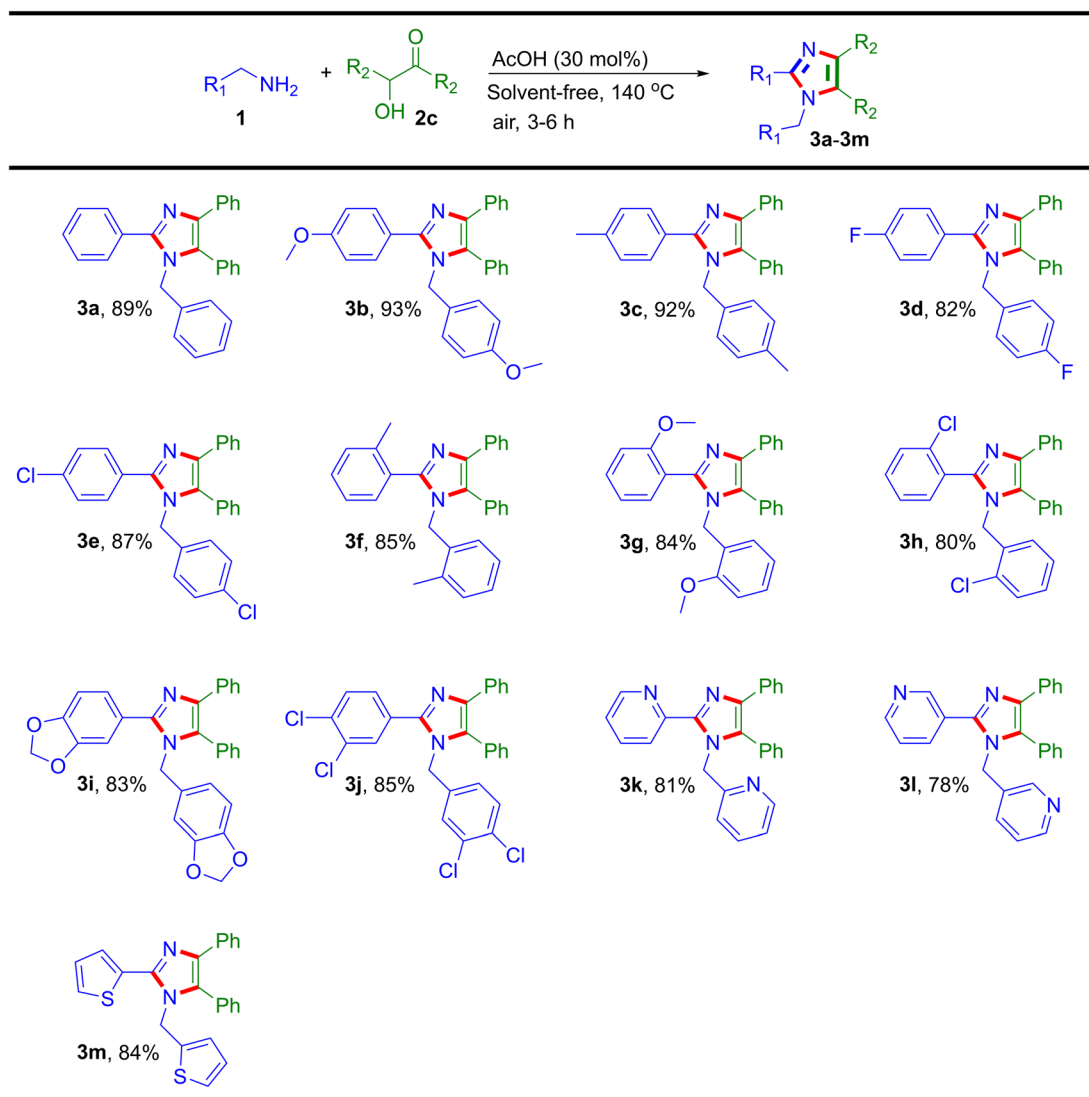
Table 2 Substrate scope of arylmethylamines with 1,2-dicarbonyls^a

^a Reaction conditions: 1 (2.1 mmol, 2.1 equiv.), 2 (1.0 mmol, 1.0 equiv.), AcOH (30 mol%), open air at 140 °C under neat condition for 3–6 h.

the utility to synthesize these polyfunctionalized imidazoles from both α -hydroxy ketone (benzoin) and 1,2-diketones (benzil) substrates by reacting with different arylmethylamines.

