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Ruthenium-bipyridine complex catalyzed C–H alkenylation of arylpyrazole derivatives

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Abstract. Direct dehydrogenative alkenylation of N-arylpyrazoles by acrylates has proven to be efficient under Ru(II) carboxylate complexes SPS-BPY and SPS-DB-BPY catalyst along with $Cu(OAc)_2 \cdot H_2O$ as an oxidant. The reaction was found to be atom-economical and was characterized by a number of substituted N-arylpyrazoles with excellent chemoselectivity. The reaction allowed a direct alkenylation to be performed under the eco-friendly solvent system. The diverse functional group tolerance of this protocol opened up a new insight to the use of ruthenium(II) bipyridine complexes as a productive method for the oxidative heterocoupling of N-arylpyrazole.

Keywords. Ru(II) bipyridine; alcoholic solvent; dialkenylation; alkenylarylpyrazoles; chemoselectivity; acrylate.

1. Introduction

The traditional Heck coupling reaction for the construction of new C–C bonds can be bartered with transition metal-catalyzed alkenylation of arenes with alkynes which is a more efficient atom-economical reaction.[1] Early reports on catalytic C–C bond formation *via* ortho-metalated complexes have laid the foundation.[2] The transition metal-catalyzed ortho-alkenylation of substituted aromatics with alkenes *via* C–H bond activation is one of the powerful methods to synthesize substituted alkenes in a highly regio- and stereoselective manner.[3] In 1968, Fujiwara's group reported a palladium mediated alkenylation of electron-rich aromatics with alkenes *via* an electrophilic metallation pathway.[4a,b] In 1993, Murai's group reported a ruthenium-catalyzed highly regioselective ortho-alkylation of electron-deficient aromatic ketones with alkenes *via* a chelation-assisted oxidative addition pathway.[4c] Recently, a less expensive and easily affordable ruthenium catalyst has gained much attention for this reaction.[5] Use of $[RuH_2(CO)(PPh_3)_3]$ as catalyst in the C–H-activated alkenylation of arenes with alkynes was first pioneered by Kakiuchi and Trost,[6] following which several reports on different transition metals like ruthenium,[7] rhodium,[8] palladium,[9] iridium,[10] rhenium,[11] nickel[12] and cobalt[13] have been successfully applied in C–H bond activation. One of the most powerful strategies for the dissociation and functionalization of C–H bonds is the chelation-assisted C–H activation approach that allows several directing groups like pyridines,[14] pyrazoles,[15] nitroso,[16] sulfoximine,[17] P=O bonds[18] and unsaturated C–C bonds[19] to assist the selective C–H bond functionalization.

Alkenylated products have profound applications in light of their existence in many natural products, agrochemicals, pharmaceuticals, functional materials and also some synthones for production of chemicals.[20] Devising synthetic protocols toward these scaffolds has remained the focus of general interest. Traditionally, multistep reactions like Wittig and Peterson olefination processes have been performed to access these scaffolds. Hydroarylation of alkenes[21] and Mizoroki–Heck coupling[22] have earlier been reported as a pronounced method for the synthesis of alkenylated products. However, the pre-functionalization of starting materials

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limits the scope of these reactions towards this pivotal framework. Normally, in the C–H bond functionalization reaction *via* deprotonation pathway, the oxidation step such as a metal with lower oxidation state into the higher oxidation state [Pd(0) to Pd(II), Rh(I) to Rh(III), and Ru(0) to Ru(II)] is required to regenerate the active catalyst. Generally, a stoichiometric amount of inorganic or organic oxidant such as AgOAc, Ag_2O, $Cu(OAc)_2$, $Fe(OAc)_2$, $PhI(OAc)_2$, benzoquinone, and $K_2S_2O_8$ is required to regenerate the active catalyst. In most of the reported metal-catalyzed alkenylation reaction, a stoichiometric amount of $Cu(OAc)_2$ has been used as an oxidant.[23] Recent reports also emphasized on the use of a catalytic amount of $Cu(OAc)_2$ along with air or oxygen for C–C alkenylation reactions.[24,25] Meanwhile, reports of some palladium-catalyzed alkenylation reactions require the use of organic acid along with molecular oxygen[26] with high reaction temperature. The use of high reaction temperature for the alkenylation of substituted aromatics with alkenes, may lead to the dimerization of alkenes as a side product in most cases.[27] Not only palladium but also ruthenium catalyzed alkenylation reactions, required higher reaction temperature. Therefore, it is high time that a convenient protocol for the alkenylation reaction is developed that avoids the use of drastic conditions thereby, suppressing the formation of homocoupled products.

