Oxidative transformation of N-substituted 2-aminophenols to 2-substituted benzoxazoles catalyzed by polymer-incarcerated and carbon-stabilized platinum nanoclusters

Woo-Jin Yoo, Hao Yuan, Hiroyuki Miyamura, and Shū Kobayashi

Abstract: The preparation of 2-substituted benzoxazoles was achieved through a sequential aerobic oxidation – enolization – oxidative cyclization reaction of N-substituted 2-aminophenols catalyzed by platinum nanoclusters supported on a polymer / carbon black composite material.

Key words: nanoparticles, platinum, oxidation, polymers, supported catalysis.

Résumé : La synthèse de benzoxazoles substitués en position 2 a été réalisée à partir de 2-aminophénols N-substitués à l'aide d'une séquence réactionnelle oxydation aérobie – énolisation – cyclisation oxydante catalysée par des nanoclusters de platine supportés sur un matériau composite polymère / noir de charbon.

Mots-clés : nanoparticules, platine, oxydation, polymères, catalyse supportée.

Introduction

The development of novel strategies for the efficient synthesis of compounds of high molecular complexity in an expedient manner is of great interest to the synthetic organic community. The utilization of catalysts for sequential reactions circumvents the necessary drain of resources caused by the act of isolation and purification of intermediates faced by traditional iterative synthetic methods.[1] Furthermore, the ability to perform one-pot tandem reactions would allow for the formation and use of highly reactive and (or) unstable intermediates in organic synthetic schemes. Whereas most sequential reactions are performed with homogenous catalysts, the use of heterogeneous catalysts would improve the synthetic utility of cascade reactions by facilitating its recovery and subsequent reuse. In addition to the ease of separation from the reaction mixture, heterogeneous systems for multicatalytic sequential reactions would allow for the use of mutually incompatible catalysts to coexist because of the site isolation of the catalytic species caused by the heterogeneous support.[2]

With our ongoing interest in the preparation of highly active immobilized metal catalysts, we have reported an efficient method for the immobilization of metal catalysts with styrene-based co-polymers through a process known as the polymer-incarcerated (PI) method.[3] We have demonstrated that various gold, platinum, and gold–bimetallic nanoclusters could be stabilized and immobilized by the polymer support and act as highly active heterogeneous catalysts for the aerobic oxidation of alcohols[4] and hydroquinones[5] under ambient pressure and temperature. Furthermore, these PI metal nanoclusters were utilized as catalysts for tandem reactions such as the oxidative esterification of alcohols[6] and sequential allylic oxidation – Michael addition reactions between 1,3-dicarbonyl compounds and allylic alcohols.[7]

As part of our continuing effort into developing aerobic oxidative reactions catalyzed by PI metal nanoclusters, we recently reported the use of platinum nanoclusters immobilized on a polymer / carbon black composite material (PI/CB–Pt) as an effective catalyst for the oxidative cyclization of phenolic and thiophenolic imines **1** to 2-substituted benzoxazoles and benzothiazoles **2** under ambient conditions (Scheme 1, eq. [1]).[8]

During the course of the aerobic oxidative cyclization reaction, we found trace amounts of *ortho*-quinones in the crude reaction mixture and believed these species to arise from the hydrolysis of *ortho*-quinone/thioquinone imines derived from the aerobic oxidation of 2-aminophenols/thiophenols. In a related work, Jiang et al.[9] described a *tert*-butyl hydroperoxide (TBHP) / I_2-mediated domino oxidative cyclization reaction with alkenes **3** and benzyl amines **4** to prepare polysubstituted oxazoles **5** (Scheme 1, eq. [2]). In their proposed mechanism, α-keto imine intermediate **6** was believed to enolize to **7** and was subsequently transformed to their desired oxazole **5** via cyclization and oxidation reactions. Inspired by the work of Jiang et al., we envisioned a similar mechanistic scenario in which N-substituted aminophenols **8** could be oxidatively converted to 2-substituted benzoxazoles **9** (Scheme 1, eq. [3]). Assuming that the PI/CB–Pt catalyst could oxidize **8** to *ortho*-quinone imine **10**, the enolization to phenolic