The mechanism of the reaction is proposed on the basis of literature and experimental results (Scheme 1).^{43,44,47} At first, the condensation of 1,2-diketone 2 with arylmethylamine 1 takes



Table 3 Substrate scope of arylmethylamines with benzoin^a

^a Reaction conditions: **1** (2.1 mmol, 2.1 equiv.), **2c** (1.0 mmol, 1.0 equiv.), AcOH (30 mol%), open air at 140 °C under neat condition for 3–6 h.

place, which gives intermediate **I** in the presence of a catalytic amount of AcOH. On the other hand, α -hydroxy ketone (benzoin) **2c** and arylmethylamine **1** condensation leads to the formation of intermediate **IV**, which is further converted into intermediate **V** to produce a similar intermediate **I** in the presence of an AcOH catalyst under aerobic conditions. Afterward, the 1,5-*H* shift of intermediate **I** produces intermediate **II**, which further cyclizes into **III** in the presence of AcOH. Lastly, the aerobic oxidation of intermediate **III** affords the anticipated product **3**.^{51,53}

Conclusions

In conclusion, the facile and convenient metal-free approach demonstrated the synthesis of polyfunctionalized imidazoles from simple starting materials. The formation of all products was achieved with good functional group tolerance, leading to further investigation towards designing different organic scaffolds.

Experimental section

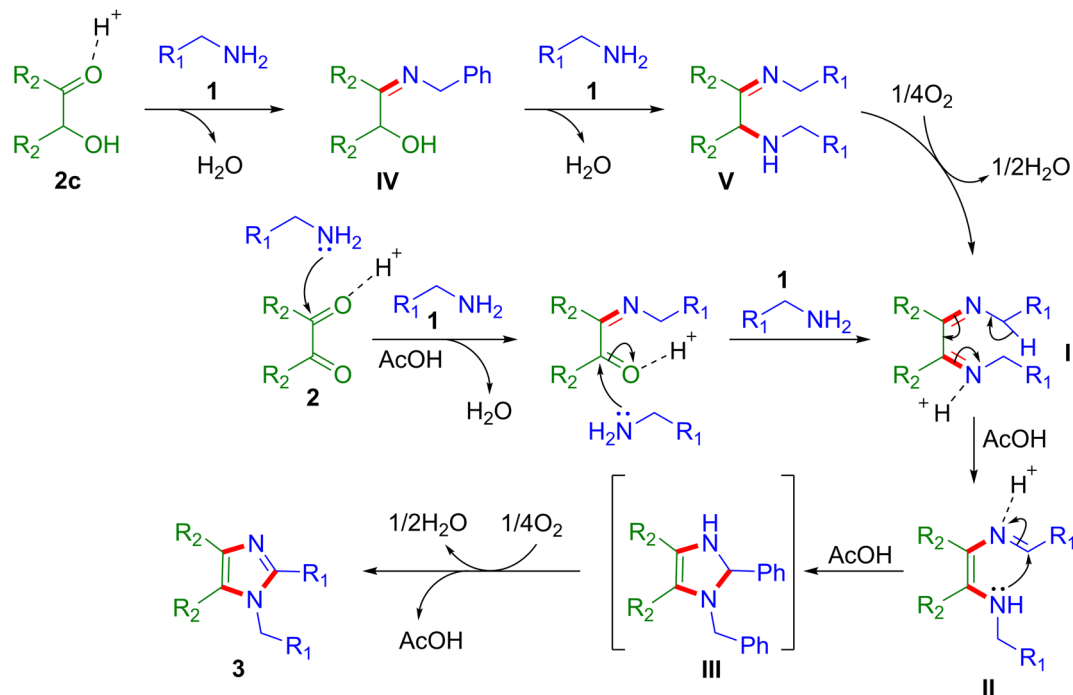
General information

The distilled solvents were used for performing reactions. The physical constants were recorded using the Buchi melting point apparatus and are uncorrected. By using silica gel plates (0.25 mm), thin-layer chromatography (TLC) was performed to study the reaction progress under a UV lamp. The synthesised compounds were analysed by NMR (¹H NMR at 400 MHz and ¹³C NMR at 100 MHz) on a JEOL NMR spectrometer and mass on 6530 Accurate-Mass Q-TOF LC/MS of Agilent Technologies.