In this work, we have tried to employ our earlier developed catalyst SPS-BPY and SPS-DB-BPY for the alkenylation of aryl pyrazoles. These two catalysts showed pronounced reactivity in hydroxylation reactions[28] and were expected to show similar results in the case of alkenylation. Eminent catalyst Ru(p-cymene)$(MesCO_2)_2$ was earlier seen to be efficient for coupling reactions. However, substituted Ru(p-cymene)$(MesCO_2)_2$(SPS-BPY and SPS-DB-BPY) complexes were also studied in the same aspect and emerged as a promising catalyst for alkenylation.

2. Experimental

2.1 *General Information*

Thin-layer chromatography plates were visualized by exposure to UV light/iodine. ^{1}H NMR spectra were obtained on 300 and 400 MHz spectrometers whereas ^{13}C NMR spectra were obtained on 75 and 125 MHz spectrometers with tetramethylsilane and chloroform-*d*, respectively, as the internal standard and solvent. Chemical shifts (δ) are reported in ppm relative to the residual solvent signal (δ = 7.26 for ^{1}H NMR and δ = 77.0 for ^{13}C NMR). Data for ^{1}H NMR are reported as follows: chemical shift (multiplicity, coupling constant, number of hydrogens). Multiplicity is abbreviated as follows: s (singlet), d (doublet), dd (double doublet), bs (broad singlet), bd (broad doublet), t (triplet), q (quartet), m (multiplet). Mass spectra were recorded on the Shimadzu model LCMS-2010EV system that was equipped with electrospray ionization (ESI) probe.

2.2 *Materials*

The following chemicals were obtained from Sigma-Aldrich, Alfa Aesar and used as received: Iodo benzene (98% pure, Sigma Aldrich, India) and its derivatives, 1H-pyrazole (98% pure, Sigma Aldrich, India), styrene (99% pure, Alfa Aesar, India) and its derivatives, ethyl acrylate, butylacrylate (>99% pure, Sigma Aldrich, India), $Cu(OAc)_2{\cdot}H_2O$ (98% pure, Alfa Aesar, India), CuI (99.5% pure, Sigma Aldrich, India), Cs_2CO_3 (99% pure, Sigma Aldrich, India), $Fe(acac)_3$ (97% pure, Sigma Aldrich, India). The solvents used for the reactions were AR grade FINAR and solvents used for column chromatography were LR grade. Silica used for column chromatography was either 60–120 or 100–200 as per requirement.

2.3 *General procedure for Ruthenium catalyzed alkenylation of aryl pyrazoles and oxazoline*

To set up the reaction, 100 mg (2 mol%) $Cu(OAc)_2{\cdot}H_2O$, 72 mg (0.5 mmol, 1 equiv.) of 1-phenylpyrazole and alkene (1.25 mmol, 2.5 equiv.) were taken in a cleaned and dried R.B. Then, 5 mol% of Ru$(MesCO_2)$(L) (p-cymene) [L-2,2′-bypyridine or 4,4′-dibromobipyridine] was added to the R.B. under argon. Thereafter, the reaction was kept under reflux conditions at 100−120 °C under a sealed condition. After cooling the reaction mixture at room temperature, 10 mL of water and 15 mL EtOAc were added; separated organic layer was washed with 10 mL of $NaHCO_3$ solution several times and dried over anhydrous Na_2SO_4. The final crude was obtained by evaporating the solvent under reduced pressure. Finally, the products were purified by column chromatography using EtOAc: Hexane mixture.

