Indian Journal of Chemistry
Vol. 59B, June 2020, pp. 842-849

A green synthesis of isoquinolines using Ru(II)/PEG-400 as homogeneous recyclable catalyst *via* C-H/N-N bond activation

Shrinivas L Nakkalwar, Hanmant M Kasralikar, Nitish S Kaminwar, Shivaji B Patwari & Vivekanand B Jadhav*

[a] Department of Chemistry, L. B. S. Mahavidyalaya, Dharmabad 431 809, Dist. Nanded, India

[b] Department of Chemistry, Shri Muktanand Mahavidyalaya, Gangapur 431 109, Dist. Aurangabad, India

E-mail:viveka22@gmail.com

Received 1 January 2019; accepted (revised) 4 February 2020

A novel and green synthesis of 1-phenyl isoquinoline derivatives has been developed by using Ru(II)/PEG-400 as homogeneous recyclable catalyst *via* C-H/N-N bond activation *via* C-H/N-N functionalization of 1-(diphenylmethylene) hydrazine and aryl substituted acetylenes. In order to realize the proposed protocol, $Cu(OAc)_2$ and $AgSbF_6$ are used as oxidant and additive respectively in PEG-400 biodegradable solvent. This protocol has a simple extraction procedure, uses biodegradable solvent, affords high atom economy, employs a reusable catalytic system, provides wide substrate scope with high yield of product, for the synthesis of isoquinoline derivatives.

Keywords: Green synthesis, homogeneous catalyst, biodegradable solvent

Isoquinoline ring has been found to possess wide range of biological and pharmacological applications such as antimalarial, anti-HIV, insect growth retarding antitumor, antimicrobial, antileukmic antibacterial, Parkinson's disease activity and is a scaffold for chiral ligands. Isoquinoline is a important source of leads for drug discovery. In addition to this, Isoquinoline represents one of important structural scaffold found in various natural products and pharmaceutical compounds. To investigate this chemical space several protocols have been developed for the synthesis of Isoquinoline ring.

Bischer–Napieralski, Pictet–Spengler, and Pomeranz–Fritsch reactions are traditional methods for synthesis isoquinolines and these often suffer from some drawbacks such as low yields, a narrow substrate scope, and drastic reaction conditions. There are certain reactions in which, a preactivated halogen group such as I or Br was used to activate the *ortho*-carbon of the aromatic imines. In these reaction, Cyclization of *o*-halobenzimines with carbon-carbon π-components using Palladium- or nickel-catalysis is one of the challenging methods to synthesize isoquinoline derivatives[1]. Now a day, C–H activation reactions[2] have exchanged route for accessing isoquinoline scaffolds with a more concise manner[3]. These methods provide straight forward way to isoquinolines synthesis, but they often require the use of a precious transition metal. Such methodology represents a one of the best strategy for the conversion of organic molecules in account of high atom and step economy, efficiency, environmental impact.

In recent years, utilization of first row transition metals has focused in the area of C–H fictionalization[4]. In this context, research workers independently reported Co (III)-catalyst for C–H/N–O bond functionalization of oximes with alkynes[5], oxidative annulations of N–H imines with alkynes in the presence of an external oxidant[6], an elegant C–H/N–H bond functionalization of amidines with diazo compounds[7], C–H/N–S bond functionalization of N-sulfinyl imines with alkynes[8] and recently C–H/N–N Functionalization[9] of arylhydrazones for the synthesis of isoquinoline.

Jun, Cheng, and Ellman *et al.*[10,11] reported the Rhodium(I)-catalyzed chelation-assisted C-Hbond activation of aromatic imines or oximes with alkynes, similarly Chiba's group reported a Rh(III)-catalyzed cyclization of aryl ketone O-acyloximes with alkynes by C-H bond activation [12a-c], and Rovis *et al.* and Li *et al.* also demonstrated a rhodium-catalyzed cyclization of aromatic ketoximes with alkynes by C-H bond activation[12d,f].