General procedure for synthesis of tetrasubstituted imidazoles (**3**)

Arylmethylamine **1** (2.1 mmol), 1,2-diketone/benzoin **2** (1.0 mmol), and AcOH (30 mol%) were stirred at 140 °C temperature





Scheme 1 The possible reaction mechanism.

under solvent-free aerobic conditions in a 25 mL round bottom flask. The progress of the reaction was monitored by thin-layer chromatography (TLC). After completion of the reaction, the reaction mixture was cooled and poured into crushed ice. After that, the mixture was stirred and filtered to obtain the crude imidazole product 3. The purified imidazole product 3 was achieved by column chromatography using hexane/ethyl acetate as eluent.

Analysis data of the synthesised tetrasubstituted imidazoles

1-Benzyl-2,4,5-triphenyl-1H-imidazole (3a). M.P.: 165–166 °C; (Lit.⁴³ 163–166 °C); white solid; ¹H-NMR (400 MHz, DMSO-*D*₆) δ 7.62 (d, *J* = 4.3 Hz, 2H), 7.41 (q, *J* = 6.7 Hz, 8H), 7.27–7.14 (m, 8H), 6.72 (d, *J* = 6.7 Hz, 2H), 5.13 (s, 2H) ppm; ¹³C-NMR (400 MHz, DMSO-*D*₆) δ 147.6, 137.8, 137.4, 135.1, 131.4, 131.1, 130.7, 129.5, 129.4, 129.1, 128.6, 127.7, 126.8, 126.6, 126.2, 48.2 ppm.

1-(4-Methoxybenzyl)-2-(4-methoxyphenyl)-4,5-diphenyl-1H-imidazole (3b). M.P.: 155–157 °C; (Lit.⁴³ 153–155 °C); off-white solid; ¹H-NMR (400 MHz, CDCl₃): δ ¹H-NMR (400 MHz, DMSO-*D*₆) δ 7.55 (d, *J* = 8.6 Hz, 2H), 7.41–7.37 (m, 5H), 7.25 (d, *J* = 3.7 Hz, 2H), 7.16 (t, *J* = 7.6 Hz, 2H), 7.08 (t, *J* = 7.3 Hz, 1H), 6.97 (d, *J* = 8.6 Hz, 2H), 6.72 (d, *J* = 8.6 Hz, 2H), 6.62 (d, *J* = 8.6 Hz, 2H), 5.02 (s, 2H), 3.75 (s, 3H), 3.62 (s, 3H) ppm; ¹³C-NMR (400 MHz, DMSO-*D*₆) δ 160.1, 158.8, 147.5, 137.1, 135.2, 131.4, 130.5, 130.3, 129.8, 129.4, 129.3, 128.6, 127.4, 126.6, 123.7, 114.6, 114.5, 55.8, 55.5, 47.6 ppm.

1-(4-Methylbenzyl)-4,5-diphenyl-2-*p*-tolyl-1H-imidazole (3c). M.P.: 131–134 °C (Lit.⁴³ 132–134 °C); white solid; ¹H-NMR (400 MHz, DMSO-*D*₆) δ 7.51 (d, *J* = 7.9 Hz, 2H), 7.42–7.38 (m, 5H), 7.26–7.15 (m, 6H), 7.09 (t, *J* = 7.0 Hz, 1H), 6.97 (d, *J* = 7.3 Hz, 2H), 6.61 (d, *J* = 7.9 Hz, 2H), 5.06 (s, 2H), 2.29 (s, 3H), 2.16 (s,

3H) ppm; ¹³C-NMR (100 MHz, DMSO-*D*₆) δ 147.6, 138.8, 137.3, 136.8, 135.2, 135.0, 131.4, 131.2, 130.6, 129.7, 129.6, 129.4, 129.3, 128.9, 128.6, 128.5, 126.7, 126.6, 126.0, 47.9, 21.4, 21.1 ppm.