2.4 *Synthesis and characterisation of the phenylpyrazoles derivatives*

2.4a *(E)-Butyl 3-(2-(1H-pyrazol-1-yl) phenyl) acrylate* ***1a***[15]: The general procedure was followed using 1-phenylpyrazole (66 μL, 0.5 mmol) and butyl acrylate (0.049 mL, 0.55 mmol) in ethanol. Purification by column chromatography (Hexane/EtOAc: 90/10) yielded **1a**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.77 (d, 1H), 7.71 (d, 1H), 7.63 (d, 1H), 7.59 (d, J = 16.0 Hz, 1H), 7.52–7.41 (m, 3H), 6.49 (t, 1H), 6.37 (d, J = 16.0 Hz, 1H); 4.16 (t, 2H), 1.67–1.61 (m, 2H), 1.42–1.36 (m, 2H), 0.94 (t, 3H); ESI-MS: $[M+H]^+$ 271.

2.4b *(E)-Butyl 3-(5-methoxy-2-(1H-pyrazol-1-yl) phenyl) acrylate* ***1b***[15]: The general procedure was followed using 4-methoxy phenylpyrazole (87 mg, 0.5 mmol) and butyl acrylate (0.049 mL, 0.55 mmol) in ethanol. Purification by column chromatography (Hexane/EtOAc: 90/10) yielded **1b**.^{1}H NMR(300 MHz, $CDCl_3$): δ 7.79 (d, 1H), 7.56 (d, 1H); 7.37 (d, 1H), 7.17 (d, 1H), 7.04 (d, J = 16.0 Hz, 1H), 7.00 (dd, 1H), 6.52 (t, 1H), 6.27 (d, J = 16.0 Hz, 1H), 4.12 (t, 2H), 3.91 (s,3H), 1.63–1.58 (m, 2H), 1.39–1.35 (m, 2H), 0.88 (t, 3H); ESI-MS $[M+H]^+$301.

2.4c *(E)-butyl 3-(5-fluoro-2-(1H-pyrazol-1-yl)phenyl) acrylate* ***1c***[15]: The general procedure was followed using 4-fluoro phenylpyrazole (87 mg, 0.5 mmol) and butyl acrylate (0.049 mL, 0.55 mmol) in ethanol. Purification by column chromatography (Hexane/EtOAc: 90/10) yielded **1c**.^{1}H NMR (300 MHz, $CDCl_3$): δ 7.76 (d,1H), 7.79 (d,1H), 7.48 (d, J = 16.0 Hz, 1H), 7.45–7.38 (m, 2H), 7.20–7.15 (m, 1H), 6.49 (t, 1H), 6.36 (d, J = 16.0 Hz, 1H), 4.16 (t, 2H), 1.67–1.61 (m, 2H), 1.44–1.35 (m, 2H), 0.94 (t, 3H); ESI-MS $(M+H)^+$ 289.

2.4d *(E)-Butyl 3-(2-fluoro-6-(1H-pyrazol-1-yl) phenyl) acrylate* ***1d***[15]: The general procedure was followed using 3-fluoro pheylpyrazoles (87 mg, 0.5 mmol) and butyl acrylate (0.049 mL, 0.55 mmol) in ethanol. Purification by column chromatography (Hexane/EtOAc: 90/10) yielded **1d**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.79 (d, 1H), 7.70 (m, 1H), 7.64 (d, 1H), 7.60 (d, J = 16.021 Hz, 1H), 7.25 (dd, 1H), 7.17–7.13 (m, 1H), 6.51 (t, 1H), 6.34 (d, J = 16.021 Hz, 1H), 4.17 (t, 2H), 1.68–1.61 (m, 2H), 1.43–1.37 (m, 2H), 0.95 (t, 3H); ESI-MS $(M+H)^+$ 289.

2.4e *1-{2,6-Bis[E-2-(Butoxycarbonyl)ethenyl]p-fluorophenyl}-1H-pyrazole* ***1e***[15]: The general procedure was followed using 4-fluoro phenylpyrazoles (87 mg, 0.5 mmol) and butyl acrylate (0.147 mL, 1.5 mmol) in ethanol under sealed tube conditions for more than 20 h. Purification by column chromatography (Hexane/EtOAc: 90/10) yielded 1**e**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.82 (d, 1H); 7.49 (d, 1H), 7.02 (d, J = 16.017 Hz, 2H), 6.55 (t, 1H), 6.30 (d, J = 16.017 Hz, 2H); 4.13 (t, 4H), 1.64–1.58 (m, 4H), 1.39–1.33 (m, 4H), 0.93 (t, 6H); ESI-MS $[M+H]^+$ 415.

