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Imidazolylidene carbene ligated palladium catalysis of the Heck reaction in the presence of air

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Five 1,3-disubstituted imidazolium salts were synthesized. Their Heck reaction activities were evaluated. A convenient, efficient and high yielding procedure based on these compounds for the arylation of olefins was developed. Heck reactions mediated by these palladium–*N*-heterocyclic carbene complexes were conducted under air and even in the presence of several common oxidants.

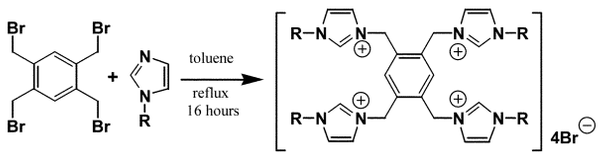
Introduction

Over the past ten years, the Heck reaction has been intensively studied for its important synthetic applications.[1] The palladium-catalyzed arylation and alkenylation of olefins have turned out to be one of the most powerful means for the formation of carbon–carbon bond in organic synthesis.[2] Traditionally, triarylphosphine palladium complexes and aryl iodide are employed for Heck reactions, and the experiments are carried out under inert atmosphere to minimize the deleterious effect of oxygen in the air. Recently, great progress has been made in the field of Heck catalysis.[3,4] Modified phosphine ligands, such as sterically demanding tri-*t*-butylphosphine and phosphine containing palladacycles and their analogs, have shown especially high coupling activities for a variety of substrates.[5] Apart from phosphine related ligands, new types of non-phosphine ligands, such as heterocyclic carbenes, imine and amine palladacycles have emerged as an alternative for the palladium catalyzed Heck reaction.[6]

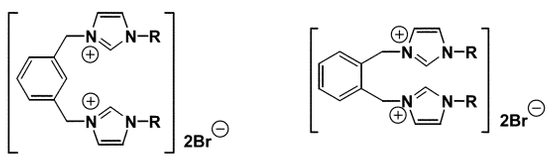
With their 'phosphine mimic'[6a] ligating properties, *N*-heterocyclic carbenes (NHC) have attracted the attention of several research groups.[7] Various NHC ligands have been synthesized within a short period of time, and some of them have been successfully used for a variety of palladium catalyzed transformations.[8] Although NHC–palladium complexes used for Heck reaction were claimed to be air and moisture stable, only a few examples carried out under air were reported by Crabtree *et al.*[9] Most reactions catalyzed by NHC–palladium complexes are conducted under an inert atmosphere. Therefore, easy to handle while highly efficient catalytic processes that are stable towards oxidants and moisture variations are still targets of pursuit. We now report here a new group of multidentate NHC–palladium(II) catalysts that exhibit outstanding activities towards the Heck reactions. By using our catalytic system, activation of aryl bromides is remarkably efficient. Good to excellent conversions have been achieved for an array of aryl bromides. Moreover, Heck reactions mediated by these complexes can also be carried out under air and even in the presence of several oxidants.

Results and discussion

Ligands used in this research are presented in Scheme 1. The *N*,*N*-disubstituted imidazolium bromides **1** to **5** were prepared simply by refluxing the corresponding benzyl bromide derivatives with 1-substituted imidazoles in toluene. The



1 : R = 2,6-diisopropylphenyl; **2** : R = mesityl; **3** : R = *tert*-butyl



4 : R = 2,6-diisopropylphenyl **5** : R = 2,6-diisopropylphenyl

Scheme 1 Synthesis of 1,3-disubstituted imidazolium salts.

1-substituted imidazoles were prepared according to a literature procedure.[10]

With compound **1** as ligand, Heck reactions of aryl bromides with *tert*-butyl acrylate were tested. It should be noted that catalysts employed in this study were neither preformed nor preactivated by any reducing agents. The catalysts were formed simply by mixing $Pd(OAc)_2$, K_2CO_3 and NHC ligands together under reaction conditions. For both electron-poor and electron-rich aryl bromides, Heck couplings proceeded equally well after refluxing in 1,4-dioxane for 20 h under argon. To our delight, further data indicated that these Heck reactions catalyzed by the same NHC–palladium complex afforded the products under air in excellent yield as well (see Table 1). Further study indicated that anhydrous solvent was not necessary either, as the reaction can proceed in commercial 1,4-dioxane with detectable amount of water and peroxide. We also utilized the zerovalent $Pd_2(dba)_3$ (dba = dibenzylidene acetone) as the palladium source, but a low yield occurred in 1,4-dioxane (see Table 1), while excellent yields were obtained in *N*-methylpyrrolidone (NMP).

