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Palladium/N-Heterocyclic Carbene Catalyzed Mono- and Double-Cyanation of Aryl Halides Using Potassium Ferrocyanide Trihydrate under Aerobic Conditions

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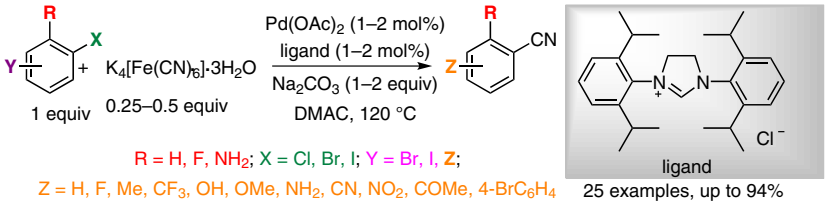

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Abstract A practical palladium/N-heterocyclic carbene catalyzed procedure for the mono- and double-cyanation of aryl halides is described using inexpensive, easy-to-handle and nontoxic potassium ferrocyanide trihydrate $\{K_4[Fe(CN)_6]\cdot 3H_2O\}$ as the cyanating agent. The reaction does not require an anhydrous solvent, or the exclusion of air or moisture. A variety of electron-rich and electron-deficient aryl halides are efficiently converted into their corresponding nitriles and dicarbonitriles.

Key words cyanation, N-heterocyclic carbene, palladium catalysis, potassium ferrocyanide, aerobic conditions

Benzonitriles and their derivatives are very important in organic chemistry as they are building blocks for many agrochemicals, dyes, herbicides, pharmaceuticals, and natural products.[1] Moreover, the nitrile moiety is a very versatile functional group in modern organic synthesis, as it can easily be converted into a variety of functional groups such as carboxylic acid, ketone, oxime, amine, amidine, ester, etc.[2]

Various methods have been reported for the introduction of cyano groups into molecules. Traditional methods include the Rosenmund von Braun reaction of aryl halides,[3] the Sandmeyer reaction of anilines,[4] and the ammoxidation of toluene and its derivatives.[5] Several drawbacks are associated with these methods which include harsh reaction conditions and the use of a stoichiometric amount of copper(I) cyanide (CuCN) leading to the generation of equimolar amounts of heavy metal waste. Recently, transition-metal-catalyzed processes for the cyanation of aryl halides under relatively mild reaction conditions have been developed, and have received significant attention. Several transition metals, such as nickel,[6] copper[7] and palladium[8] have been reported to catalyze the cyanation reactions of aryl halides with a variety of cyanating agents, including alkali cyanides, zinc cyanide $[Zn(CN)_2]$, copper(I) cyanide, trimethylsilyl cyanide (TMSCN), potassium ferrocyanide $\{K_4[Fe(CN)_6]\}$, acetone cyanohydrins, etc. The relatively nontoxic and inexpensive potassium ferrocyanide has many advantages over other cyanide sources. Among these transition metal catalysts, palladium catalysts tolerate a wide variety of functional groups and are less sensitive to air and humidity, hence it is still the metal of choice for this transformation. However, palladium-catalyzed reactions have many important limitations, including requirements for anhydrous solvents, inert atmospheres, expensive and toxic ligands, special apparatus for reagent handling, and harsh conditions. Consequently, there is significant interest in developing efficient and more practical protocols for the synthesis of benzonitriles.

N-Heterocyclic carbenes (NHCs), as very versatile ligands, have been applied widely in catalysis and in coordination chemistry.[9] They offer a useful alternative to the common phosphine ligands due to their similar electronic properties. N-Heterocyclic carbene metal complexes show remarkable stability to a wide scope of reaction conditions due to their strong σ-donating nature. Moreover, the versatility of these carbene ligands allows the electronic and steric properties of metal–N-heterocyclic carbene complexes to be easily tuned. We have developed an interest in the synthesis and catalytic properties of transition metal–N-heterocyclic carbene complexes.[10] Herein, we report a method for the mono- and double-cyanation of aryl halides catalyzed by palladium with a readily available N-heterocyclic carbene ligand under aerobic conditions, utilizing inexpensive, easy-to-handle and nontoxic potassium ferrocyanide trihydrate $\{K_4[Fe(CN)_6]\cdot 3H_2O\}$ as the cyanating agent.