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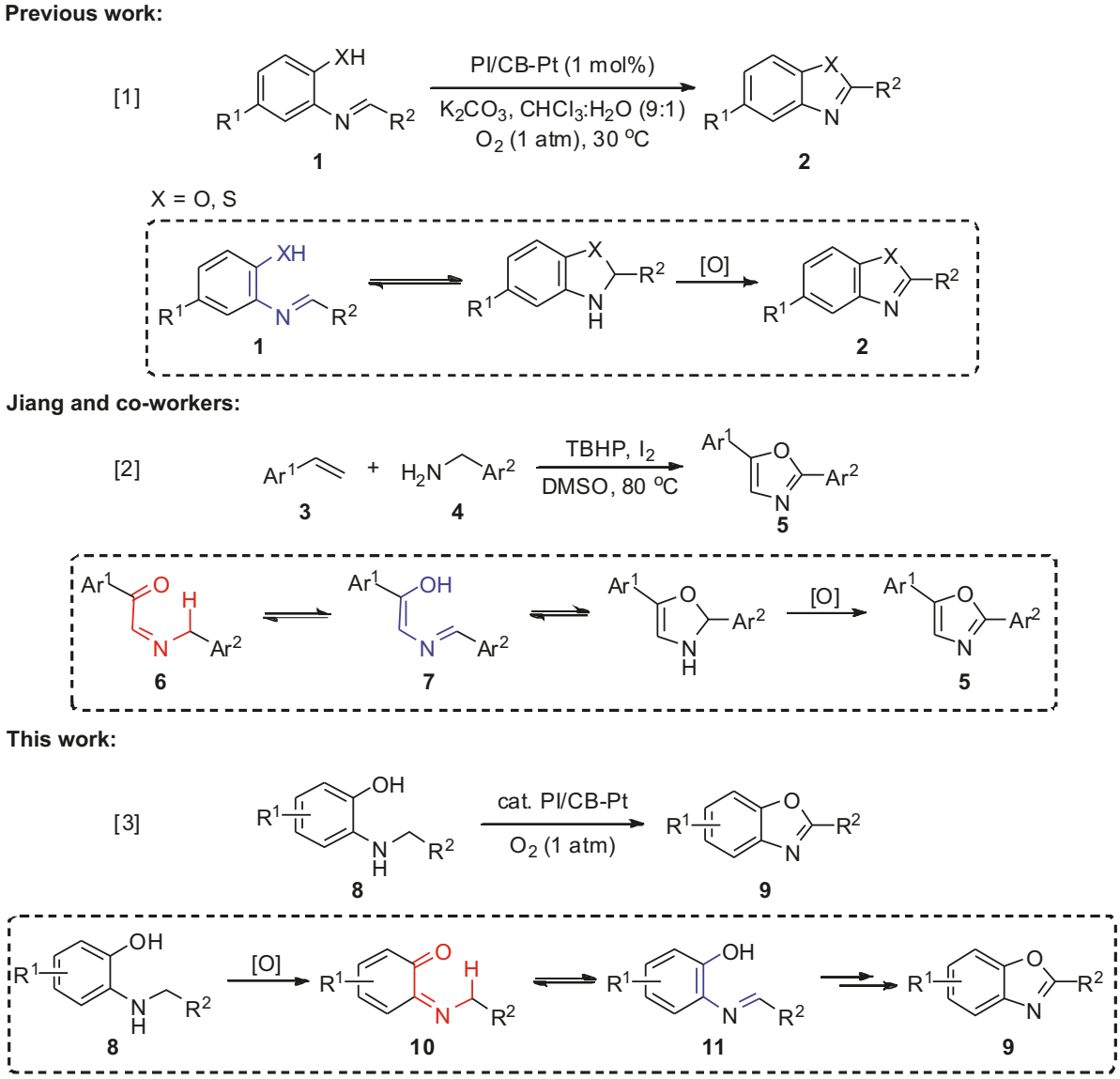
Scheme 1. Oxidative preparation of oxazoles.



imine **11** should be highly favorable because of the rearomatization of the benzene ring.

In this paper, we report the preparation of benzoxazoles **9** from N-substituted 2-aminophenols **8** under mild aerobic oxidative conditions through a tandem reaction consisting of an aerobic oxidation – enolization – oxidative cyclization sequence catalyzed by polymer-supported platinum nanoclusters.

Results and discussion

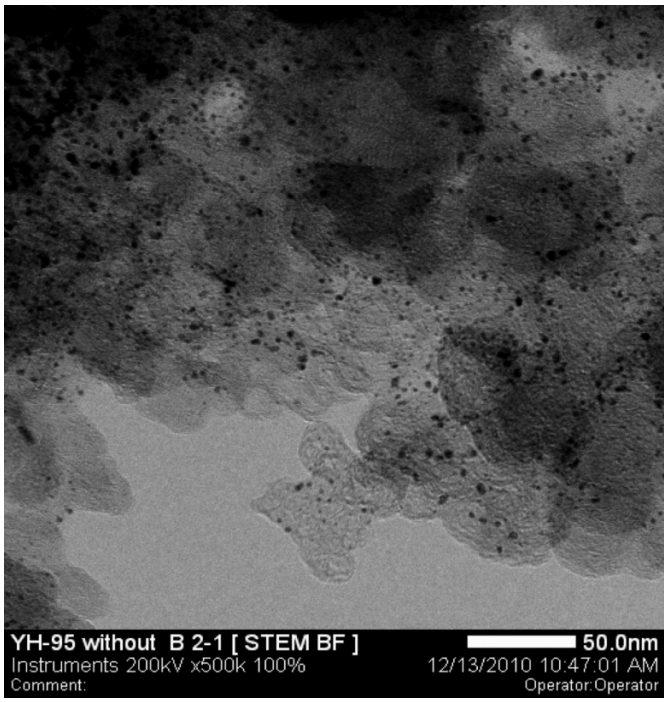
We began our studies by preparing PI/CB–Pt catalyst (Pt particle size = 2.1 ± 0.7 nm; Fig. 1) following our previously reported procedure (Scheme 2) and attempted to perform the sequential oxidative transformation of aminophenol **8a** to 2-substituted benzoxazole **9a** (Table 1).

However, our initial attempts to synthesize benzoxazole **9a** by applying our previous conditions for the oxidative cyclization reaction failed, and only trace amounts of the desired product **9a** was observed (Table 1, entry 1). Since **8a** was fully converted and *ortho*-quinone was observed in the crude reaction mixture, we attributed this disappointing result to the relative instability of the reactive *ortho*-quinone imine intermediate. Thus, by introducing a substituent group to the aromatic ring of the aminophenol (**8b**) to stabilize the intermediate, 2-substituted benzoxazole **9b** was obtained with a poor yield (Table 1, entry 2). We found that, by diluting the reaction mixture (Table 1, entry 3) and reducing the amount of water (Table 1, entry 4), a modest improvement for the sequential oxidative transformation of **8b** was provided. However, it should be noted that water plays an important role and excluding water from the system reduces the ability of PI/CB–Pt to catalyze the aerobic oxidation reactions (Table 1, entry 5).