The activity evaluation of ligands **1** to **5** was carried out in refluxing 1,4-dioxane under air. The results are shown in Fig. 1. The reaction rates of complexes $Pd_2(dba)_3$/**1** and $Pd(OAc)_2$/**1** were also studied by using 4-bromo-acetophenone with *tert*-butyl acrylate in NMP in an oil bath at 120 °C. Quite contrary to Herrmann *et al.*'s case,[11] no induction period was observed with $Pd(OAc)_2$/**1** being used, whereas utilizing $Pd_2(dba)_3$ as the palladium source in our catalytic process does not enhance the arylation yield nor accelerate the reaction rate (see Fig. 2).

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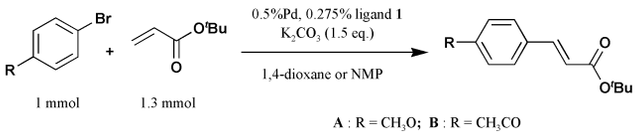
Table 1 Heck reaction of aryl bromides with *tert*-butyl acrylate[a]



1 mmol 1.3 mmol

A : R = CH_3O; **B** : R = CH_3CO

ArBr	Atmosphere	Pd source	Solvent	Yield [b]
A	Argon	$Pd(OAc)_2$	1,4-dioxane[c]	82%
B	Argon	$Pd(OAc)_2$	1,4-dioxane[c]	99%
A	Air	$Pd(OAc)_2$	1,4-dioxane	90%
B	Air	$Pd(OAc)_2$	1,4-dioxane	98%
A	Air	$Pd(OAc)_2$	1,4-dioxane[d]	84%
B	Air	$Pd(OAc)_2$	1,4-dioxane[d]	93%
A	Argon	$Pd_2(dba)_3$	1,4-dioxane[c]	18(62)%
B	Argon	$Pd_2(dba)_3$	1,4-dioxane[c]	60(39)%
A	Air	$Pd_2(dba)_3$	1,4-dioxane	47(33)%
B	Air	$Pd(OAc)_2$	NMP	99%
B	Air	$Pd_2(dba)_3$	NMP	97%
A	Argon	$Pd_2(dba)_3$	NMP[c]	82%
B	Argon	$Pd_2(dba)_3$	NMP[c]	98%

[a] For reaction conditions see Experimental. Reactions in anhydrous 1,4-dioxane were carried out in oil bath, 105 °C, for 20 h. Reactions in commercial NMP were carried out in oil bath, 120 °C, for 2 h. [b] Yield represent isolated yield based on aryl bromide, yields in parentheses are recovery of starting material. [c] Reaction system was thoroughly degassed by vacuum and purged with argon at least three times. [d] Commercial 1,4-dioxane was directly used without further purification.

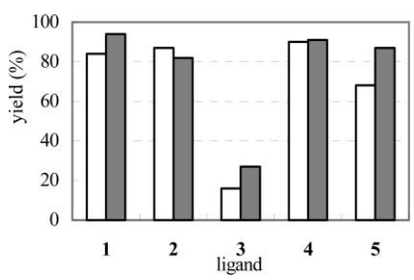


Fig. 1 Activity evaluation of ligand **1** to **5**: 4-bromoacetophenone (1 mmol), K_2CO_3 (1.5 mmol), $Pd(OAc)_2$ (0.5% mmol), ligands **1**, **2** and **3** (0.275% mmol), ligands **4** and **5** (0.55% mmol). The reaction was conducted in 1,4-dioxane (10 ml) in an oil bath at 105 °C. ■ With styrene (1.3 mmol) for 4 h. □ With *t*-butyl acrylate (1.3 mmol) for 6 h. Yields represent isolated yield based on aryl bromide.

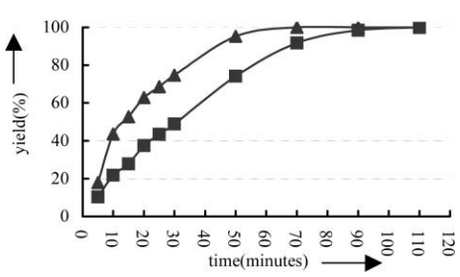
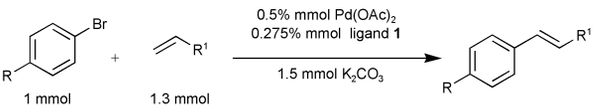


Fig. 2 Reaction rates of complexes $Pd_2(dba)_3$/**1** *vs.* $Pd(OAc)_2$/**1**. For reaction operations see the Experimental. ■ $Pd_2(dba)_3$/**1**. ▲ $Pd(OAc)_2$/**1**. The yields were determined by ^{1}H-NMR. Samples were taken in every 5 min in the first 30 min period, then at an interval of 20 min after the initial 30 min period.