2.4f *1-{2,6-Bis[E-2-(Butoxycarbonyl)ethenyl]m-fluorophenyl}-1H-pyrazole* ***1f***[15]: The general procedure was followed using 3-fluoro phenylpyrazoles (87 mg, 0.5 mmol) and butyl acrylate (0.147 mL, 1.5 mmol) in ethanol under sealed tube conditions for more than 20 h. Purification by column chromatography (Hexane/EtOAc: 90/10) yielded 1**f**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.84 (d, 1H), 7.70 (dd, 1H), 7.51 (d, 1H), 7.33–7.27 (m, 2H), 6.98 (dd, 2H), 6.56 (t, 1H), 6.31 (dd, 2H), 4.31 (t, 4H), 1.64–1.57 (m, 4H), 1.40–1.33 (m, 4H), 0.93 (t, 6H); ESI-MS $[M+H]^+$ 415.

2.4g *1-{2,6-Bis[(E)-2-(Butoxycarbonyl)ethenyl]p-methoxyphenyl}-1H-pyrazole* ***1g***[15]: The general procedure was followed using 4-methoxy phenylpyrazoles (87 mg, 0.5 mmol) and butyl acrylate (0.147 mL, 1.5 mmol) in ethanol under sealed tube conditions for more than 20 h. Purification by column chromatography (petroleum ether/Et_2O : 90/10) yielded **1g**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.8 (d 1H), 7.47 (d, 1H), 7.22 (s, 2H), 7.04 (d, J = 16.02 Hz, 1H), 6.52 (t, 1H), 6.27 (d, J = 16.02 Hz, 2H), 4.12 (t, 4H), 3.92 (s, 3H), 1.65–1.59 (m, 4H), 1.40–1.34 (m, 4H), 0.93 (t, 6H). ESI-MS $[M+H]^+$ 427.

2.4h *(2E)-Butyl 3-(2-(4,5-dihydrooxazol-2-yl)phenyl) acrylate* ***1h***[15]: The general procedure was followed using phenyloxazoline (66 μL, 0.5 mmol) and butylacrylate (0.07 mL, 0.55 mmol) in ethanol for 4 h. Purification by column chromatography (Hexane/EtOAc: 70/30) yielded **1h**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.53 (d, J = 16.0 Hz, 1H), 7.86 (dd,1H), 7.65 (dd, 1H), 7.51–7.41 (m, 2H), 6.36 (d, J = 16.0 Hz, 1H), 4.45 (t, 2H), 4.21 (t, 2H), 4.07 (t, 2H), 1.73–1.65 (m, 2H), 1.49–1.43 (m, 2H), 0.97 (t, 3H); ESI-MS: $(M+H)^+$ = 274.

2.4i *(2E)-butyl 3-(2-(4,5-dihydro-4,4-dimethyloxazol-2-yl)phenyl)acrylate* ***1i***[15]: The general procedure was followed using 4,4′-dimethylphenyloxazoline (66 μL, 0.5 mmol) and butylacrylate (0.07 mL, 0.55 mmol) in ethanol for 6 h. Purification by column chromatography (Hexane/EtOAc: 70/30) yielded **1i**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.48 (d, J = 16.0 Hz, 1H), 7.81 (dd, 1H), 7.65 (dd, 1H), 7.48–7.38 (m, 2H), 6.37 (d, J = 16 Hz, 1H), 4.21 (t, 2H), 4.13 (s, 2H), 1.72–1.65 (m,2H), 1.50–1.45 (m, 2H), 1.25 (s, 6H), 0.97 (t, 3H); ESI-MS: $(M+H)^+$ = 302.