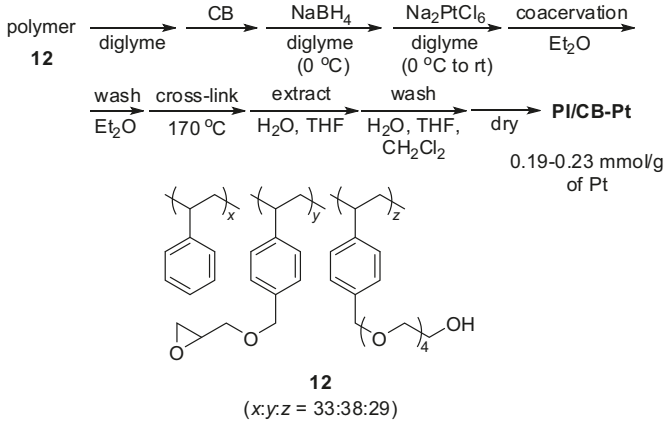
Next, we examined the scope of the tandem oxidative transformation reaction of N-substituted 2-aminophenols **8b**–**8l** (Table 2).

We initially examined the effect of the substituents on the aromatic ring of the 2-aminophenols and found that, by adjusting the position of the methyl group to be para to the

Fig. 1. Typical STEM image of platinum nanoclusters immobilized on a polymer / carbon black composite material (PI/CB–Pt).



Scheme 2. Synthetic procedure for the preparation of platinum nanoclusters immobilized on a polymer / carbon black composite material (PI/CB–Pt).



12
(*x*:*y*:*z* = 33:38:29)

amine (**8c**), an improvement of the yield for benzoxazole **9c** (Table 2, entry 2) resulted, whereas the introduction of a more stabilizing group (*t*-Bu) lead to the quantitative conversion of **8d** to benzoxazole **9d** (Table 2, entry 3). Various 2-aryl benzoxazoles **9e**–**9h** bearing electron-rich and -poor substituents were prepared through the sequential oxidative transformation of N-substituted 2-aminophenols **8e**–**8h** with excellent yields (Table 2, entries 4–7). The synthesis of benzoxazoles with alkenyl (**9i**) and alkynyl (**9j**) substituents was achieved in moderate yields, but required a stoichiometric amount of base (Table 2, entries 8 and 9). Finally, benzoxazoles that possessed a primary aliphatic substituent at the 2-position (**9k** and **9l**) were prepared under our optimized reaction conditions with good results (Table 2, entries 10 and 11).

A tentative mechanism for the sequential oxidative transformation of N-substituted 2-aminophenols **8** to benzoxazoles **9** is shown in Scheme 3.

Based on our previous observations of the conversion of 2-aminophenols to *ortho*-quinones, we envisioned a reaction pathway in which N-substituted 2-aminophenol **8** would be oxidized to the corresponding *ortho*-quinone imine **10**, catalyzed by PI/CB–Pt. The facile enolization of **10** to phenolic imine **11** would restore aromaticity to the system and, after oxidative cyclization, would provide the desired benzoxazole **9**. Although the direct oxidation of **8** to **11** is a distinct possibility, this reaction pathway was discounted, since aerobic oxidation of amines to imines with metal nanoclusters is relatively difficult and requires high reaction temperatures.[10]

We also examined the possibility of an aerobic oxidation of **8** in the absence of the platinum catalyst. We performed control studies in which aminophenol **8d** was subjected to our optimized reaction conditions in the absence of PI/CB–Pt and also with our hybrid polymer / carbon black support material without platinum nanoclusters. In both cases, only trace amounts of **10** and **11** were detected by ^{1}H NMR of the crude reaction mixture.

Finally, we examined the possibility of recovery and reuse of our PI/CB–Pt catalyst for the sequential oxidative transformation of **8d**, and found that the catalyst could be reused for five cycles without noticeable loss of catalytic activity (Scheme 4).

Conclusion

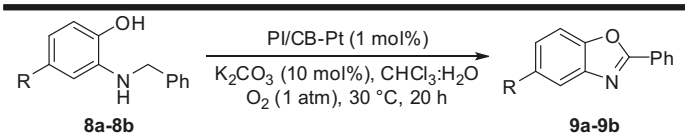
In summary, we have developed a sequential aerobic oxidation – enolization – oxidative cyclization reaction of N-substituted 2-aminophenols to 2-substituted benzoxazoles catalyzed by platinum nanoclusters supported on a polymer / carbon black composite material. The reaction was shown to be remarkably mild and could be utilized to prepare 2-substiuted benzoxazoles with aryl, alkenyl, alkynyl, and aliphatic groups. Further investigations into improving the substrate scope and exploring additional oxidative methods towards the preparation of aromatic heterocycles are now in progress.

Experimental

Preparation method for PI/CB–Pt

Ketjen black (0.3751 g) was added to a solution of polymer **12** (0.3751 g) in diglyme (25 mL). After stirring the heterogeneous solution for 15 min, a solution of $NaBH_4$ (95.3 mg, 2.52 mmol) in diglyme (5.4 mL) was added dropwise, then a solution of $Na_2PtCl_6{\cdot}6H_2O$ (117.8 mg, 0.21 mmol) in diglyme (15 mL) was added dropwise at 0 °C. After stirring for 4 h at room temperature, Et_2O (200 mL) was added dropwise. The polymer-coated carbon black was washed several times with Et_2O and dried at room temperature. After light grinding with a motor and pestle, the recovered solid powder was heated at 170 °C for 4 h under a balloon of argon. After cooling to room temperature, the cross-linked polymer-coated carbon black was stirred in a THF–H_2O (1:1, 40 mL) mixture overnight. After being filtered and then washed with H_2O, tetrahydrofuran (THF), and dichloromethane (DCM), the recovered solid was dried

Table 1. Optimization of reaction conditions.