The mechanism for the Heck reaction with NHC–palladium complexes has been proposed as proceeding through a cationic Pd(0)/Pd(II) pathway.[12] It is interesting to note that our catalytic process is able to proceed in the presence of several oxidants that appear to be incompatible with the commonly accepted Pd(0)–Pd(II) catalytic cycle for the Heck reaction (see Table 2). To the best of our knowledge, Heck reactions in the presence of oxidants are not recorded in the literature. Although the exact mechanism of this reaction is unclear, the Heck reaction

Table 2 Heck reaction in the presence of oxidants[a]



1 mmol 1.3 mmol

R	R^1	Mol% Pd	Time	Oxidant [b]	Yield [c]
MeO	$CO_2{}^tBu$	0.5	20 h	$NaBO_3$	64%
MeO	Ph	0.5	10 h	$NaBO_3$	85%
MeO	$CO_2{}^tBu$	0.5	20 h	NMO	97%
MeO	Ph	0.5	14 h	NMO	98%
MeCO	Ph	0.5	20 h	$NaIO_4$	75%
MeCO	Ph	0.5	20 h	$NaBO_3$	78%
MeCO	$CO_2{}^tBu$	0.5	20 h	NMO	95%
MeCO	Ph	0.5	14 h	NMO	91%
MeO	$CO_2{}^tBu$	0.01	70 h	Air	78%
MeCO	$CO_2{}^tBu$	0.0004	45 h	Air	92%[d]

[a] All reactions were conducted under air. Reactions in commercial 1,4-dioxane were carried out in oil bath, 105 °C. [b] 1.5 mmol of oxidant was added. [c] Yields represent isolated yield based on aryl bromide (average of two runs). [d] Reaction was carried out in commercial NMP in oil bath, 120 °C. NMO = *N*-methylmorpholine *N*-oxide.

occurring in the presence of oxidant suggests that a catalytic cycle such as Pd(II)–Pd(IV)[13] might be the possible pathway. Results summarized in Table 2 are of valuable for better understanding of NHC-ligated palladium catalyzed Heck reaction.

To further demonstrate the efficiency of our ligands in palladium catalyzed arylation of olefins, various aryl bromides were tested. The results are summarized in Table 3. It is noteworthy that our catalytic system is efficient towards the highly electron-rich aryl bromides (entries 1, 5, 11, 12). Unfortunately, it is inactive towards the activation of electron-rich aryl chlorides. For electron-poor 4-chloroacetophenone (entry 17), 57% yield was obtained after stirring in NMP in an oil bath at 120 °C for 24 h. Unlike phosphine ligated Pd catalysts, there was no visible palladium black formation during the entire process, either in the presence or absence of air.