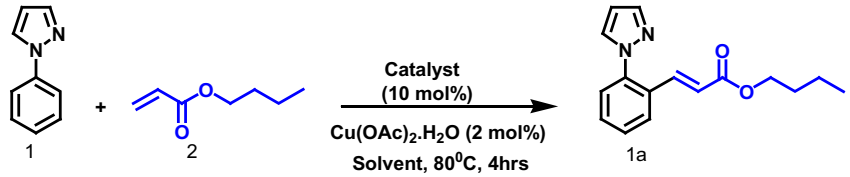
2.4j *1-{2,6-Bis[(E)-2-(Butoxycarbonyl)ethenyl]p-acetylphenyl}-1H-pyrazole* ***1j***[15]: The general procedure was followed using 1-(4-(1H-pyrazol-1-yl)phenyl)ethanone (93 mg, 0.5 mmol) and butyl acrylate (0.147 mL, 1.5 mmol) in ethanol under sealed tube conditions for more than 20 h. Purification by column chromatography (Hexane/EtOAc: 70/30) yielded **1j**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.28 (s, 2H), 7.86 (d, 1H), 7.53 (d, 1H), 7.15 (d, J = 16 Hz, 2H), 6.58 (t, 1H), 6.42 (d, J = 16 Hz, 2H), 4.15 (t, 4H), 2.71 (s, 3H), 1.65–1.42 (m, 4H), 1.41–1.37 (m, 4H), 0.94 (t, 6H); ESI-MS: $(M+H)^+$ = 439.

2.4k *1-{2,6-Bis[(E)-2-(Butoxycarbonyl)ethenyl] benzamidophenyl}-1H-pyrazole* ***1k***[15]: The general procedure was followed using 4-(1H-pyrazol-1-yl)benzonitrile (43 mg, 0.25 mmol) and butyl acrylate (0.147 mL, 1.5 mmol) in ethanol under sealed tube conditions for more than 20 h. Purification by column chromatography (Hexane/EtOAc: 70/30) yielded **1k**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.16 (s, 2H), 7.85 (d, 1H), 7.52 (d,1H), 7.11 (d, J = 16 Hz, 2H), 6.58 (t, 1H), 6.41 (d, J = 16 Hz, 2H), 4.14 (t, 4H), 1.66–1.58 (m, 4H), 1.42–1.34 (m, 4H), 0.93 (t, 6H); ESI-MS: $(M+H)^+$ = 440.

2.4l *(E)-ethyl 3-(2-(1H-pyrazol-1-yl)phenyl)acrylate **1l***: The general procedure was followed using 1-phenylpyrazole (66 μL, 0.5 mmol) and ethyl acrylate (0.52 mmol) in ethanol. Purification by column chromatography (Hexane/EtOAc: 97/3) yielded **1l**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.76 (d, 1H), 7.69 (d, 1H), 7.62 (d, 1H), 7.59 (d, J = 16.0 Hz, 1H), 7.53–7.40 (m, 3H), 6.51 (t, 1H), 6.35 (d, J = 16.0 Hz, 1H); 4.16 (t, 2H), 0.97 (t, 3H); ESI-MS: $[M+H]^+$ 243.

2.4m *(E)-ethyl 3-(5-methoxy-2-(1H-pyrazol-1-yl)phenyl)acrylate **1m***: The general procedure was followed using 1-phenylpyrazole (66 μL, 0.5 mmol) and ethyl acrylate (0.52 mmol) in ethanol. Purification by column chromatography (Hexane/EtOAc: 97/3) yielded **1 m**. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.71 (d, 1H), 7.55 (d, 1H), 7.36 (dd, 1H), 7.17 (d, 1H), 7.06 (d, J = 16.0 Hz, 1H), 6.97–7.04 (m, 1H), 6.51 (t, 1H), 6.36 (d, J = 16.0 Hz, 1H); 4.13 (t, 2H), 3.91 (s, 3H), 1.02 (t, 3H); ESI-MS: $[M+H]^+$ 273.

2.4n *(E)-ethyl 3-(5-fluoro-2-(1H-pyrazol-1-yl)phenyl) acrylate **1n***: The general procedure was followed using 1-phenylpyrazole (66 μL, 0.5 mmol) and ethyl acrylate (0.52 mmol) in ethanol. Purification by column chromatography (Hexane/EtOAc: 95/5) yielded **1n**. ^{1}H NMR (300 MHz,



Scheme 1. Representative screening reaction of phenyl pyrazole with butyl acrylate.

Table 1. Solvent optimization of SPS-BPY and SPS-DB-BPY.