1-(4-Fluorobenzyl)-2-(4-fluorophenyl)-4,5-diphenyl-1H-imidazole (3d). M.P.: 161–163 °C (Lit.⁴³ 159–162 °C); white solid; ¹H-NMR (400 MHz, DMSO-*D*₆) δ 7.68–7.64 (m, 2H), 7.41 (d, *J* = 9.2 Hz, 5H), 7.26 (t, *J* = 8.6 Hz, 4H), 7.17 (t, *J* = 7.6 Hz, 2H), 7.10 (t, *J* = 7.0 Hz, 1H), 6.97 (t, *J* = 8.6 Hz, 2H), 6.73 (t, *J* = 6.4 Hz, 2H), 5.08 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-*D*₆) δ 164.1, 162.9, 161.6, 160.5, 146.7, 137.4, 134.9, 133.8, 131.4, 131.3, 131.0, 130.7, 129.5, 129.5, 128.6, 128.4, 128.3, 127.8, 127.8, 126.8, 126.6, 116.3, 116.0, 116.0, 115.8, 47.6 ppm.

1-(4-Chlorobenzyl)-2-(4-chlorophenyl)-4,5-diphenyl-1H-imidazole (3e). M.P.: 158–160 °C (Lit.⁴³ 159–162 °C); white solid; ¹H-NMR (400 MHz, DMSO-*D*₆) δ 7.64 (d, *J* = 7.9 Hz, 2H), 7.48 (d, *J* = 8.6 Hz, 2H), 7.43–7.39 (m, 5H), 7.28 (d, *J* = 3.7 Hz, 1H), 7.23–7.16 (m, 4H), 7.11 (t, *J* = 7.3 Hz, 1H), 6.75 (d, *J* = 8.6 Hz, 2H), 5.11 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-*D*₆) δ 146.4, 137.7, 136.6, 134.8, 134.2, 132.3, 131.3, 131.0, 130.9, 130.7, 130.0, 129.6, 129.3, 129.1, 128.6, 128.1, 126.9, 126.6, 47.7 ppm.

1-(2-Methylbenzyl)-2-(2-methylphenyl)-4,5-diphenyl-1H-imidazole (3f). M.P.: 178–180 °C; brown solid; ¹H-NMR (400 MHz, DMSO-*D*₆) δ 7.42 (d, *J* = 7.3 Hz, 2H), 7.37–7.33 (m, 4H), 7.29–7.25 (m, 4H), 7.17 (t, *J* = 7.3 Hz, 3H), 7.09 (t, *J* = 7.3 Hz, 1H), 7.03–6.96 (m, 2H), 6.88 (d, *J* = 7.3 Hz, 1H), 6.47 (d, *J* = 6.7 Hz, 1H), 4.84 (s, 2H), 2.21 (s, 3H), 1.75 (s, 3H) ppm; ¹³C-NMR (100 MHz, DMSO-*D*₆) δ 147.4, 138.4, 136.9, 135.9, 135.2, 134.5, 131.2, 130.9, 130.5, 130.2, 129.7, 129.4, 129.2, 128.6, 127.4, 126.7, 126.5, 126.1, 125.8, 45.5, 20.0, 18.7 ppm; HRMS: *m/z* [M + H]⁺ calcd for C₃₀H₂₆N₂: 415.2096; found: 415.2182.



1-(2-Methoxybenzyl)-2-(2-methoxyphenyl)-4,5-diphenyl-1H-imidazole (3g). M.P.: 135–136 °C; (Lit.⁴³ 132–134 °C); yellow solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 7.37 (d, *J* = 12.2 Hz, 7H), 7.21–6.94 (m, 8H), 6.69 (d, *J* = 6.7 Hz, 2H), 6.40 (d, *J* = 6.1 Hz, 1H), 4.82 (s, 2H), 3.71 (s, 3H), 3.48 (s, 3H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 157.6, 156.0, 145.8, 137.1, 135.3, 132.6, 131.4, 131.4, 131.2, 129.9, 129.4, 129.1, 128.7, 128.6, 127.0, 126.5, 125.5, 120.9, 120.6, 112.0, 110.8, 55.9, 55.7, 43.1 ppm.