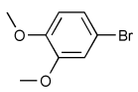
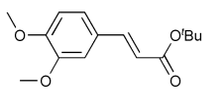
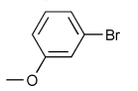
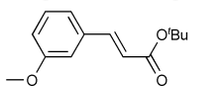
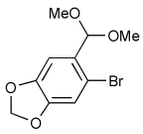
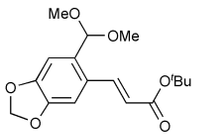
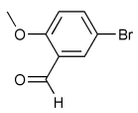
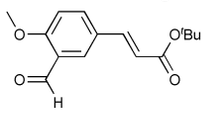
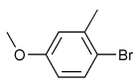
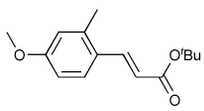
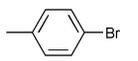
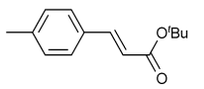
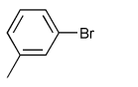
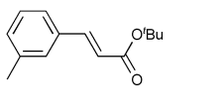
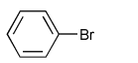
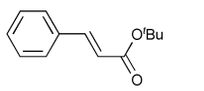
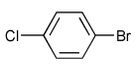
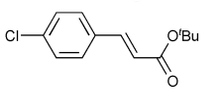
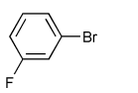
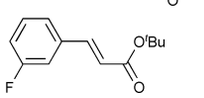
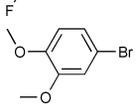
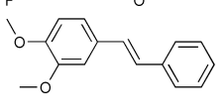
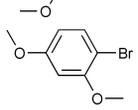
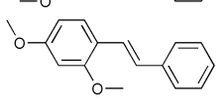
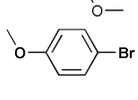
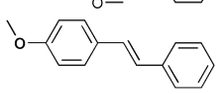
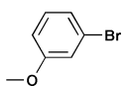
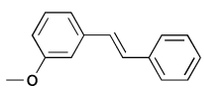
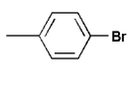
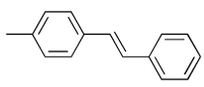
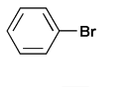
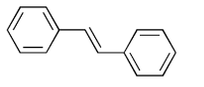
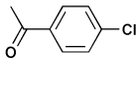
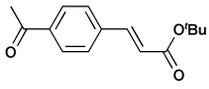
In summary, the multidentate carbene ligated palladium-catalyst system disclosed herein represents an easy to handle, robust, and high yielding procedure for Heck couplings. The catalytic system is especially stable towards air, moisture and even oxidants. The ligands are also easily accessible. The result of this research is not so much as providing an effective catalyst for the Heck reaction, although it does, but as the first observation that Heck reaction mediated by NHC–palladium complexes could take place in the presence of strong oxidizing agents, which might be a valuable contribution to the understanding of the mechanism of the Heck reaction catalyzed by imidazoylidene-ligated palladium.

Experimental

General experimental

Infrared (IR) spectra (ν_{max}) were recorded on a Perkin-Elmer 1800 Fourier transform infrared spectrophotometer in KBr plates. Proton nuclear magnetic resonance (^{1}H-NMR) spectra were recorded on a Bruker Avance 300 spectrometer at 300 MHz. Carbon-13 nuclear magnetic resonance (^{13}C-NMR) was recorded on a Bruker Avance 300 spectrometer at 75.5 MHz. HRMS was recorded on an API QSTAR Pulsar I System. MS (FAB+) spectra were recorded on a VG AutoSpec 3000 spectrometer. Chemical shifts are reported as δ values in parts per million (ppm) relative to tetramethylsilane (TMS) for all recorded NMR spectra. Low resolution mass spectra were recorded on a Finnigan Trace 2000 GC-MS spectrometer. Melting points were determined on an XT-4 microscopic melting-point detector and are uncorrected. Starting materials and reagents used in reactions were obtained commercially from

Table 3 Heck reaction with *tert*-butyl acrylate/styrene by using **1** as ligand[a]

Entry	ArBr	Time	Product[c]	Yield[b]
1		16 h		92%
2		16 h		89%
3		80 h		70%
4		17 h		98%
5		80 h		58%
6		20 h		86%
7		16 h		98%
8		20 h		70%
9		18 h		67%
10		20 h		82%
11		20 h		98%
12		21 h		72%
13		16 h		94%
14		15 h		92%
15		24 h		91%
16		20 h		80%
17		24 h		57%[d]

[a] Reaction conditions and time are not optimized. [b] Yields represent isolated yield based on aryl halides. [c] Mainly *trans* products were obtained and confirmed by ^{1}H-NMR, ^{13}C-NMR and GC-MS. [d] Reaction was carried out in NMP with 1% palladium/ligand **1** in oil bath, 120 °C.

Acros, Aldrich and Fluka, and were used without purification, unless otherwise indicated. Anhydrous 1,4-dioxane was freshly distilled from sodium benzophenone ketyl. Reactions carried out under argon were degassed by high vacuum and purged with argon at least three times. No precaution should be excised when reactions are carried out under air.

General method for preparation of ligands 1 to 5

1-Mesitylimidazole, [1-(2,6-diisopropylphenyl)imidazole or 1-*tert*-butylimidazole] (4.4 or 2.2 mmol) and 1,2,4,5-tetrabromomethylbenzene [1,3-dibromomethylbenzene or 1,2-dibromomethylbenzene] (4 or 2 mmol) were stirred in toluene (10 ml) at reflux for 16 h. The precipitate was filtered and washed with dry ethyl ether (3 × 10 ml) to afford the product (90–95%) as a white powder. Pure samples were obtained after recrystallization from appropriate solvent (acetone or methanol).