Sl. No.	Solvent[a]	Yield(%)[b] SPS-BPY Hetero:homo	Yield(%)[b] SPS-DB-BPY Hetero:homo
1	Acetonitrile	10:28	15:2
2	Acetone	6:20	5:0
3	DCM	20:30	25:12
4	DMF	14:9	20:2
5	THF	24:36	34:5
6	Toluene	27:12	38:6
7	MeOH	58:10	66:3
8	EtOH	62:20	68:13
9	Propanol	55:16	62:10
10	Ipropanol	41:23	48:12
11	Butanol	32:22	40:6
12	1,4-dioxane	26:33	32:12
13	1,2-DCE	30:20	47:20
14	Chloroform	21:14	33:16
15	DMSO	17:23	19:3

[a]Reagents and conditions: 1 (0.5 mmol), 2 (1.25 mmol) $Cu(OAc)_2$ (2 mol%), 8 h at 120 °C.
[b]Isolated yields.

Table 2. Oxidant optimization of SPS-BPY and SPS-DB-BPY.

Sl. No.	Oxidant[a]	Yield(%)[b]SPS-BPY	Yield(%)[b]SPS-DB-BPY
1	$PhI(OAc)_2$	58	62
2	$Cu(OAc)_2$	62	68
3	TBHP	30	21
4	Oxone	45	52
5	H_2O_2	51	53
6	O_2	5	12
7	$K_2S_2O_8$	15	25
8	Benzoquinone	trace	12

[a]Reagents and conditions: 1 (0.5 mmol), 2 (1.25 mmol), EtOH, 8 h at 120 °C.
[b]Isolated yields.

$CDCl_3$): δ 7.70 (d, 1H), 7.63 (d, 1H), 7.50 (d, J = 16.0 Hz, 1H), 7.36–7.46 (m, 2H), 7.15–7.20 (m, 1H), 6.49 (t, 1H), 6.36 (d, J = 16.0 Hz, 1H); 4.16 (t, 2H), 1.10 (t, 3H); ESI-MS: $[M+H]^+$ 261.

3. Results and Discussion

Earlier, phenylpyrazole was chosen to react with acrylates for C–C coupling reactions under solvent-free conditions using $Ru(MesCO_2)_2$(p-cymene) catalyst by our group.[15] We were further interested to study the catalytic behaviour of bipyridine ligands on of ruthenium(II) catalyst in C–C alkenylation. Therefore, our as-prepared catalyst SPS-BPY and SPS-DB-BPY that were earlier reported for hydroxylation reactions[27] were further examined for sp^2–sp^2 alkenylation as depicted in Scheme 1 . The inceptive screening was done using simple phenyl pyrazole and butyl acrylate, SPS-BPY and $Cu(OAc)_2$ as a well-known oxidant for coupling reactions. After some initial success with different catalysts, oxidant and solvent screening was performed towards obtaining improved results. Polar aprotic solvents like DMF, acetonitrile, acetone, etc., did not produce good yields though a relatively moderate yield was obtained under 1,2-DCE medium.

On the other hand, the yield dramatically increased (by 19%) when the reaction was performed under EtOH medium, as detailed in Table 1. The addition of alcoholic solvent facilitated direct coordination and the subsequent H-bond interactions thereby enhancing the solubility and catalytic activity.[29] The respective percentage yields for selective products are tabulated in