It is known that sterically hindered ligands demonstrating strong electron-donating properties lead to more active catalysts. Therefore, different types of N-heterocyclic car-

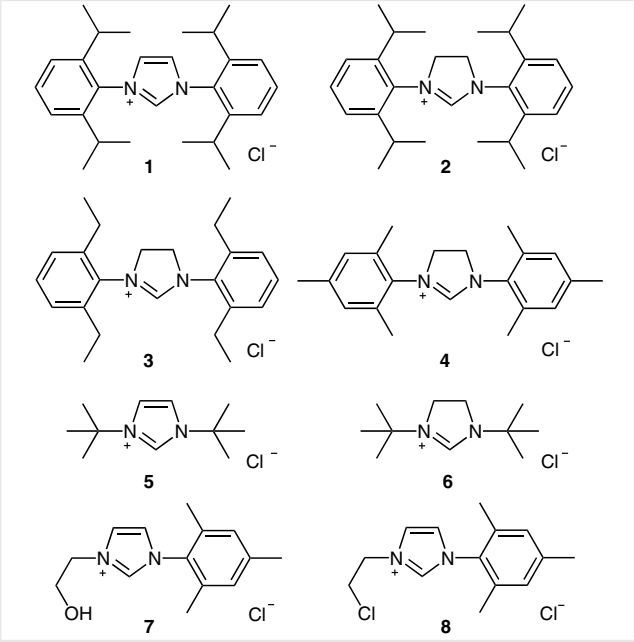
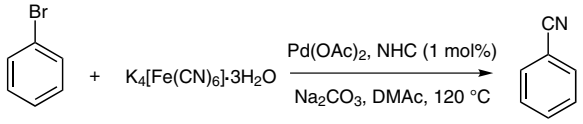


Figure 1 Structures of the N-heterocyclic carbenes

benes (Figure 1) were chosen and evaluated in the reaction of bromobenzene with potassium ferrocyanide trihydrate using palladium(II) acetate [$Pd(OAc)_2$] (1 mol%), and sodium carbonate (Na_2CO_3) as the base under aerobic conditions (Table 1). When the reaction was carried out in *N*,*N*-dimethylacetamide (DMAc) at 120 °C for 20 hours, carbene **2** was found to be the most effective ligand under the tested conditions, leading to the highest yield of 82%. Interestingly, it was found that higher yields were obtained with the more sterically hindered N-heterocyclic carbene ligands with similar electronic properties (Table 1, entries 2–4). However, the electronic effect in aryl-substituted N-heterocyclic carbenes was different from that in alkyl-substituted examples. Unsaturated N-heterocyclic carbene **1** bearing aryl substituents was less active than its saturated analogue **2**, whereas unsaturated ligand **5** possessing alkyl substituents was more active than its saturated equivalent **6**. Further experiments showed that the reaction catalyzed by **2** was complete in five hours (Table 1, entry 9), whilst longer reaction times led to decreased yields. The yield decreased to 64% when the palladium(II) acetate loading was reduced

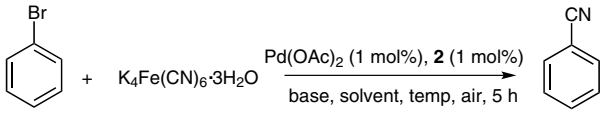
Table 1 Palladium-Catalyzed Cyanation of Bromobenzene with Different N-Heterocyclic Carbene Ligands[a]



Entry	$Pd(OAc)_2$ (mol%)	NHC	Atm	Time (h)	GC yield (%)[b]
1	1	**1**	air	20	47
2	1	**2**	air	20	82
3	1	**3**	air	20	72
4	1	**4**	air	20	11
5	1	**5**	air	20	38
6	1	**6**	air	20	11
7	1	**7**	air	20	33
8	1	**8**	air	20	42
9	1	**2**	air	5	85
10	0.5	**2**	air	5	64
11	0.5	–	air	5	33
12	0.5	**2**	N_2	5	51

[a] Reaction conditions: a mixture of bromobenzene (1 mmol), $K_4[Fe(CN)_6]·3H_2O$ (0.25 mmol), $Pd(OAc)_2$ (0.01–0.005 mmol), NHC (0.01 mmol), Na_2CO_3 (1 mmol) and DMAc (1 mL) in a 3 mL vial was heated at 120 °C with stirring.
[b] GC yield with dodecane as an internal standard.