Compound 1. White crystals, mp 254–255 °C. IR ν_{max} (KBr)/cm^{-1}: 3436 (s), 3119 (m), 3071 (m), 2966 (s), 2931 (m), 2871 (m), 1619 (w), 1546 (m), 1467 (m), 1460 (m), 1404 (w), 1388 (w), 1368 (m), 1313 (w), 1183 (m), 1145 (w), 1104 (w), 1069 (w), 1002 (w), 1018 (w), 958 (w), 936 (w). ^{1}H-NMR (300 MHz, DMSO) δ: 10.15 (4H, s, $H_{imidazole}$-2), 8.29 (4H, t, J = 1.3 Hz, $H_{imidazole}$-5), 8.23 (4H, t, J = 1.3 Hz, $H_{imidazole}$-4), 7.99 (2H, s, $H_{benzene}$), 7.63 (4H, t, J = 7.8 Hz, $H_{2,6\text{-diisopropylbenzene}}$-4), 7.45 (8H, d, J = 7.8 Hz, $H_{2,6\text{-diisopropylbenzene}}$-3,5), 5.99 (8H, s, H_{benzyl}), 2.29 (8H, septet, J = 6.6 Hz, Me_2CH), 1.14 (24H, d, J = 6.6 Hz, CH_3), 1.12 (24H, d, J = 6.6 Hz, CH_3). ^{13}C-NMR (75 MHz, DMSO) δ: 145.44, 138.42, 135.02, 134.30, 131.91, 130.81, 125.70, 124.80, 123.84, 49.35, 28.47, 24.21, 24.18. MS (FAB$^+$) m/z: 1280 (1.5%), 1202 (0.5), 1066 (0.3), 667 (1), 583 (1), 517 (1), 437 (3), 357 (6), 321 (12), 229 (100). HRMS (ESI$^+$) m/z: found 1281.4978 [M + 2H − Br]$^{3+}$, $C_{70}H_{92}Br_3N_8$ requires 1281.4995.

Compound 2. White powder, mp 246–247 °C. IR ν_{max} (KBr)/cm^{-1}: 3414 (s), 3123 (s), 2979 (m), 1659 (m), 1609 (m), 1548 (s), 1484 (m), 1447 (m), 1402 (m), 1330 (w), 1290 (w), 1199 (m), 1156 (m), 1108 (s), 1069 (w), 1036 (w), 987 (w), 935 (w). ^{1}H-NMR (300 MHz, DMSO) δ: 9.77 (4H, s, $H_{imidazole}$-2), 8.14 (4H, t, J = 1.6 Hz, $H_{imidazole}$-5), 8.04 (4H, t, J = 1.6 Hz, $H_{imidazole}$-4), 7.81 (2H, s, $H_{benzene}$), 7.14 (8H, s, $H_{mesitylene}$-3,5), 5.88 (8H, s, H_{benzyl}), 2.33 (12H, s, CH_3), 2.02 (24H, s, CH_3). ^{13}C-NMR (75 MHz, DMSO) δ: 140.60, 138.26, 134.92, 134.69, 133.49, 131.46, 129.62, 124.41, 123.74, 49.27, 21.01, 17.76. MS (FAB$^+$) m/z: 1116 (2%), 1034 (0.5), 848 (1), 661 (1), 583 (1.5), 499 (3), 314 (16), 279 (4), 187 (100), 146 (10). HRMS (ESI$^+$) m/z: found 1115.3267 [M + 4H − Br]$^{5+}$, $C_{58}H_{70}Br_3N_8$ requires 1115.3273.

Compound 3. Pale yellow powder, mp > 300 °C. IR ν_{max} (KBr)/cm^{-1}: 3497 (m), 3425 (m), 3288 (m), 3129 (m), 3039 (s), 2980 (m), 1630 (w), 1563 (m), 1478 (w), 1446 (w), 1376 (w), 1349 (w), 1319 (w), 1292 (w), 1234 (w), 1209 (s), 1137 (m), 1017 (w). ^{1}H-NMR (300 MHz, DMSO) δ: 9.68 (4H, s, $H_{imidazole}$-2), 8.07 (4H, t, J = 1.8 Hz, $H_{imidazole}$-5), 7.88 (4H, t, J = 1.8 Hz, $H_{imidazole}$-4), 7.62 (2H, s, $H_{benzene}$), 5.72 (8H, s, H_{benzyl}), 1.62 (36H, s, CH_3). ^{13}C-NMR (75 MHz, DMSO) δ: 135.47, 134.53, 132.16, 123.10, 120.89, 60.27, 48.75, 29.39. MS (FAB$^+$) m/z: 867 (4%), 785 (1), 662 (4), 537 (2), 458 (3), 309 (3), 252 (11), 217 (14), 195 (7), 125 (100), 69 (35). HRMS (ESI$^+$) m/z: found 867.2659 [M + 4H − Br]$^{5+}$, $C_{38}H_{62}Br_3N_8$ requires 867.2647.