1-(2-Chlorobenzyl)-2-(2-chlorophenyl)-4,5-diphenyl-1H-imidazole (3h). M.P.: 143–145 °C (Lit.⁴³ 142–144 °C); white solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 7.55 (d, *J* = 7.9 Hz, 1H), 7.50 (d, *J* = 7.3 Hz, 1H), 7.46–7.33 (m, 6H), 7.28 (d, *J* = 6.7 Hz, 2H), 7.20–7.09 (m, 7H), 6.64 (d, *J* = 7.3 Hz, 1H), 4.95 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 145.2, 137.3, 134.8, 134.3, 134.0, 133.0, 131.9, 131.2, 131.2, 130.7, 130.3, 130.2, 130.0, 129.6, 129.5, 128.7, 128.2, 127.9, 127.8, 126.9, 126.5, 45.8 ppm.

2-(Benzo[d][1,3]dioxol-5-yl)-1-(benzo[d][1,3]dioxol-5-ylmethyl)-4,5-diphenyl-1H-imidazole (3i). M.P.: 178–180 °C (Lit.⁴³ 175–177 °C); white solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 7.44–7.34 (m, 6H), 7.29–7.24 (m, 2H), 7.18–7.14 (m, 3H), 7.10 (t, *J* = 7.0 Hz, 1H), 6.96 (d, *J* = 7.9 Hz, 1H), 6.69 (d, *J* = 7.9 Hz, 1H), 6.24 (s, 1H), 6.13 (d, *J* = 7.9 Hz, 1H), 6.04 (s, 2H), 5.89 (s, 2H), 4.99 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 148.3, 147.9, 147.3, 146.8, 137.1, 135.1, 131.7, 131.3, 131.2, 130.4, 129.5, 129.4, 128.7, 128.6, 126.7, 126.6, 125.1, 123.2, 119.5, 109.4, 109.0, 108.7, 106.7, 101.9, 101.6, 47.9 ppm.

1-(3,4-Dichlorobenzyl)-2-(3,4-dichlorophenyl)-4,5-diphenyl-1H-imidazole (3j). M.P.: 160–163 °C (Lit.⁴³ 158–161 °C); white solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 7.87 (d, *J* = 1.2 Hz, 1H), 7.69 (d, *J* = 8.6 Hz, 1H), 7.59 (dd, *J* = 7.9, 1.8 Hz, 1H), 7.43–7.41 (m, 6H), 7.28 (d, *J* = 3.7 Hz, 2H), 7.18 (t, *J* = 7.3 Hz, 2H), 7.12 (t, *J* = 7.3 Hz, 1H), 6.98 (s, 1H), 6.70 (d, *J* = 8.6 Hz, 1H), 5.14 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 145.1, 138.5, 137.9, 134.6, 132.3, 132.0, 131.7, 131.5, 131.4, 131.3, 130.8, 130.6, 130.5, 129.7, 129.7, 129.0, 128.7, 128.7, 127.1, 126.7, 47.5 ppm.

2-(4,5-Diphenyl-1-(pyridin-2-ylmethyl)-1H-imidazole-2-yl)pyridine (3k). M.P.: 166–168 °C (Lit.⁴³ 165–167 °C); light yellow solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 8.94–8.87 (m, 1H), 8.81 (d, *J* = 8.6 Hz, 1H), 8.60 (d, *J* = 7.9 Hz, 1H), 8.45 (d, *J* = 7.9 Hz, 1H), 8.36 (d, *J* = 7.3 Hz, 1H), 8.08 (d, *J* = 7.9 Hz, 1H), 7.81–7.68 (m, 3H), 7.64–7.50 (m, 1H), 7.22–7.17 (m, 2H), 7.05 (d, *J* = 7.9 Hz, 1H), 6.79–6.72 (m, 1H), 6.46 (d, *J* = 7.9 Hz, 1H), 6.16–6.11 (m, 1H), 6.09–6.03 (m, 1H), 5.95 (s, 1H), 5.78 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 152.9, 148.5, 148.1, 147.2, 137.5, 131.4, 130.0, 129.0, 128.3, 127.8, 127.5, 126.8, 126.2, 125.6, 124.3, 124.1, 122.7, 121.8, 121.1, 119.1, 110.0, 109.1, 107.2, 106.6, 102.2, 50.3 ppm.