Table 2 Palladium-Catalyzed Cyanation of Bromobenzene under Different Conditions[a]

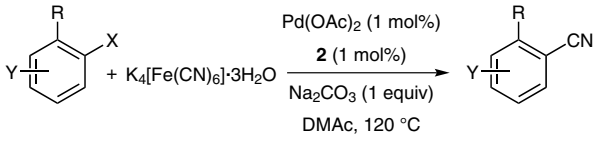


Entry	Base	Solvent	Temp (°C)	GC yield (%)[b]
1	Na_2CO_3	DMAc	120	85
2	K_2CO_3	DMAc	120	55
3	Cs_2CO_3	DMAc	120	0
4	K_3PO_4	DMAc	120	18
5	NaOAc	DMAc	120	38
6	KOAc	DMAc	120	49
7	*t*-BuOK	DMAc	120	22
8	Na_2CO_3	toluene	120	0
9	Na_2CO_3	1,4-dioxane	120	20
10	Na_2CO_3	NMP	120	18
11	Na_2CO_3	DMF	120	79
12	Na_2CO_3	DMAc (anhyd)	120	20
13	Na_2CO_3	DMSO	120	0
14	Na_2CO_3	hexan-1-ol	120	0
15	Na_2CO_3	H_2O	120	0
16	Na_2CO_3	DMAc	60	0
17	Na_2CO_3	DMAc	80	0
18	Na_2CO_3	DMAc	100	23
19	Na_2CO_3	DMAc	140	44

[a] Reaction conditions: a mixture of bromobenzene (1 mmol), $K_4[Fe(CN)_6]·3H_2O$ (0.25 mmol), $Pd(OAc)_2$ (0.01 mmol), NHC (0.01 mmol), base (1 mmol) and solvent (1 mL) in a 3 mL vial was heated at 60–140 °C with stirring.
[b] GC yield with dodecane as an internal standard.

by half (Table 1, entry 10). A control experiment without the N-heterocyclic carbene additive afforded a lower 33% yield (Table 1, entry 11). In addition, running the reaction under an inert atmosphere did not improve the yield (Table 1, entries 10 and 12).

Table 3 Palladium-Catalyzed Mono-Cyanation[a]



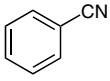
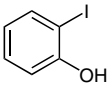
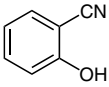
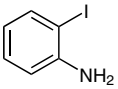
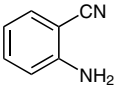
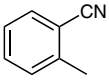
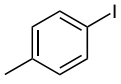
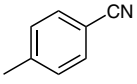
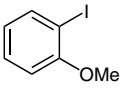
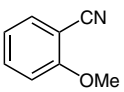
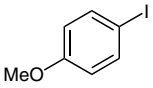
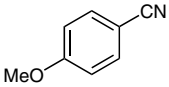
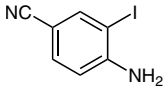
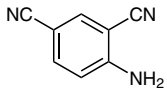
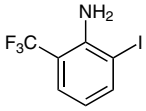
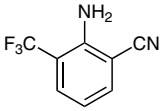
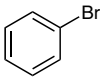
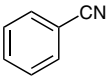
Entry	Aryl halide	Time (h)	Product	Yield (%)[b]
1		5		71
2		20		81
3		8		87
4		5		90
5		5		91
6		10		90
7		8		91
8		7		94
9		8		92
10		5		66

Table 3 (continued)