Now a days, a less-expensive ruthenium catalyst has been widely used in the cyclization reaction rather than rhodium catalyst because of its remarkable regioselectivity and the economy[13,14]. Masilamani Jeganmohan *et al.*[15,16] reported the complete

regioselective synthesis of isoquinolines by cyclization of ketoximes with unsymmetrical alkynes in the presence of catalytic amount of Ru(II) and NaOAc and also repored an unprecedented redox-free Ru(II) catalysis of benzimidates with alkenes in green ethanol solvent. Recently, Bhalchandra M. Bhanage *et al.*[17] reported *N*–tosylhydrazone directed annulations reaction with internal alkynes for the synthesis of isoquinoline using ruthenium catalysed homogeneous recyclable catalytic media. According to our knowledge, there is no report on simple easily available without any leaving group substituted hydrazine directed annulations reaction with internal alkynes in green protocol. Herein, we report an extraordinary ruthenium catalyzed homogeneous recyclable catalytic media for hydrazine with alkynes, in consideration with the advantages presented by PEG-400 as a green and sustainable solvent using $Cu(OAc)_2$ as oxidant and $AgSbF_6$ as additive at ambient temperature for the synthesis of 1-Phenyl Isoquinoline derivatives (Scheme I). This methodology accounts for high atom economy, efficiency, environmental impact, and elegance as it reduces the unnecessary prefunctionalization of starting material.

Experimental Section

All chemical and solvents were used as commercial anhydrous grade without further purification. PEGs were dried prior to use by the literature methods. Aluminium sheets 20 × 20 cm, Silica gel 60 $F_{254,}$ Merck grade was used for thin layer chromatography to determine progress of reaction. Melting points were determined in open capillary tube and are uncorrected. IR, ^{1}H and ^{13}C NMR spectra were recorded on a Brucker AV-400 MHz and 100 MHz spectrometer in $CDCl_3$, DMSO solvent. Mass spectra were taken on Polaris-Q Thermoscintific MS.

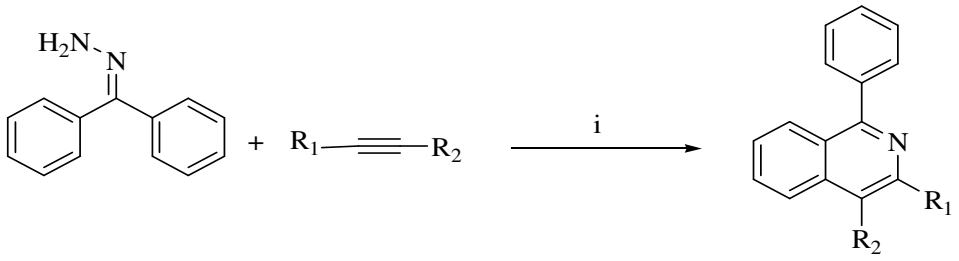
Synthetic Procedure

A Screw capped vial a spinevane triangular shaped Teflon stirrer bar were added aryl hydrazone(1mmol), Diphenylacetate (1.5mmol), $[Ru(p\text{cymene})Cl_2]_2$ (10 mol%), silver hexafluoroantimonate ($AgSbF_6$) (10mol%) and copper acetate $Cu(OAc)_2$ (1mmol) and PEG 400 (0.5 mL) under an air atmosphere the reaction mixture was stirred at 110°C in a oil bath for 12hrs. After completion of the reaction, the reaction mixture was allowed to cool down to RT and then extracted with 5–7 mL of diethyl ether for three to four times. Extracted diethyl ether was concentrated under reduced pressure to get the crude residue, which was then purified by silica gel column chromatography using pet ether/ethyl acetate as eluent to afford the desired pure Isoquinoline product.

1,3,4-Triphenylisoquinoline, 3a: White solid. m.p. 187-191°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ 7.16-7.18 (m, 3H), 7.30-7.31 (d, 2H), 7.36-7.50 (m, 5H), 7.50-7.57(m,5H), 7.80-7.81(d,1H), 7.83-7.84(d,1H), 8.16-8.19(d,1H); ^{13}C NMR (300 MHz, $CDCl_3$): δ159.16, 149.61, 140.87, 139.79, 137.52, 136.94, 131.31, 130.42, 130.20, 129.89, 129.72, 128.49, 128.27, 127.50, 127.46, 127.25, 126.95, 126.54, 125.98, 125.40.

3,4-Bis(4-fluorophenyl)-1-phenylisoquinoline, 3b: White solid. m.p. 183-184°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ 7.12-7.17 (dd, 2H), 7.34-7.38 (dd, 2H), 7.48-7.52 (m, 2H), 7.62-7.76(m,2H),7.77-7.80(m,4H),7.82-7.86(m,1H),7.93-8.04(d,1H),8.05-8.06(d,2H),8.43-8.45 (d,1H); ^{13}C NMR (300MHz, $CDCl_3$): δ163.36, 163.23, 160.91, 160.77, 160.08, 148.82, 132.90,132.82,132.14,132.06,130.19,130.12, 128.64,128.33,127.62,125.66,115.68,115.47,114.70,1 14.70,114.49,77.32,77.00,76.68.