3-(4,5-Diphenyl-1-(pyridin-3-ylmethyl)-1H-imidazole-2-yl)pyridine (3l). M.P.: 190–192 °C; faint yellow solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 8.85 (s, 1H), 8.58 (d, *J* = 3.7 Hz, 1H), 8.30 (d, *J* = 3.1 Hz, 1H), 8.04 (d, *J* = 7.9 Hz, 1H), 7.91 (s, 1H), 7.44–7.31 (m, 8H), 7.21–7.11 (m, 5H), 5.14–5.28 (2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 150.3, 149.5, 149.1, 147.9, 144.9, 138.0, 136.4, 134.7, 134.2, 133.0, 131.3, 131.3, 130.7, 129.7, 128.7, 127.3, 127.0, 126.7, 124.2, 46.2 ppm; HRMS: *m/z* [M + H]⁺ calcd for C₂₆H₂₀N₄: 389.1688; found: 389.1774.

4,5-Diphenyl-2-(thiophen-2-yl)-1-(thiophen-2-ylmethyl)-1H-imidazole (3m). M.P.: 170–173 °C (Lit.⁴³ 169–171 °C); white solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 7.62 (d, *J* = 6.1 Hz, 1H), 7.44–7.36 (m, 10H), 7.17–6.83 (m, 4H), 6.55 (d, *J* = 5.5 Hz, 1H), 5.36 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 141.5, 140.0, 137.6, 134.6, 133.1, 131.5, 130.7, 130.5, 129.7, 129.6, 128.7, 128.5, 128.3, 127.6, 127.0, 126.7, 126.5, 126.3, 125.8, 44.1 ppm.

1-(2-Chlorobenzyl)-2-(2-chlorophenyl)-1H-phenanthro[9,10-*d*]imidazole (3n). M.P.: 185–187 °C; dark brown solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 8.96–8.91 (m, 1H), 8.85 (d, *J* = 6.7 Hz, 2H), 8.58 (d, *J* = 7.9 Hz, 1H), 8.31 (t, *J* = 7.9 Hz, 1H), 7.87 (d, *J* = 8.6 Hz, 1H), 7.66 (t, *J* = 7.9 Hz, 2H), 7.60 (t, *J* = 6.4 Hz, 2H), 7.47 (t, *J* = 6.1 Hz, 2H), 7.36–7.29 (m, 1H), 7.23 (t, *J* = 7.9 Hz, 1H), 7.08 (d, *J* = 8.6 Hz, 1H), 6.56 (d, *J* = 7.9 Hz, 1H), 5.72 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 141.8, 133.9, 131.4, 130.9, 130.6, 129.6, 128.5, 127.8, 127.8, 127.3, 126.9, 126.9, 126.6, 126.2, 126.1, 125.3, 124.8, 124.5, 124.4, 123.5, 123.2, 42.4; HRMS: *m/z* [M + H]⁺ calcd for C₂₈H₁₈Cl₂N₂: 453.0847; found: 453.0925.

1-(4-Methoxybenzyl)-2-(4-methoxyphenyl)-1H-phenanthro[9,10-*d*]imidazole (3o). M.P.: 123–125 °C (Lit.⁴² 122–124 °C); white solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 8.87–8.61 (m, 4H), 8.26–8.08 (m, 1H), 7.71–7.47 (m, 5H), 7.06–6.86 (m, 6H), 5.82 (s, 2H), 3.79 (s, 3H), 3.65 (s, 3H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 158.2, 157.5, 153.9, 137.6, 132.3, 131.2, 129.4, 129.4, 129.3, 129.3, 127.5, 127.5, 127.4, 127.4, 127.2, 127.1, 126.1, 122.5, 115.1, 114.9, 114.9, 114.8, 114.7, 55.9, 55.6, 45.3 ppm; HRMS: *m/z* [M + H]⁺ calcd for C₃₀H₂₄N₂O₂: 445.1838; found: 445.1919.