Compound 4. White crystals, mp 291–292 °C. IR ν_{max} (KBr)/cm^{-1}: 3429 (m), 3114 (m), 3055 (m), 2964 (s), 2930 (m), 2870 (m), 1662 (w), 1615 (w), 1558 (m), 1544 (m), 1461 (m), 1401 (m), 1368 (w), 1312 (w), 1253 (w), 1185 (m), 1105 (w), 1069 (w), 1060 (w), 957 (w), 890 (w). ^{1}H-NMR (300 MHz, CD_3OD) δ: 9.72 (2H, s, $H_{imidazole}$-2), 8.17 (2H, s, $H_{imidazole}$-5), 8.06 (1H, s, $H_{benzene}$-2), 7.96 (2H, s, $H_{imidazole}$-4), 7.70–7.65 (5H, m), 7.48 (4H, d, J = 7.7 Hz, $H_{2,6\text{-diisopropylbenzene}}$-3,5), 5.79 (4H, s, H_{benzyl}), 2.38 (4H, septet, J = 6.6 Hz, Me_2CH), 1.25 (12H, d, J = 6.6 Hz, CH_3), 1.23 (12H, d, J = 6.6 Hz, CH_3). ^{13}C-NMR (75 MHz, CD_3OD)

δ: 146.75, 139.23, 136.82, 133.04, 131.89, 131.79, 130.98, 130.55, 126.99, 125.79, 124.84, 54.09, 29.91, 24.55, 24.29. MS (FAB^+) *m/z*: 641 (9%), 559 (9), 423 (6), 332 (35), 229 (52), 207 (46), 115 (100). HRMS (ESI^+) *m/z*: found 641.3276 [M + 2H − Br]$^{3+}$, $C_{38}H_{50}BrN_4$ requires 641.3218.

Compound 5. White powder, mp > 300 °C. IR ν_{max} (KBr)/cm^{-1}: 3605 (m), 3253 (m), 3180 (m), 3136 (w), 3099 (m), 3045 (m), 2964 (s), 2941 (s), 2871 (w), 1669 (w), 1615 (w), 1563 (w), 1547 (m), 1464 (m), 1451 (m), 1369 (w), 1315 (w), 1283 (w), 1247 (w), 1192 (m), 1119 (w), 1001 (w), 906 (w). ^{1}H-NMR (300 MHz, DMSO) δ: 9.95 (2H, s, $H_{imidazole}$-2), 8.27 (2H, t, J = 1.6 Hz, $H_{imidazole}$-5), 8.24 (2H, t, J = 1.6 Hz, $H_{imidazole}$-4), 7.64 (2H, t, J = 7.8 Hz, $H_{2,6\text{-diisopropylbenzene}}$-4), 7.55 (2H, dd, J = 3.3, 5.7 Hz, $H_{benzene}$-3,6), 7.47 (4H, d, J = 7.8 Hz, $H_{2,6\text{-diisopropylbenzene}}$-3,5), 7.31 (2H, dd, J = 3.3, 5.7 Hz, $H_{benzene}$-4,5), 5.93 (4H, s, H_{benzyl}), 2.28 (4H, septet, J = 6.7 Hz, Me_2CH), 1.16 (12H, d, J = 6.7 Hz, CH_3), 1.14 (12H, d, J = 6.7 Hz, CH_3). ^{13}C-NMR (75 MHz, DMSO) δ: 145.39, 138.68, 133.38, 131.90, 130.87, 130.12, 129.34, 125.94, 124.80, 124.23, 49.78, 28.54, 24.16, 24.02. MS (FAB^+) *m/z*: 641 (30%), 561 (4), 413 (16), 331 (60), 229 (100), 144 (12), 104 (47). HRMS (ESI^+) *m/z*: found 641.3240 [M + 2H − Br]$^{3+}$, $C_{38}H_{50}BrN_4$ requires 641.3218.