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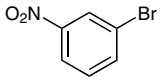
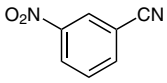
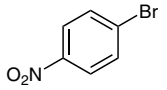
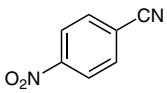
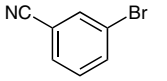
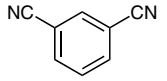
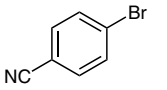
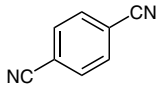
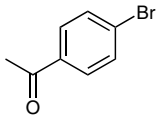
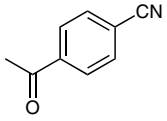
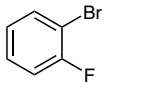
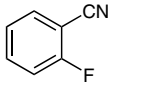
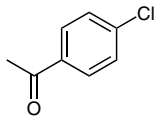
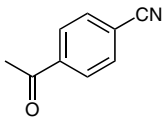
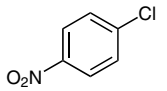
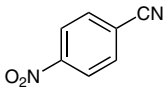
11		11		67
12		7		72
13		1		92
14		1		91
15		3		88
16		5		86
17[c]		10		63
18[c]		10		46

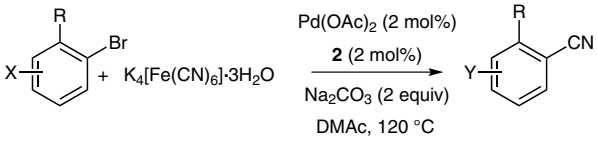
[a] Reaction conditions: a mixture of the aryl halide (5 mmol), $K_4[Fe(CN)_6]·3H_2O$ (1.25 mmol), $Pd(OAc)_2$ (0.05 mmol), NHC (0.05 mmol), Na_2CO_3 (5 mmol) and DMAc (5 mL) in an 8 mL vial was heated at 120 °C with stirring.
[b] Average yield of the isolated product over two runs.
[c] $Pd(OAc)_2$ (2 mol%) was used.

To further optimize the reaction conditions, additional experiments were carried out using bromobenzene and potassium ferrocyanide trihydrate, with variation of the base, solvent, and temperature. It is known that the solvent and base are very important parameters determining the reaction efficiency. Firstly, the effects of bases including sodium carbonate, potassium carbonate (K_2CO_3), cesium carbonate (Cs_2CO_3), potassium phosphate (K_3PO_4), sodium acetate (NaOAc), potassium acetate (KOAc) and potassium *tert*-butoxide (KO*t*-Bu) were investigated (Table 2, entries 1–7). Among the bases tested, sodium carbonate proved to be the most efficient. Potassium carbonate and potassium acetate both gave moderate yields (~50%), whereas cesium carbonate was ineffective. We further evaluated the effect of solvents on the reaction (Table 1, entries 1 and 8–15). *N*,*N*-Dimethylacetamide (not anhydrous) proved to be the best solvent tested; *N*,*N*-dimethylformamide (without drying) gave

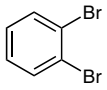
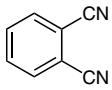
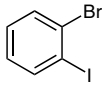
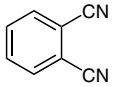
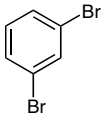
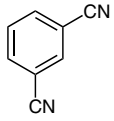
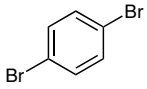
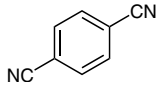
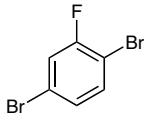
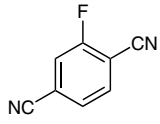
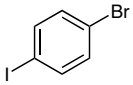
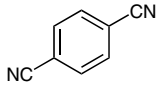
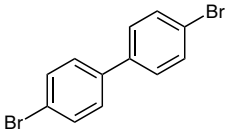
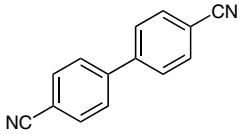
a relatively good yield (79%) (Table 2, entry 11). However, the yield decreased dramatically when anhydrous *N*,*N*-dimethylacetamide was used as the reaction solvent (Table 2, entry 12). Toluene, dimethyl sulfoxide, hexan-1-ol and water were ineffective as solvents, whilst the use of 1,4-dioxane and *N*-methyl-2-pyrrolidinone (NMP) gave poor yields of the desired product. As shown in Table 2 (entries 16–19), reaction temperatures both lower and higher than 120 °C led to significant reductions in the yields. Therefore, based on the above results, the best conditions for the cyanation reaction were as follows: Na_2CO_3 as the base and *N*,*N*-dimethylacetamide as the solvent in the presence of palladium(II) acetate (1 mol%) and N-heterocyclic carbene **2** at 120 °C in air.