2-(Benzo[d][1,3]dioxol-5-yl)-1-(benzo[d][1,3]dioxol-5-ylmethyl)-1H-phenanthro[9,10-*d*]imidazole (3p). M.P.: 270–272 °C; brown solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 9.48 (d, *J* = 1.2 Hz, 1H), 8.93 (t, *J* = 9.5 Hz, 1H), 8.89 (s, 1H), 8.82 (d, *J* = 8.6 Hz, 1H), 8.78 (d, *J* = 3.7 Hz, 1H), 8.71 (d, *J* = 4.3 Hz, 1H), 8.63 (d, *J* = 7.3 Hz, 1H), 8.48 (d, *J* = 7.9 Hz, 1H), 8.43–8.38 (m, 1H), 8.11 (d, *J* = 7.3 Hz, 1H), 7.84–7.71 (m, 3H), 7.68–7.63 (m, 1H), 7.58–7.55 (m, 1H), 7.50 (t, *J* = 7.3 Hz, 1H), 7.38 (d, *J* = 7.9 Hz, 1H), 7.27 (dd, *J* = 7.3, 4.9 Hz, 1H), 6.00 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 152.4, 151.1, 150.2, 149.4, 148.3, 147.9, 137.4, 134.8, 134.0, 133.1, 128.5, 128.0, 127.9, 127.7, 127.3, 126.5, 126.0, 124.9, 124.6, 124.3, 124.2, 122.9, 121.7, 121.4, 48.6 ppm; HRMS: *m/z* [M + H]⁺ calcd for C₃₀H₂₀N₂O₄: 473.1423; found: 473.1517.

2-(Pyridin-4-yl)-1-(pyridin-4-ylmethyl)-1H-phenanthro[9,10-*d*]imidazole (3q). M.P.: 210–212 °C; brown solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 8.90 (t, *J* = 9.5 Hz, 2H), 8.36 (d, *J* = 7.3 Hz, 2H), 8.20 (d, *J* = 6.7 Hz, 2H), 7.76–7.70 (m, 9H), 7.01 (s, 2H) ppm; ¹³C-NMR (100 MHz, DMSO-D₆) δ 146.9, 144.4, 142.0, 134.1, 133.6, 129.1, 128.9, 128.8, 128.4, 128.3, 127.2, 127.1, 126.8, 125.9, 125.5, 125.0, 124.8, 124.6, 122.7, 120.9, 120.8, 118.1, 45.6 ppm; HRMS: *m/z* [M + H]⁺ calcd for C₂₆H₁₈N₄: 387.1531; found: 387.1625.

2-(Thiophen-2-yl)-1-(thiophen-2-ylmethyl)-1H-phenanthro[9,10-*d*]imidazole (3r). M.P.: 258–262 °C; brown solid; ¹H-NMR (400 MHz, DMSO-D₆) δ 8.95–8.89 (m, 1H), 8.81 (d, *J* = 8.6 Hz, 1H), 8.57 (d, *J* = 7.9 Hz, 1H), 8.31–8.26 (m, 1H), 7.80 (d, *J* = 4.3 Hz, 1H), 7.77–7.68 (m, 1H), 7.65 (d, *J* = 7.3 Hz, 1H), 7.62–7.55 (m, 3H), 7.45 (t, *J* = 5.2 Hz, 1H), 7.21 (t, *J* = 4.3 Hz, 1H), 6.97 (t, *J*



= 4.0 Hz, 2H), 6.21 (s, 2H) ppm; ^{13}C -NMR (100 MHz, DMSO- D_6) δ 140.2, 139.1, 129.9, 129.0, 128.8, 128.3, 128.2, 128.1, 128.0, 127.7, 127.2, 126.9, 126.5, 126.5, 125.9, 125.7, 125.0, 124.1, 122.9, 122.8, 122.5, 121.8, 121.1, 47.3 ppm; HRMS: m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{24}\text{H}_{16}\text{N}_2\text{S}_2$: 397.0755; found: 397.0839.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

There are no conflicts to declare.

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