General method for Heck couplings

Palladium acetate (2.8 mg, 0.0125 mmol), NHC ligand **5** (10.2 mg, 0.0075 mmol) and K_2CO_3 (517.5 mg, 3.75 mmol, 1.5 eq.) in 1,4-dioxane (5 ml) were stirred at room temperature under air for 30 min. Aryl bromide (2.5 mmol) and *tert*-butyl acrylate or styrene (3.25 mmol, 1.3 eq.) were added followed by another portion of 1,4-dioxane (5 ml). The mixture was then heated to reflux (105 °C, using an oil bath). An alternative way to carry out the reaction is to put substrates with palladium, base and ligand **5** together in 1,4-dioxane then heat to reflux (105 °C, oil bath). The reaction was monitored by thin-layer chromatography. After removal of the solvent, the residue was diluted with water (50 ml) and extracted with ethyl acetate (3 × 15ml). The organic phases were combined and washed with brine and dried over anhydrous Na_2SO_4. The solvent was removed and the residue was chromatographed in silica gel to afford the pure products. All compounds were subjected to ^{1}H-NMR, ^{13}C-NMR and GC-MS analysis. Physical data of selective compounds were listed below.

***trans*-3,4-Dimethoxystilbene.** White needles, mp 103 °C. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 7.44 (2H, dd, J = 0.9, 7.8 Hz), 7.29 (2H, t, J = 7.8 Hz), 7.18 (1H, dd, J = 0.9, 7.8 Hz), 7.01 (1H, brs), 7.00 (1H, d, J = 15.9 Hz), 6.99 (1H, d, J = 7.8 Hz), 6.90 (1H, d, J = 15.9 Hz), 6.79 (1H, d, J = 7.8 Hz), 3.88 (3H, s, CH_3O), 3.83 (3H, s, CH_3O). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: 149.54, 149.36, 137.94, 130.87, 129.08, 128.88, 127.71, 127.22, 126.69, 120.32, 111.64, 109.18, 56.34, 56.27. MS (*m/z*): 240 (M^+, 92%), 225 (100), 197 (26), 181 (34), 178 (82), 165 (96), 152 (92). HRMS (ESI^+) *m/z*: found 263.1046 [M + Na]$^+$, $C_{16}H_{16}O_2Na$ requires 263.1047.

***trans*-2,4-Dimethoxystilbene.** White needles, mp 62 °C. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 7.50 (2H, dd, J = 1.5, 7.5 Hz), 7.49 (1H, d, J = 8.4 Hz), 7.39 (1H, d, J = 16.4 Hz), 7.33 (2H, t, J = 7.5 Hz), 7.22 (1H, m), 7.00 (1H, d, J = 16.4 Hz), 6.52 (1H, dd, J = 2.4, 8.4 Hz), 6.47 (1H, d, J = 2.4 Hz), 3.86 (3H, s, CH_3O), 3.83 (3H, s, CH_3O). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: 160.96, 158.49, 138.74, 128.94, 127.64, 127.45, 127.34, 126.71, 123.74, 120.02, 105.44, 98.96, 55.93, 55.81. MS (*m/z*): 240 (M^+, 100%), 197 (22), 165 (36), 152 (16). HRMS (ESI^+) *m/z*: found 263.1045 [M + Na]$^+$, $C_{16}H_{16}O_2Na$ requires 263.1047.

(*E*)-3-(3,4-Dimethoxyphenyl) acrylic acid *tert*-butyl ester. Pink syrup. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 7.52 (1H, d, J = 15.9 Hz), 7.07 (1H, dd, J = 1.8, 8.2 Hz), 7.03 (1H, d, J = 1.8 Hz), 6.84 (1H, d, J = 8.2 Hz), 6.23 (1H, d, J = 15.9 Hz), 3.90 (6H, s, CH_3O), 1.52 (9H, s, CH_3). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: 166.94, 151.23, 149.54, 143.85, 128.04, 122.81, 118.31, 111.38, 109.87, 80.68, 56.32, 56.24, 28.62. MS (*m/z*): 208 (M^+ − C_4H_8, 100%), 193 (40), 119 (35), 77 (50). HRMS (ESI^+) *m/z*: found 287.1263 [M + Na]$^+$, $C_{15}H_{20}O_4Na$ requires 287.1259.