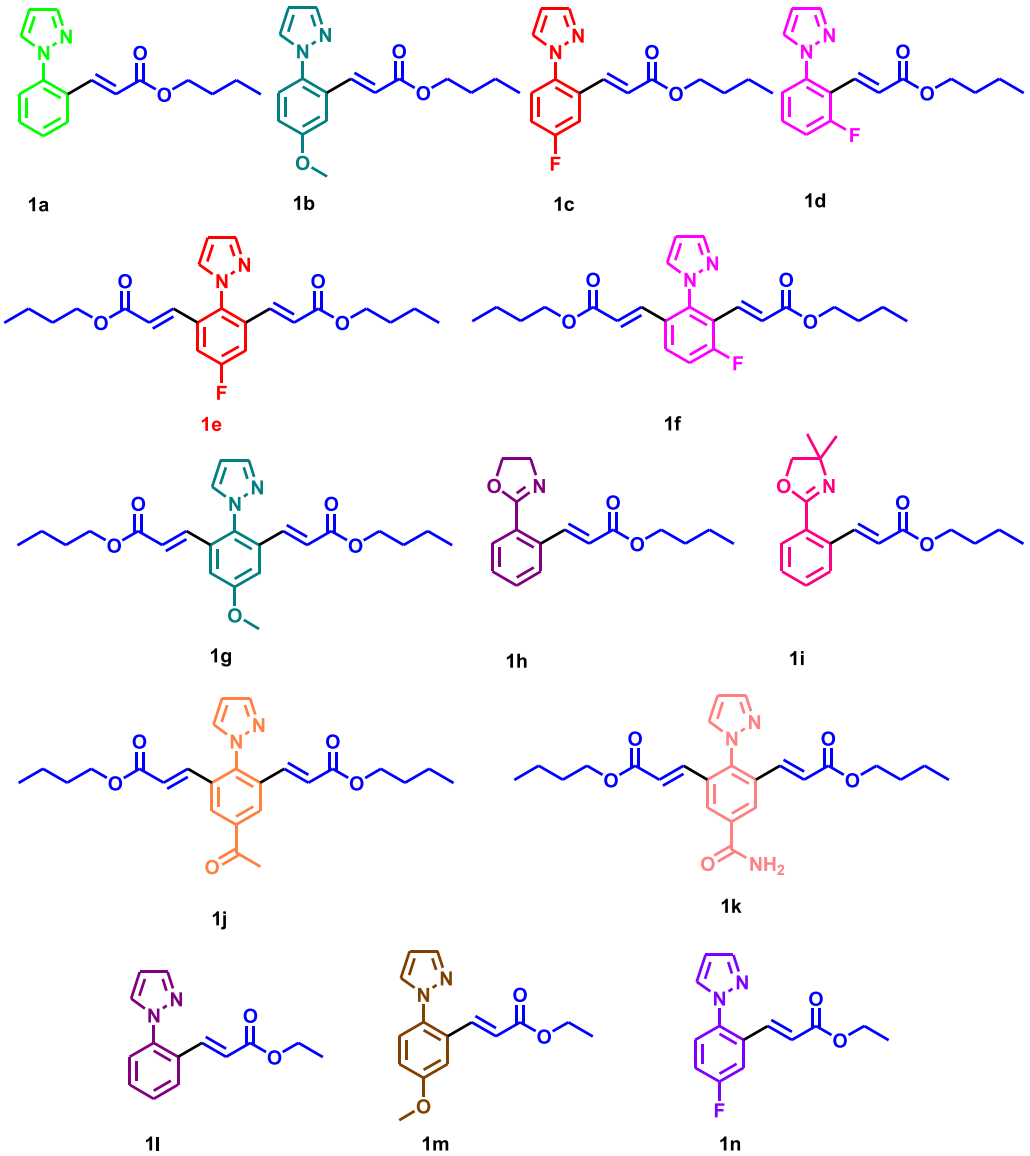


Figure 1. Derivatives synthesized to exhibit functional group tolerance.

Table 3. Yields of the derivatives synthesized with both the catalysts.

Sl. No.	Derivative[a]	SPS-BPY[b]	SPS-DB-BPY[b]
1	**1a**	62	68
2	**1b**	45	58
3	**1c**	63	72
4	**1d**	56	61
5	**1e**[c]	21	32
6	**1f**[c]	15	18
7	**1g**[c]	7	16
8	**1h**[#]	19	33
9	**1i**[#]	16	26
10	**1j**[c]	62	68
11	**1k**[c]	56	61
12	**1l**[d]	65	68
13	**1m**[d]	61	66
14	**1n**[d]	64	70

[a]Arylpyrazole (0.5 mmol), butyl acrylate (1.25 mmol) $Cu(OAc)_2$ (2 mol%), catalyst (10 mol%), 5–6 h at 120 °C.
[b]Isolated yields.
[c]Arylpyrazole (0.5 mmol) butyl acrylate (2 mmol) $Cu(OAc)_2$ (2 mol%), catalyst (20 mol%), 20 h at 120 °C.
[d]Arylpyrazole (0.5 mmol) ethyl acrylate (1.25 mmol) $Cu(OAc)_2$ (2 mol%), catalyst (10 mol%), 8 h at 120 °C.
[#]The procedure was same as mentioned in [a].

Table 3. Apart from increasing yields, minimum homo-coupling product was obtained under SPS-DB-BPY catalyst in the presence of an alcoholic solvent, e.g., EtOH. Screening with alcoholic solvents of longer chain length, a sharp rise in the steric crowding decreases the yields of the reaction.