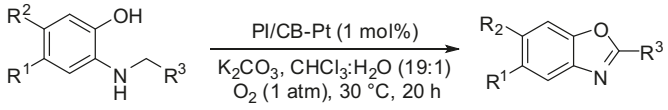
8a-8b **9a-9b**

Entry	Aminophenol	R	Ratio of $CHCl_3$–H_2O	Conc. (mol/L)	Product	Yield (%)[a]
1	**8a**	H	9:1	0.25	**9a**	<5
2	**8b**	Me	9:1	0.25	**9b**	28
3	**8b**	Me	9:1	0.05	**9b**	35
4	**8b**	Me	19:1	0.05	**9b**	48
5	**8b**	Me	1:0	0.05	**9b**	28

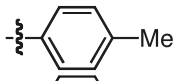
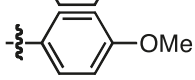
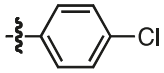
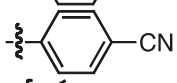
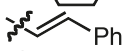
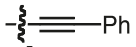
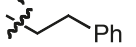
Note: Aminophenols **8a** and **8b** (0.25 mmol), K_2CO_3 (0.025 mmol), and platinum nanoclusters immobilized on a polymer / carbon black composite material (PI/CB–Pt) catalyst (1 mol%) in $CHCl_3$–H_2O at 30 °C under a balloon pressure of oxygen gas.

[a]Yield based on **8a** and **8b** and determined by ^{1}H NMR analysis of the crude reaction mixture using 1,1,2,2-tetrachloroethane as an internal standard.

Table 2. Substrate scope of the sequential oxidative transformation of N-substituted 2-aminophenols.



8b-8l **9b-9l**

Entry	Aminophenol	R^1	R^2	R^3	Product	Yield (%)[a]
1	**8b**	Me	H	Ph	**9b**	31
2	**8c**	H	Me	Ph	**9c**	65
3	**8d**	*t*-Bu	H	Ph	**9d**	Quant.
4	**8e**	*t*-Bu	H		**9e**	90
5	**8f**	*t*-Bu	H		**9f**	97
6	**8g**	*t*-Bu	H		**9g**	87
7	**8h**	*t*-Bu	H		**9h**	Quant.
8	**8i**	*t*-Bu	H		**9i**	70[b]
9	**8j**	*t*-Bu	H		**9j**	67[b]
10	**8k**	*t*-Bu	H		**9k**	79
11	**8l**	H	Me		**9l**	84

Note: Aminophenols **8b–8l** (0.25 mmol), K_2CO_3 (0.025 mmol), and platinum nanoclusters immobilized on a polymer / carbon black composite material (PI/CB–Pt) catalyst (1 mol%) in $CHCl_3$–H_2O (19:1, c = 0.05 mol/L) at 30 °C under a balloon pressure of oxygen gas.

[a]Yield based on **8b–8l** and determined by weight of the isolated products **9b–9l**.

[b]One equivalent of K_2CO_3 was used. Quant., quantitative.

under vacuum to provide the desired heterogeneous catalyst (PI/CB–Pt, 0.83 g; Pt loading, 0.2090 mmol/g).

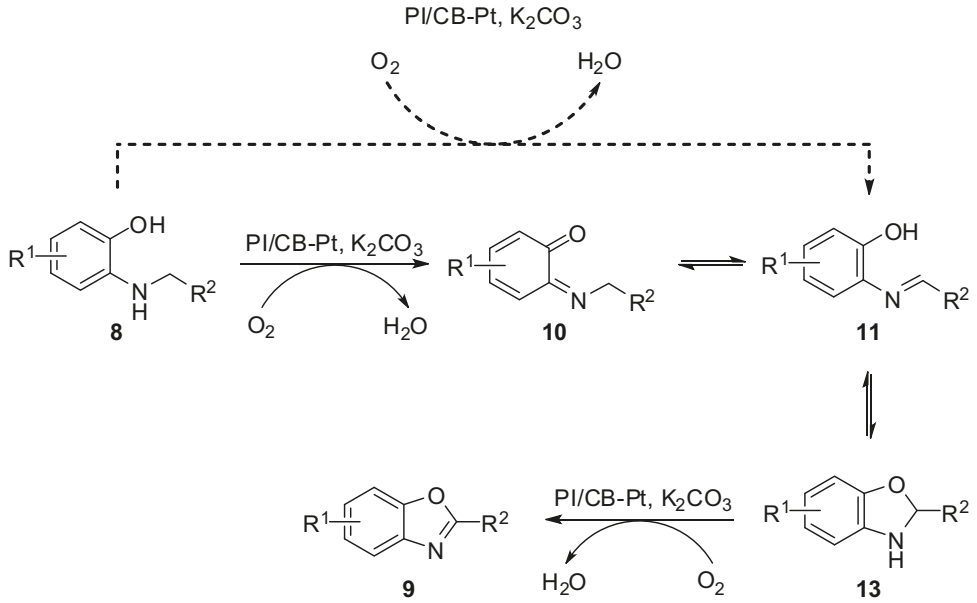
General experimental procedure for the preparation of N-substituted 2-aminophenols via reductive amination

Benzaldehyde (305 μL, 3.00 mmol) was added to a solution of 2-amino-4-*tert*-butylphenol (0.4857 g, 2.940 mmol) in EtOH (15 mL), and the reaction mixture was stirred for 4 h at room temperature. Then, $NaBH_4$ (0.1135 g, 3.00 mmol) was added portionwise and was allowed to stir for 1 h. After the reaction was completed, the reaction was quenched with H_2O (20 mL), extracted with CH_2Cl_2, and the combined organic layers were washed with a saturated brine solution. The extracted crude product was dried over $MgSO_4$, filtered, concentrated under reduced pressure, and then purified by column chromatography (EtOAc:hexane = 1:4) to provide the desired product **8d** (0.6130 g, 2.40 mmol, 82%) as a white solid.