To further assess the scope and limitations of this cyanation methodology, a series of aryl halides was chosen and reacted under the optimized conditions (Table 3). Rapid reactions and high yields were observed for both non-activated (electron-rich) and activated (electron-poor) aryl iodides (Table 3, entries 1–9). Even aryl iodides substituted with strong electron-donating groups (such as, OH, NH_2 and OMe) reacted smoothly to give the corresponding products in good yields, albeit after slightly longer reaction times. Sterically hindered aryl iodides also underwent the reaction without any difficulty affording high yields of cyanated products (Table 3, entries 2–4 and 8–9). In addition, the reactions proceeded efficiently with less active aryl bromides bearing electron-withdrawing groups (Table 3, entries 11–

Table 4 One-Pot Palladium-Catalyzed Double-Cyanation[a]



1 equiv 0.25 equiv (X = Br, I, 4-BrC_6H_4; R = H, F; Y = CN, 4-NCC_6H_4)

Entry	Aryl halide	Time (h)	Product	Yield (%)[b]
1		10		86
2		3		89
3		5		89
4		10		87
5		12		80
6		1		90
7		9		93

[a] Reaction conditions: a mixture of the aryl halide (2.5 mmol), $K_4[Fe(CN)_6]·3H_2O$ (1.25 mmol), $Pd(OAc)_2$ (0.05 mmol), NHC (0.05 mmol), Na_2CO_3 (5 mmol) and DMAc (5 mL) in an 8 mL vial was heated at 120 °C with stirring.
[b] Average yield of the isolated product over two runs.

16); even a relatively electron-neutral system (Table 3, entry 10) underwent the reaction in five hours to afford a good 66% yield of the isolated product. However, the reactions with aryl chlorides gave lower yields, even with a higher catalyst loading (Table 3, entries 17 and 18). It is noteworthy that the various functional groups were all tolerated.

This methodology was also extended to the synthesis of dicarbonitriles via dicyanation in a one-pot process (Table 4). The dicyanation reactions proceeded efficiently in 12 hours or less to give the corresponding dicarbonitriles in good yields. Compared to aryl dibromides, shorter reaction times were required and higher yields were obtained for iodo-substituted aryl bromides, for example, 1,2-dibromobenzene (10 h, 86% yield, Table 4, entry 1) versus 1-bromo-2-iodobenzene (3 h, 89% yield, Table 4, entry 2); and 1,4-dibromobenzene (10 h, 87% yield, Table 4, entry 4) versus 1-bromo-4-iodobenzene (1 h, 90% yield, Table 4, entry 6). Under these conditions, the double-cyanation also occurred simultaneously on two separated benzene rings (Table 4, entry 7).

In conclusion, we have developed a practical palladium/N-heterocyclic carbene catalyzed procedure for the mono- and double-cyanation of aryl halides utilizing inexpensive, easy-to-handle and nontoxic reagents under aerobic conditions. The protocol gives high yields in the cyanation reactions of a variety of aryl iodides and bromides, and moderate yields in the reaction of aryl chlorides. This method might be applicable as an industrial process as the reaction is tolerant of moisture and air.

All starting materials, reagents and solvents were obtained from commercial sources and were used without purification. Column chromatography was performed using Shangdong Yantai Silica Co. Ltd. silica gel (300 mesh). Petroleum ether (PE) refers to the fraction boiling in the 30–60 °C range. Melting points were determined using a Beijing Keyi Electronic Optical Instrument Company, model XT5B microscope melting point apparatus. IR spectra were recorded as KBr pellets on an FTIR-Tensor 27 spectrometer. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker DPX 400 MHz spectrometer at room temperature and referenced to the residual solvent signals. Coupling constants (*J*) are given in Hz. GC–MS was performed using an Agilent 6890-5973N mass spectrometer.