3,4-Bis(4-(trifluoromethyl)phenyl)-1-phenylisoquinoline, 3c: White solid. m.p.208-210°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ 7.43-7.79 (m, 10H), 7.80-7.89 (m, 4H), 7.98-8.00 (d, 2H), 8.40-8.43(d,1H); ^{13}C NMR (300MHz, $CDCl_3$): δ160.80, 148.15, 143.99, 141.03, 139.29, 136.50,131.



1 **2(a-n)** **3(a-n)**

Scheme I — Reagent and conditions: [Ru (p-cymene)Cl2]2, Cu (OAc)2, AgSbF6, PEG-400, 110°C, air atm,10-12 h, 85-95%

68,130.67,130.12,129.83,129.45,129.19,128.89,128.81,128.44,127.82,127.37,125.68,125.55,124.74,123.04, 122.97,77.25,77.00,76.75.

Diethyl 4,4-(1-Phenylisoquinoline-3,4-diyl)dibenzoate, 3d: White solid. m.p.173-176°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ 1.54-1.65 (t, 6H), 4.50-4.66 (q, 4H), 7.57-7.60 (d, 2H), 7.66-7.85(m,6H),8.00-8.08(m,4H), 8.27-8.30(q,2H),8.40-8.43(d,1H); ^{13}C NMR(300MHz, $CDCl_3$):δ166.49,166.31,160.51,148.47,144.87,142.05, 139.27,136.49,131.37,130.51,130.40,130.18,129.71,129.69,129.43,129.08,128.97,128.84,128.41,127.78,127.23,125.69,125.63,77.32,77.00,76.68,61.15,60.91,14.34,14.29.

3,4-Bis(4-methoxyphenyl)-1-phenylisoquinoline, 3e: White solid. m.p.175-176°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ 3.99 (t, 3H), 4.10 (t, 3H), 6.96-6.99 (d, 2H), 7.17-7.20(m, 2H),7.44-7.47(m,2H),7.48-7.62(d,2H), 7.65-7.96(m,5H), 7.99-8.03(d,1H),8.04-8.07(t,2H) 8.38-8.40 (d, 2H); ^{13}C NMR (300MHz, $CDCl_3$): δ 159.77, 159.60, 158.83, 149.22, 142.13, 139.76, 138.97, 136.90, 130.21, 128.57, 128.51, 128.27, 122.98, 116.74, 115.33, 113.61, 113.15, 77.42, 77.00, 76.58, 55.26, 55.08.

3,4-Bis(4-chlorophenyl)-1-phenylisoquinoline, 3f: White solid. m.p.189-191°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ7.98-8.80 (q, 1H), 8.09-8.16 (q, 3H), 8.23-8.48 (q, 3H), 8.49-8.55(q, 5H),8.58-8.61(q,2H), 8.71-8.74(d,2H), 9.10-9.13(d,1H); ^{13}C NMR (300MHz, $CDCl_3$): δ 160.47,148.15, 142.24,139.37, 139.03, 136.59,134.37, 133.74, 131.12, 130.49, 130.42, 130.12, 129.80,129.50,128.76,128.61,128.47, 128.37, 127.82,127.67,127.40,127.09,125.67,125.56,77.25,77.00,76.75

1-Phenyl-3,4-dim-tolylisoquinoline, 3g: White solid. m.p.224-226°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ2.57 (s, 3H), 2.66 (s, 3H), 7.28-7.41 (q, 1H), 7.46(s, 1H), (q,2H),7.49-7.92(m,5H), 8.03-8.06(d,1H), 8.13-8.16 (d, 2H), 8.47-8.50(d,1H); ^{13}C NMR (300MHz, $CDCl_3$): δ 159.55, 149.60, 140.72, 139.86, 137.70, 137.49, 137.01, 136.93, 131.90, 131.16, 130.21, 129.83, 129.76, 128.42, 128.36, 128.23, 128.11, 127.89, 127.69, 127.47, 127.38, 127.17, 126.40, 126.11,125.33,77.42,77.00,76.58, 21.41.