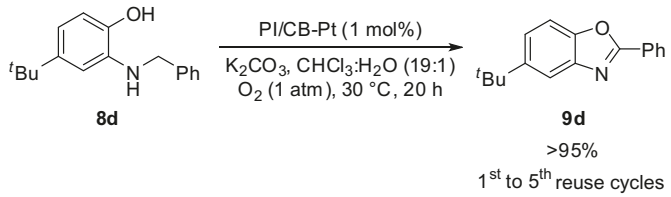
2-(Benzylamino)-4-methylphenol (8b)

mp 108 °C. IR (KBr, cm^{-1}): 3316 (m), 3090 (s), 3061 (s), 3035 (s), 2719 (s), 2342 (w), 1933 (w), 1851 (w), 1601 (s),

Scheme 3. Tentative mechanism for the platinum nanoclusters immobilized on a polymer / carbon black composite material (PI/CB–Pt)-catalyzed sequential oxidative transformation of N-substituted 2-aminophenols.



Scheme 4. Recovery and reuse of platinum nanoclusters immobilized on a polymer / carbon black composite material (PI/CB–Pt).



1362 (m), 1124 (s). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.35–7.28 (m, 4H), 7.22 (t, J = 7.6 Hz, 1H), 6.48–6.38 (d, J = 6.0 Hz, 3H), 4.75 (s, 1H), 4.27 (s, 2H), 2.19 (s, 3H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 141.1, 139.3, 136.8, 131.0, 128.5, 127.3, 127.1, 118.0, 114.3, 113.2, 48.5, 21.1. DART-HRMS (*m*/*z*) calcd for $C_{14}H_{16}N_1O_1$ [(M + H)$^+$]: 214.12319; found: 214.12368.

2-(Benzylamino)-5-methylphenol (8c)

mp 102 °C. IR (KBr, cm^{-1}): 3312 (s), 3032 (s), 2918 (s), 2865 (s), 1934 (w), 1842 (w), 1722 (w), 1615 (m), 1524 (s), 1451 (s), 1123 (s). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.35–7.29 (m, 4H), 7.25–7.22 (t, J = 6.0 Hz, 1H), 6.59 (s, 2H), 6.46 (s, 1H), 4.67 (s, 1H), 4.26 (s, 2H), 2.16 (s, 3H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 144.1, 139.4, 134.1, 128.5, 128.3, 127.6, 127.1, 121.6, 115.4, 113.5, 49.2, 20.5. DART-HRMS (*m*/*z*) calcd for $C_{14}H_{16}N_1O_1$ [(M + H)$^+$]: 214.12319; found: 214.12326.

2-(Benzylamino)-4-(*tert*-butyl)phenol (8d)

mp 99 °C. IR (KBr, cm^{-1}): 3460 (w), 3335 (m), 3207 (s), 2958 (s), 2870 (m), 1953 (w), 1852 (w), 1816 (w), 1604 (s), 1524 (s), 1410 (m), 1268 (s), 1132 (s). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.48–7.34 (m, 5H), 7.85–6.69 (d, J = 9.1 Hz, 3H), 5.27 (s, 1H), 4.41 (s, 2H), 1.35 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 144.3, 141.4, 139.2, 136.1, 128.5, 127.7, 127.1, 114.7, 114.2, 110.5, 48.9, 33.9, 31.5. DART-HRMS (*m*/*z*) calcd for $C_{17}H_{22}N_1O_1$ [(M + H)$^+$]: 256.17014; found: 256.17079.

4-(tert-Butyl)-2-((4-methylbenzyl)amino)phenol (8e)

mp 73–74 °C. IR (KBr, cm^{-1}): 3326 (s), 2956 (s), 2900 (s), 1598 (s), 1466 (s), 1409 (s), 1348 (s), 1274 (s), 1183 (s), 1044 (s). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.24 (d, J = 7.6 Hz, 2H), 7.10 (d, J = 7.6 Hz, 2H), 6.73–6.58 (m, 3H), 4.25 (s, 2H), 2.31 (s, 3H), 1.23 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 144.4, 141.6, 136.7, 136.4, 129.6, 129.2, 127.8, 127.2, 114.6, 110.4, 48.8, 33.8, 31.5, 21.0. DART-HRMS (*m*/*z*) calcd for $C_{18}H_{24}N_1O_1$ [(M + H)$^+$]: 270.18579; found: 270.18579.

4-(tert-Butyl)-2-((4-methoxybenzyl)amino)phenol (8f)

mp 87 °C. IR (KBr, cm^{-1}): 3513 (w), 3330 (s), 2953 (s), 2904 (s), 2867 (s), 1603 (s), 1520 (s), 1467 (m), 1362 (m), 1254 (s), 1184 (s), 1131 (s), 1041 (s). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.32 (d, J = 8.2 Hz, 2H), 6.90–6.63 (m, 5H), 4.64–4.20 (m, 3H), 3.80 (s, 3H), 1.27 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 158.7, 144.4, 141.4, 136.2, 131.6, 129.0, 114.6, 113.9, 110.5, 55.3, 48.4, 33.7, 31.5. DART-HRMS (*m*/*z*) calcd for $C_{18}H_{24}N_1O_2$ [(M + H)$^+$]: 286.18070; found: 286.18094.