Mono-Cyanation; General Procedure

To a vial (8 mL) were added $Pd(OAc)_2$ (112 mg, 0.05 mmol), NHC **2** (213 mg, 0.05 mmol), $K_4[Fe(CN)_6]\cdot 3H_2O$ (528 mg, 1.25 mmol), Na_2CO_3 (530 mg, 5 mmol), and an aryl halide (5 mmol) under aerobic conditions. The mixture was stirred vigorously at 120 °C. Samples were taken from the reaction mixture periodically, quenched with H_2O, extracted with EtOAc, and analyzed by GC–MS. After completion of the reaction, the mixture was allowed to cool to r.t., quenched with H_2O and extracted with EtOAc (3 × 15 mL). The combined extracts were dried ($MgSO_4$) and the solvent was evaporated. The crude residue was purified by column chromatography on silica gel (EtOAc–PE).

Benzonitrile (Table 3, Entry 1)

Yield: 366 mg (71%); colorless oil.

IR (KBr): 3066, 2927, 2854, 2689, 2360, 2342, 2229, 2177, 1967, 1829, 1792, 1716, 1685, 1598, 1490, 1447, 1287, 1178, 1070, 1026, 926, 758, 687, 547 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.54–7.49 (m, 3 H), 7.39–7.35 (m, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.6, 131.9, 128.9, 118.6, 112.1.

2-Hydroxybenzonitrile (Table 3, Entry 2)

Yield: 482 mg (81%); colorless oil.

IR (KBr): 3066, 2939, 2878, 2727, 2605, 2357, 2225, 1505, 1401, 1307, 1245, 1191, 1159, 1102, 1018, 962, 848, 760, 728, 598 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.44 (dd, *J* = 7.8, 1.6 Hz, 1 H), 7.35 (m, 1 H), 7.05 (dd, *J* = 8.4, 0.5 Hz, 1 H), 6.84 (td, *J* = 7.7, 1.0 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 171.6, 160.3, 134.0, 133.0, 119.3, 116.3, 99.6.

2-Aminobenzonitrile (Table 3, Entry 3)

Yield: 514 mg (87%); white solid; mp 48–49 °C.

IR (KBr): 3459, 3367, 3224, 3078, 2360, 2208, 1867, 1716, 1626, 1541, 1493, 1456, 1313, 1265, 1155, 1028, 846, 745, 669, 554, 493 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.40–7.29 (m, 2 H), 6.76–6.70 (m, 2 H), 4.43 (br s, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 149.6, 133.9, 132.3, 117.9, 117.6, 115.1, 95.8.

2-Methylbenzonitrile (Table 3, Entry 4)

Yield: 527 mg (90%); colorless liquid.

IR (KBr): 3066, 3030, 2926, 2858, 2360, 2329, 2225, 1716, 1601, 1487, 1457, 1384, 1290, 1214, 1110, 1043, 949, 761, 712, 562 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.60 (dd, *J* = 7.7, 1.2 Hz, 1 H), 7.48 (dt, *J* = 7.6, 1.2 Hz, 1 H), 7.34–7.25 (m, 2 H), 2.55 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 141.9, 132.6, 132.5, 130.2, 126.2, 118.1, 112.7, 20.5.

4-Methylbenzonitrile (Table 3, Entry 5)

Yield: 533 mg (91%); white solid; mp 26–27 °C.

IR (KBr): 3037, 2360, 2227, 1716, 1684, 1606, 1541, 1508, 1456, 1178, 1022, 818, 669, 546 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.53 (d, *J* = 8.2 Hz, 2 H), 7.26 (dd, *J* = 7.9, 0.5 Hz, 2 H), 2.41 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 143.7, 132.0, 129.8, 119.2, 109.3, 21.8.

2-Methoxybenzonitrile (Table 3, Entry 6)

Yield: 599 mg (90%); colorless liquid.