(*E*)-3-(3-Formyl-4-methoxyphenyl) acrylic acid *tert*-butyl ester. White needles, mp 120–121 °C. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 10.45 (1H, s), 7.98 (1H, d, J = 2.3 Hz), 7.68 (1H, dd, J = 2.3, 8.9 Hz), 7.53 (1H, d, J = 16.0 Hz), 7.01 (1H, d, J = 8.9 Hz), 6.32 (1H, d, J = 16.0 Hz), 3.96 (3H, s, CH_3O), 1.52 (9H, s, CH_3). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: 189.59, 166.57, 163.11, 142.19, 135.59, 128.39, 127.90, 125.25, 120.01, 112.52, 80.93, 56.33, 28.57. MS (*m/z*): 262 (M^+, 30%), 206 (100), 189 (98), 160 (41). HRMS (ESI^+) *m/z*: found 285.1100 [M + Na]$^+$, $C_{15}H_{18}O_4Na$ requires 285.1102.

(*E*)-3-(4-Chlorophenyl) acrylic acid *tert*-butyl ester. Pale yellow crystals, mp 66–67 °C. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 7.54 (1H, d, J = 15.9 Hz), 7.45 (1H, d, J = 8.7 Hz), 7.35 (1H, d, J = 8.7 Hz), 6.35 (1H, d, J = 15.9 Hz), 1.54 (9H, s, CH_3). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: 166.36, 142.43, 136.17, 133.53, 129.47, 129.46, 121.17, 81.01, 28.56. MS (*m/z*): 238 (M^+, 100%), 181 (30), 166 (55), 137 (75), 75 (65). HRMS (ESI^+) *m/z*: found 239.0832 [M + H]$^+$, $C_{13}H_{16}O_2Cl$ requires 239.0839.

(*E*)-3-[2-(Dimethoxymethyl)-4,5-methylenedioxyphenyl] acrylic acid *tert*-butyl ester. Pale yellow needles, mp 73–74 °C. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 7.93 (1H, d, J = 15.7 Hz), 7.11 (1H, s), 7.04 (1H, s), 6.16 (1H, d, J = 15.7 Hz), 5.99 (2H, s), 5.51 (1H, s), 3.32 (6H, s, CH_3O), 1.53 (9H, s, CH_3). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: 166.69, 149.33, 148.34, 140.20, 132.68, 127.80, 120.49, 107.76, 106.28, 101.92, 101.11, 80.74, 53.68, 28.58. MS (*m/z*): 322 (M^+, 15%), 221 (72), 159 (100). HRMS (ESI^+) *m/z*: found 345.1317 [M + Na]$^+$, $C_{17}H_{22}O_6Na$ requires 345.1314.

(*E*)-3-(4-Methoxy-2-methylphenyl) acrylic acid *tert*-butyl ester. Colorless oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 7.83 (1H, d, J = 15.8 Hz), 7.52 (1H, d, J = 8.3 Hz), 6.73 (1H, dd, J = 2.0, 8.3 Hz), 6.71 (1H, d, J = 2.0 Hz), 6.20 (1H, d, J = 15.8 Hz), 3.81 (3H, s, CH_3O), 2.42 (3H, s, CH_3), 1.52 (9H, s, CH_3). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: 167.24, 161.18, 141.13, 139.93, 128.26, 126.54, 118.83, 116.18, 112.41, 80.58, 55.60, 28.63, 20.43. MS (*m/z*): 248 (M^+, 60%), 192 (100), 175 (95), 146 (93), 131 (55). HRMS (ESI^+) *m/z*: found 271.1302 [M + Na]$^+$, $C_{15}H_{20}O_3Na$ requires 271.1310.

(*E*)-3-(3-Fluorophenyl) acrylic acid *tert*-butyl ester. Pale yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 7.47 (1H, d, J = 15.9 Hz), 7.26 (1H, m), 7.20 (1H, d, J = 5.7 Hz), 7.13 (1H, dd, J = 1.5, 7.9 Hz), 6.99 (1H, m), 6.28 (1H, d, J = 15.9 Hz), 1.46 (9H, s, CH_3). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: 166.20, 163.35 ($^1J_{CF}$ = 246.4 Hz), 142.45 ($^4J_{CF}$ = 2.7 Hz), 137.30 ($^3J_{CF}$ = 7.7 Hz), 130.70 ($^3J_{CF}$ = 8.3 Hz), 124.28 ($^4J_{CF}$ = 2.8 Hz), 121.96, 117.12 ($^2J_{CF}$ = 21.4 Hz), 114.51 ($^2J_{CF}$ = 21.9 Hz), 81.06, 25.80. MS (*m/z*): 222 (M^+, 19%), 207 (15), 165 (73), 149 (100), 121 (36), 101 (42). HRMS (ESI^+) *m/z*: found 245.0953 [M + Na]$^+$, $C_{13}H_{15}O_2FNa$ requires 245.0953.

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