4-(tert-Butyl)-2-((4-chlorobenzyl)amino)phenol (8g)

mp 83 °C. IR (KBr, cm^{-1}): 3319 (s), 2961 (s), 2900 (s), 2864 (s), 1869 (w), 1739 (w), 1599 (s), 1518 (s), 1347 (m), 1185 (s), 1128 (s), 1048 (s). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.10 (d, J = 2.1 Hz, 4H), 6.56–6.39 (m, 3H), 4.91 (s, 1H), 4.12 (s, 2H), 1.10 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 144.5, 141.3, 137.8, 135.8, 132.7, 128.9, 128.6, 114.9, 114.2, 110.5, 48.1, 34.2, 31.4. DART-HRMS (*m*/*z*) calcd for $C_{17}H_{21}N_1O_1Cl_1$ [(M + H)$^+$]: 290.12117; found: 290.13109.

4-(((5-(tert-Butyl)-2-hydroxyphenyl)amino)methyl) benzonitrile (8h)

mp 128 °C. IR (KBr, cm^{-1}): 3393 (s), 2961 (s), 2869 (s),

2232 (s), 1924 (w), 1705 (w), 1608 (s), 1523 (s), 1417 (s), 1275 (s), 1129 (s), 1012 (w). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.59 (d, J = 7.6 Hz, 2H), 7.49 (d, J = 7.6 Hz, 2H), 6.67–6.64 (m, 2H), 6.53 (s, 1H), 4.44 (s, 2H), 1.26 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 145.7, 144.2, 141.1, 135.5, 132.3, 127.9, 118.8, 114.5, 113.8, 110.3, 109.6, 48.0, 34.1, 31.4. DART-HRMS (*m/z*) calcd for $C_{18}H_{21}N_2O_1$ [$(M + H)^+$]: 281.16539; found: 281.16648.

4-*(tert-*Butyl)-2-(cinnamylamino)phenol (8i)

mp 98–99 °C. IR (KBr, cm^{-1}): 3317 (s), 3061 (m), 2957 (s), 2861 (m), 1601 (s), 1521 (s), 1415 (s), 1364 (m), 1196 (s), 1133 (s), 1047 (w). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.45–7.31 (m, 5H), 6.97 (s, 1H), 6.77–6.70 (m, 3H), 6.44–6.40 (m, 1H), 5.62 (s, 1H), 4.31 (d, J = 5.5 Hz, 2H), 1.68 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 144.1, 141.8, 136.8, 136.0, 131.8, 128.4, 127.3, 127.0, 126.3, 115.0, 114.3, 110.7, 46.9, 34.2, 31.6, 31.5. DART-HRMS (*m/z*) calcd for $C_{19}H_{24}N_1O_1$ [$(M + H)^+$]: 282.18579; found: 282.18705.

4-*(tert-*Butyl)-2-((3-phenylprop-2-yn-1-yl)amino)phenol (8j)

IR (NaCl, film, cm^{-1}): 3061 (m), 2959 (s), 2905 (s), 2868 (s), 2362 (w), 2337 (w), 1951 (w), 1885 (w), 1733 (s), 1604 (s), 1523 (s), 1489 (s), 1420 (s), 1250 (s), 1197 (s). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.30–7.21 (m, 2H), 7.16–7.09 (m, 3H), 6.83 (s, 1H), 6.57–6.54 (m, 2H), 4.13–3.97 (m, 2H), 1.19 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 143.8, 142.4, 135.0, 128.1, 127.9, 122.9, 115.6, 114.0, 111.3, 86.6, 83.3, 34.9, 31.3, 20.9, 14.0. DART-HRMS (*m/z*) calcd for $C_{19}H_{22}N_1O_1$ [$(M + H)^+$]: 280.17014; found: 280.17017.

5-Methyl-2-((3-phenylpropyl)amino)phenol (8l)

mp 69–71 °C. IR (KBr, cm^{-1}): 3412 (w), 3285 (m), 2955 (s), 2852 (s), 2663 (s), 1901 (w), 1818 (w), 1746 (w), 1585 (s), 1478 (s), 1445 (s), 1371 (s), 1180 (s), 1084 (m). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.35–7.22 (m, 5H), 6.96 (t, J = 7.6 Hz, 1H), 6.80 (d, J = 8.2 Hz, 1H), 6.71 (d, J = 7.6 Hz), 2.92 (t, J = 6.8 Hz, 2H), 2.76 (t, J = 7.6 Hz, 2H), 2.29 (s, 3H), 2.00–1.94 (m, 2H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 152.2, 141.5, 133.5, 132.8, 128.4, 128.3, 125.9, 125.4, 121.6, 111.8, 48.7, 33.4, 32.3, 17.3. DART-HRMS (*m/z*) calcd for $C_{16}H_{20}N_1O_1$ [$(M + H)^+$]: 242.15449; found: 242.15469.

Experimental procedure for the preparation of 4-(*tert*-butyl)-2-((3-phenylpropyl)amino)phenol (8k)

1-Bromo-3-phenylpropane (3.0 mL, 20 mmol) was added to a heterogeneous mixture of 2-amino-4-*tert*-butylphenol (6.573 g, 39.78 mmol) and $KHCO_3$ (8.763 g, 87.52 mmol) in DMF (10 mL), and the reaction mixture was stirred overnight at room temperature. The reaction mixture was diluted with EtOAc (30 mL) and H_2O (30 mL), extracted with EtOAc, and the combined organic layers were washed with a saturated brine solution. The extracted crude product was dried over $MgSO_4$, filtered, concentrated under reduced pressure, and then purified by column chromatography (EtOAc:hexane = 1:5) to provide the desired product **8k** (5.617 g, 19.82 mmol, 95%) as a white solid, mp 107–108 °C. IR (KBr, cm^{-1}): 3414 (s), 3330 (s), 3235 (s), 2959 (s), 2863 (s), 1940 (w), 1870 (w), 1806 (w), 1598 (s), 1522 (s), 1475 (s), 1417 (s), 1312 (m), 1208 (s), 1106 (m). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.34–7.21 (m, 6H), 6.74 (s, 2H), 2.77 (s, 2H), 2.00 (s, 2H), 1.31 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 141.7, 128.4, 125.9, 33.3, 31.6. DART-HRMS (*m/z*) calcd for $C_{19}H_{26}N_1O_1$ [$(M + H)^+$]: 284.20144; found: 284.20186.