IR (KBr): 3055, 3024, 2975, 2920, 2849, 2563, 2358, 2218, 1732, 1696, 1606, 1576, 1510, 1458, 1420, 1306, 1260, 1177, 1115, 1025, 830, 684, 547 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.54–7.51 (m, 2 H), 7.01–6.94 (m, 2 H), 3.90 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 161.0, 134.3, 133.5, 120.6, 116.4, 111.1, 101.4, 55.8.

4-Methoxybenzonitrile (Table 3, Entry 7)

Yield: 606 mg (91%); colorless liquid.

IR (KBr): 3081, 3024, 2955, 2920, 2848, 2562, 2341, 2218, 1732, 1696, 1606, 1575, 1510, 1445, 1420, 1305, 1259, 1177, 1024, 831, 683, 547 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.62–7.56 (m, 2 H), 6.98–6.93 (m, 2 H), 3.86 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 162.9, 134.1, 119.4, 114.9, 104.1, 55.7.

4-Aminoisophthalonitrile (Table 3, Entry 8)

Yield: 673 mg (94%); yellow solid; mp 215–216 °C.

IR (KBr): 3472, 3374, 3227, 3045, 2348, 2299, 2220, 1639, 1607, 1557, 1429, 1351, 1325, 1282, 1226, 1168, 1144, 911, 829, 790, 732, 690 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.89 (d, *J* = 1.6 Hz, 1 H), 7.39 (dd, *J* = 8.4, 2.0 Hz, 1 H), 6.70 (d, *J* = 8.4 Hz, 1 H), 4.63 (br s, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 152.1, 137.1, 136.9, 117.8, 115.4, 101.1, 96.5.

2-Amino-3-(trifluoromethyl)benzonitrile (Table 3, Entry 9)

Yield: 856 mg (92%); white solid; mp 73–75 °C.

IR (KBr): 3473, 3375, 3349, 3242, 3074, 2921, 2224, 1645, 1572, 1519, 1435, 1359, 1273, 1236, 1143, 1074, 960, 905, 826, 783, 728, 638, 595, 544 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.63 (m, 1 H), 7.52 (dd, *J* = 8.8, 1.9 Hz, 1 H), 6.81 (d, *J* = 8.8 Hz, 1 H), 4.85 (br s, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 151.9, 130.8 (q, *J* = 6.8 Hz), 130.0 (q, *J* = 4.1 Hz), 123.5 (q, *J* = 269.2 Hz), 120.0 (q, *J* = 33.8 Hz), 116.3, 115.0, 95.2.

3-Nitrobenzonitrile (Table 3, Entry 11)

Yield: 492 mg (67%); light yellow solid; mp 109–110 °C.

IR (KBr): 3079, 2924, 2853, 2360, 2236, 1844, 1716, 1540, 1473, 1355, 1288, 1079, 903, 816, 789, 733, 669, 558 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 8.54 (t, *J* = 1.8 Hz, 1 H), 8.48 (m, 1 H), 8.00 (dt, *J* = 7.7, 1.3 Hz, 1 H), 7.75 (t, *J* = 8.0 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 148.2, 137.6, 130.6, 127.5, 127.2, 116.5, 114.1.

4-Nitrobenzonitrile (Table 3, Entry 12)

Yield: 533 mg (72%); light yellow solid; mp 108–109 °C.

IR (KBr): 3105, 3074, 2924, 2856, 2360, 2232, 1940, 1716, 1697, 1602, 1524, 1488, 1348, 1315, 1294, 1187, 1105, 1015, 859, 747, 682, 539 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 8.39–8.33 (m, 2 H), 7.93–7.86 (m, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 150.0, 133.4, 124.2, 118.3, 116.7.

1,3-Benzenedicarbonitrile (Table 3, Entry 13)

Yield: 589 mg (92%); white solid; mp 133–134 °C.

IR (KBr): 3078, 3045, 2920, 2371, 2235, 1749, 1541, 1480, 1423, 1239, 1183, 1148, 906, 872, 806, 679 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.96 (m, 1 H), 7.90 (dd, *J* = 8.0, 1.6 Hz, 2 H), 7.66 (m, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 136.1, 135.5, 130.5, 116.7, 114.3.

1,4-Benzenedicarbonitrile (Table 3, Entry 14)

Yield: 583 mg (91%); white solid; mp 143–144 °C.