The yields of the reaction in comparison to our earlier report [15] were found to diminish which may be attributed to the strong σ-donating power of the bipyridine ligands used in the catalyst. Several oxidant screenings were performed and the best results were found to be with $Cu(OAc)_2$ (2 mol%), as shown in Table 2.

The reaction of phenylpyrazoles and substituted phenylpyrazoles with butyl acrylates and 2 mol% of $Cu(OAc)_2 \cdot H_2O$ exhibited a wealth of functional group tolerance leading to 60–80% yield *of E*-monoalkenylated derivatives (**1a–1d**,**1h**, **1i**) and *E*-dialkenylated derivatives (**1e–1g**,**1j**, **1k**). The lowest yield was found with methoxy phenylpyrazole compared to its parent compound proving that electron donating groups decelerated the reaction. The presence of electron withdrawing groups at *para* position increased the yield of the reaction whereas same groups in *meta* position slows down the reaction. On adding butyl acrylate about 1.5–2 equiv. under sealed tube conditions for more than 20 h and 20 mol% of catalyst, a significant amount of dialkenylated pyrazoles (**1e–1g**,**1j**, **1k**) were obtained. Initially, with 10 mol% of catalyst and 1.25 mmol of the corresponding alkene partner, only 8% of the dialkenylated **1e** product was obtained. Therefore, to enhance the yields of the dialkenylated products excess of catalyst, about double the equivalent of alkene and longer reaction time were employed. On implication of the above mole percentages, a clear hike of 24% was observed for the dialkenylated product **1e**.

The reaction is not restricted to the use of butyl acrylates but is also applicable with other acrylates. We have conducted the above alkenylation with ethyl acrylates (Figure 1) exhibiting satisfactory yields of **1l**, **1m** and **1n**. The results are incorporated in Table 3. Apart from ester-substituted alkenes, several other electron-deficient, as well as electron-rich alkenes, are expected to show similar results which are under investigation. The yields of the above derivatives with both catalysts SPS-BPY and SPS-DB-BPY are depicted in Table 3. The highest yield of about 72% was found with *para*-fluoro derivative, a mild electron withdrawing substituent. Under the optimized conditions, the formation of bis-alkenylated products of oxazolines was difficult. The oxidative addition during the di-alkenylation step is retarded due to the presence of the weak directing group.

Since no additional phosphine ligand was used, the directing atom is unable to coordinate well with the catalyst thereby preventing the oxidative addition.[30] Therefore, the existing reaction conditions lead to exclusive monoalkenylated **1h–1i**. In the case of strong electron withdrawing group substituted phenyl-pyrazole derivatives **1j–1k**, we have found exclusively bi-coupling products. The electron withdrawing groups highly facilitate the oxidative addition process and probably leads to the formation of bis-alkenylated products. On using 0.5 mmol of the acrylate, 12% of monoalkenylated product and 43% of bis-alkenylated product (**1j**) were formed. Since with 1:1 ratio of the coupling partners substantial amount of bis-alkenylated product was formed, we enhanced the equivalents of the acrylate and found di-coupled products in 68% yield of **1j**. When the reactions were carried out with derivatives that are prone to oxidation in the presence of the oxidant $Cu(OAc)_2$ (e.g., **1j**, **1k**), it was found that these substrates exclusively show the alkenylated product without affecting the functional group. Therefore, this method can prove to be efficient in terms of functional group tolerance.

4. Conclusions

We have reported the ruthenium-catalyzed C–H alkenylation of phenylpyrazoles and phenyl oxazolines. It

is presumed that C–C bond formation enables effective intermolecular alkenylation which proceeded with excellent positional selectivity. The optimized catalyst SPS-BPY and SPS-DB-BPY were found to be highly chemoselective along with $Cu(OAc)_2 \cdot H_2O$ as an oxidant. The use of alcoholic solvents to get better yields make the reaction environment-friendly and reduces the difficulty in work-up procedures, thereby resulting in a cleaner reaction. A range of functional group tolerance was achieved with these catalysts and it opens up an alternative to the conventional routes for alkenylation. Mechanistic details of these catalysts are still under sporadic investigation.

Supplementary Information (SI)

All additional information pertaining to spectral data for the characterization of compounds are given in the supporting information. Supplementary Information is available at www.ias.ac.in/chemsci.

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