General experimental procedure for the sequential oxidative transformations of N-substituted 2-aminophenols

In a screw cap glass test tube, PI/CB–Pt (0.0210 g, 0.0025 mmol, 1 mol%), **8d** (0.0638 g, 0.250 mmol), and K_2CO_3 (0.0025 g, 0.025 mmol) were added and then partially dissolved in $CHCl_3$ (4.75 mL) and H_2O (0.25 mL). The reaction mixture was allowed to stir for 20 h at 30 °C under an O_2 balloon. After the completion of the reaction, the heterogeneous catalyst was removed by filtration and washed with CH_2Cl_2. $MgSO_4$ (0.02 g) was added to the resulting filtrate, and the dried crude reaction mixture was filtered again and then concentrated under reduced pressure. The crude product was purified by preparative thin-layer chromatography (EtOAc:hexane = 1:9) to provide **9d** (0.0626 g, 0.249 mmol, 100%) as a white solid.

5-Methyl-2-phenylbenzooxazole (9b)

^{1}H NMR ($CDCl_3$, 600 MHz) δ: 8.24–8.22 (m, 2H), 7.54–7.50 (m, 4H), 7.44 (d, J = 8.2 Hz, 1H), 7.14 (d, J = 8.2 Hz, 1H), 2.47 (s, 3H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ 163.1, 149.0, 142.2, 134.4, 131.4, 128.9, 127.5, 127.3, 126.2, 119.9, 109.9, 21.5. This is a known compound and the spectral data are identical to those reported in the literature.[11]

6-Methyl-2-phenylbenzooxazole (9c)

^{1}H NMR ($CDCl_3$, 600 MHz) δ: 8.16 (s, 2H), 7.57 (d, J = 7.6 Hz, 1H), 7.45 (s, 1H), 7.09 (d, J = 8.2 Hz, 1H), 2.43 (s, 3H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 162.5, 151.0, 139.8, 135.5, 131.3, 128.8, 127.4, 127.3, 125.8, 119.3, 110.7, 21.8. This is a known compound and the spectral data are identical to those reported in the literature.[12]

5-(*tert-*Butyl)-2-phenylbenzooxazole (9d)

^{1}H NMR ($CDCl_3$, 600 MHz) δ: 8.25–8.22 (m, 2H), 7.79 (d, J = 2 Hz, 1H), 7.52–7.47 (m, 4H), 7.41–7.39 (dd, J = 2 Hz, 1H), 1.38 (s, 3H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 163.1, 148.7, 148.1, 142.0, 131.3, 128.9, 127.5, 127.3, 122.8, 116.5, 109.7, 34.9, 31.7. This is a known compound and the spectral data are identical to those reported in the literature.[13]

2-(4-Methylphenyl)-5-*tert-*butylbenzooxazole (9e)

^{1}H NMR ($CDCl_3$, 600 MHz) δ: 8.12 (d, J = 8.2 Hz, 2H), 7.78 (d, J = 1.4 Hz, 1H), 7.45 (d, J = 8.2 Hz, 1H), 7.39–7.36 (dd, J = 2 Hz, 1H), 7.29 (d, J = 8.3 Hz, 2H), 2.41 (s, 3H), 1.38 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 163.4, 148.7, 148.0, 142.0, 141.8, 129.6, 127.4, 124.6, 122.5, 116.3, 109.5, 34.9, 31.7, 21.6. This is a known compound and the spectral data are identical to those reported in the literature.[14]

2-(4-Methoxylphenyl)-5-*tert-*butylbenzooxazole (9f)

mp 134.8 °C. IR (KBr, cm^{-1}): 3069 (m), 3003 (w), 2957 (s), 2372 (w), 2043 (w), 1898 (w), 1609 (s), 1499 (s), 1471

(m), 1337 (m), 1256 (s), 1170 (m), 1055 (m), 1026 (s). ^{1}H NMR ($CDCl_3$, 500 MHz) δ: 8.15 (d, J = 8.5 Hz, 2H), 7.75 (d, J = 1.7 Hz, 1H), 7.43 (d, J = 8.5 Hz, 1H), 7.34 (d, J = 8.5 Hz, 1H), 6.98 (d, J = 8.5 Hz, 2H), 3.84 (s, 3H), 1.37 (s, 9H). ^{13}C NMR ($CDCl_3$, 125 MHz) δ: 163.2, 162.1, 148.6, 147.8, 142.1, 129.2, 122.2, 119.8, 116.1, 114.2, 109.4, 55.3, 34.8, 31.7. DART-HRMS calcd for $C_{18}H_{20}N_1O_2$ [$(M + H)^+$]: 282.14940; found: 282.14963.