IR (KBr): 3097, 3052, 2368, 2232, 1942, 1689, 1541, 1504, 1402, 1277, 1200, 845, 642 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.80 (s, 4 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.9, 117.1, 116.9.

4-Acetylbenzonitrile (Table 3, Entry 15)

Yield: 639 mg (88%); white solid; mp 53–54 °C.

IR (KBr): 3095, 2923, 2852, 2360, 2228, 1942, 1686, 1603, 1560, 1522, 1473, 1401, 1355, 1293, 1262, 1073, 961, 831, 647, 592 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 8.04 (d, *J* = 8.4 Hz, 2 H), 7.77 (d, *J* = 8.4 Hz, 2 H), 2.64 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 196.5, 139.8, 132.4, 128.6, 117.8, 116.3, 26.7.

2-Fluorobenzonitrile (Table 3, Entry 16)

Yield: 521 mg (86%); colorless liquid.

IR (KBr): 3360, 2918, 2849, 2235, 1733, 1654, 1635, 1541, 1507, 1472, 1263, 874, 833, 761 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.61 (m, 2 H), 7.28–7.19 (m, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.2 (d, *J* = 258.9 Hz), 135.2 (d, *J* = 8.3 Hz), 133.6, 124.9 (d, *J* = 3.8 Hz), 116.6 (d, *J* = 19.4 Hz), 114.0, 101.6 (d, *J* = 15.3 Hz).

Double-Cyanation; General Procedure

To a vial (8 mL) were added $Pd(OAc)_2$ (112 mg, 0.05 mmol), NHC **2** (213 mg, 0.05 mmol), $K_4[Fe(CN)_6]·3H_2O$ (528 mg, 1.25 mmol), Na_2CO_3 (530 mg, 5 mmol), and an aryl halide (2.5 mmol) under aerobic conditions. The mixture was stirred vigorously at 120 °C. Samples were taken from the reaction mixture periodically, quenched with H_2O, extracted with EtOAc, and analyzed by GC–MS. After completion of the reaction, the mixture was allowed to cool to r.t., quenched with H_2O and extracted with EtOAc (3 × 10 mL). The combined extracts were dried ($MgSO_4$) and the solvent was evaporated. The crude residue was purified by column chromatography on silica gel (EtOAc–PE).

1,2-Benzenedicarbonitrile (Table 4, Entry 2)

Yield: 285 mg (89%); white solid; mp 137–140 °C.

IR (KBr): 3079, 3042, 2360, 2232, 2006, 1737, 1661, 1589, 1572, 1484, 1447, 1206, 965, 806, 770 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.88–7.81 (m, 2 H), 7.80–7.74 (m, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 133.7, 133.3, 116.0, 115.5.

2-Fluoro-1,4-benzenedicarbonitrile (Table 4, Entry 5)

Yield: 292 mg (80%); white solid; mp 122–124 °C.

IR (KBr): 3085, 3053, 2920, 2762, 2684, 2570, 2335, 2047, 1954, 1826, 1781, 1704, 1604, 1550, 1489, 1404, 1268, 1197, 1151, 1120, 980, 931, 897, 887, 853, 777, 720, 666, 640, 627 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.92 (d, *J* = 8.0 Hz, 1 H), 7.68 (dd, *J* = 8.0, 1.3 Hz, 1 H), 7.28 (d, *J* = 1.1 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 166.8 (d, *J* = 203.8 Hz), 135.7, 129.4, 122.2, 118.7, 116.0, 113.0 (d, *J* = 17.9 Hz), 110.2 (d, *J* = 36.5 Hz).

Biphenyl-4,4′-dicarbonitrile (Table 4, Entry 7)

Yield: 475 mg (93%); white solid; mp 218–221 °C.

IR (KBr): 2360, 2226, 1716, 1683, 1603, 1541, 1507, 1489, 1396, 1311, 1179, 1005, 817, 669, 544 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.82–7.75 (m, 4 H), 7.74–7.66 (m, 4 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 143.5, 132.9, 127.9, 118.4, 112.4.

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Supporting Information

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