2-(4-Chlorophenyl)-5-*tert*-butylbenzooxazole (9g)

mp 167.1 °C. IR (KBr, cm^{-1}): 3061 (m), 2962 (s), 2905 (w), 2869 (w), 2369 (w), 1891 (s), 1600 (m), 1479 (s), 1399 (m), 1362 (m), 1275 (s), 1200 (m), 1088 (s), 1050 (s), 1009 (m). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 8.14 (d, J = 8.2 Hz, 2H), 7.77 (s, 1H), 7.47–7.44 (t, J = 8.2 Hz, 3H), 7.39 (d, J = 2 Hz, 1H), 1.38 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 162.1, 148.7, 148.3, 141.9, 137.5, 129.2, 128.7, 125.8, 123.1, 116.5, 109.7, 35.0, 31.7. DART-HRMS calcd for $C_{17}H_{17}N_1O_1Cl_1$ [$(M + H)^+$]: 286.09987; found: 286.09902.

2-(4-Cyanophenyl)-5-*tert*-butylbenzooxazole (9h)

mp 207.2 °C. IR (KBr, cm^{-1}): 3061 (m), 2968 (s), 2905 (w), 2875 (m), 2225 (m), 1899 (w), 1746 (w), 1616 (m), 1573 (m), 1549 (m), 1479 (s), 1404 (s), 1367 (s), 1332 (s), 1278 (s), 1200 (m), 1133 (w), 1052 (s), 1013 (w). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 8.24 (d, J = 8.3 Hz, 2H), 7.74–7.70 (t, J = 8.3 Hz, 3H), 7.44–7.38 (m, 2H), 1.32 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 160.9, 148.8, 148.7, 141.7, 132.6, 131.2, 127.7, 124.0, 118.2, 116.9, 114.4, 109.9, 34.9, 31.7. DART-HRMS calcd for $C_{18}H_{17}N_2O_1$ [$(M + H)^+$]: 277.13409; found: 277.13372.

5-(*tert*-Butyl)-2-styrylbenzooxazole (9i)

mp 93.6 °C. IR (KBr, cm^{-1}): 3030 (w), 2972 (w), 2950 (w), 2903 (w), 2868 (w), 2367 (w), 2341 (w), 1956 (w), 1886 (w), 1863 (w), 1741 (w), 1637 (m), 1608 (w), 1576 (m), 1531 (s), 1472 (w), 1450 (m), 1335 (m), 1265 (s), 1187 (s), 1121 (m), 1072 (m). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.77–7.72 (m, 2H), 7.58 (d, J = 7.6 Hz, 2H), 7.43–7.33 (m, 5H), 7.06 (d, J = 16.5 Hz, 1H), 1.38 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 162.9, 148.4, 148.0, 142.1, 139.0, 135.2, 129.6, 128.9, 127.5, 123.0, 116.4, 114.1, 109.4, 34.9, 31.7. DART-HRMS calcd for $C_{19}H_{20}N_1O_1$ [$(M + H)^+$]: 278.15449; found: 278.15541.

5-(*tert*-Butyl)-2-phenylethynylbenzooxazole (9j)

mp 110.6 °C. IR (KBr, cm^{-1}): 3078 (w), 3037 (w), 2960 (s), 2867 (m), 2222 (s), 1891 (w), 1603 (w), 1543 (s), 1480 (s), 1362 (m), 1327 (m), 1299 (m), 1268 (m), 1149 (s), 1116 (m), 945 (s). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.74 (s, 1H), 7.64 (d, J = 8.2 Hz, 2H), 7.47–7.37 (m, 5H), 1.37 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 148.6, 148.3, 147.8, 141.0, 132.2, 130.2, 128.6, 124.2, 120.3, 116.7, 109.7, 93.1, 77.7, 34.9, 31.7. DART-HRMS calcd for $C_{19}H_{18}N_1O_1$ [$(M + H)^+$]: 276.13884; found: 276.13927.

5-(*tert*-Butyl)-2-phenethylbenzooxazole (9k)

mp 42 °C. IR (KBr, cm^{-1}): 3068 (w), 3030 (w), 2953 (m), 2867 (w), 2492 (w), 2371 (w), 1618 (m), 1576 (s), 1477 (m), 1452 (m), 1365 (m), 1266 (m), 1226 (m), 1202 (w), 1161 (m), 1178 (m), 1077 (m), 1032 (w). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.62 (d, J = 1.4 Hz, 1H), 7.32–7.26 (m, 2H), 7.23–7.11 (m, 5H), 3.13 (s, 4H), 1.29 (s, 9H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 166.3, 148.7, 147.6, 141.2, 140.1, 128.2, 126.4, 122.1, 116.1, 109.4, 34.8, 32.8, 31.7, 30.4. DART-HRMS calcd for $C_{19}H_{22}N_1O_1$ [$(M + H)^+$]: 280.17014; found: 280.17142.

6-Methyl-2-phenethylbenzooxazole (9l)

IR (KBr, cm^{-1}): 3061 (w), 3029 (m), 2925 (m), 2860 (w), 2362 (w), 1905 (w), 1608 (s), 1577 (s), 1495 (m), 1451 (m), 1242 (s), 1148 (m), 1037 (m). ^{1}H NMR ($CDCl_3$, 600 MHz) δ: 7.22 (t, J = 6.9 Hz, 3H), 7.17 (t, J = 7.6 Hz, 2H), 7.16–7.09 (m, 2H), 7.02 (d, J = 7.6 Hz, 1H), 3.19–3.10 (m, 4H), 2.53 (s, 3H). ^{13}C NMR ($CDCl_3$, 150 MHz) δ: 165.4, 150.5, 140.4, 140.2, 130.0, 128.6, 128.3, 126.4, 124.7, 124.2, 107.6, 33.1, 30.7, 16.5. DART-HRMS calcd for $C_{17}H_{16}N_1O_1$ [$(M + H)^+$]: 238.12319; found: 238.12273.

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