1-Phenyl-3,4-dip-tolylisoquinoline, 3h: White solid. m.p.218-220°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ3.79(s, 3H), 3.90 (s, 3H), 6.90-7.12 (q, 1H), 7.18(s, 1H), 7.28-7.42 (t,2H),7.67-7.47(q,1H), 7.69-7.80 (m,5H), 7.93-7.96 (d, 1H), 7.98-8.01 (d,2H), 8.34-8.37(d,1H); ^{13}C NMR (300 MHz, $CDCl_3$): δ 156.25, 156.09, 155.32, 145.71, 138.62,136.25, 135.46, 133.39, 126.70, 125.06, 125.00, 124.75, 119.47, 113.23, 111.82, 110.10, 109.64, 73.91, 73.49, 73.07, 51.75, 51.57.

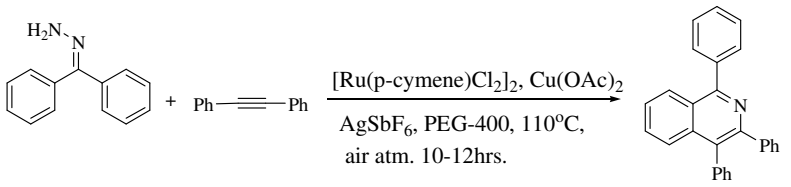
3,4-Bis(3-methoxyphenyl)-1-phenylisoquinoline, 3i: White solid. m.p.194-196°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ 4.95(s, 3H), 5.06 (s, 3H), 8.06-8.26 (m, 1H), 8.28 (s, 1H), 8.34-8.60(m,1H),8.68(s,2H), 8.83-8.85(m,1H), 8.86-8.87(m,1H),8.87-8.96 (m,5H),9.14(d,1H), 9.16-9.17(d,2H),9.50-9.53(d,1H).^{13} C NMR (300MHz,$CDCl_3$): δ 160.47, 160.30, 159.54, 149.92, 142.83,140.47,139.68,137.60, 130.91, 130.05, 129.27, 129.22, 128.97, 123.69, 117.44, 116.03, 114.32, 113.85,78.13,77.70,77.28,55.96,55.78.

3,4-Bis(3-chlorophenyl)-1-phenylisoquinoline, 3j: White solid. m.p.213-215°C. ^{1}H NMR (300 MHz, $CHCl_3$): δ 7.46-7.51(t, 1H), 7.55-7.58 (q, 3H), 7.59-7.73 (q, 3H), 7.75-7.95 (m, 5H), 7.97-8.08(q,2H),8.18-8.21(d,2H), 8.57-8.80 (d,2H).^{13}C NMR(300MHz,$CDCl_3$):δ 158.06,145.74,139.83,136.96,134.18,131.96,131.33, 128.71, 128.02, 127.71, 127.39, 127.09, 126.35,126.20,126.06,125.97, 125.41, 125.27,124.99,124.68,123.26,123.15,74.85,74.85,74.59,74.34.

Results and Discussion

For optimization of the isoquinoline synthesis, initially various catalysts were tested for the model reaction of benzophenone hydrazone **1a** as a starting substrate and diphenylacetylene **2a** as a coupling partner. A summary of the experiment optimization is provided in Table I. It was found that, [Ru (p-cymene)Cl_2]$_2$ was the most efficient catalyst compared with SnCl4, InCl3, DMAP and *L*-Proline which exhibited from moderate to poor catalytic properties. When benzophenone hydrazone **1a** was treated with diphenylacetylene **2a** without presence of any catalyst only using $Cu(OAc)_2$, NaOAc as a oxidants and $AgSbF_6$ (10 mol %) as additive in EtOH, it was found that only $Cu(OAc)_2$ gives the better yield than NaOAc as oxidant (entry 1and 2), using this result we further used $Cu(OAc)_2$ as oxidant for different catalysts as well as solvents. When the reaction was performed using [Ru (p-cymene)Cl_2]$_2$ (5mole %) as catalyst, $Cu(OAC)_2$ as oxidant and $AgSbF_6$ as additive in PEG-400 as green solvent gives the isoquinoline with good yield (90%) within 10 hrs at 110°C in an air atm pressure. Before this when reaction was performed using $SnCl_4$ as catalyst, $Cu(OAc)_2$ and NaOAc as oxidants and $AgSbF_6$ as additive in EtOH and toluene, it furnished desired

Table I — Optimization of reaction parameters



1a **2a** **3a**

Entry	Catalyst	Solvent	Oxidant	Catalytic loading (mol %)	Additives	Temp °C	Time (h)	Yield (%)
1	–	EtOH	$Cu(OAc)_2$	–	$AgSbF_6$	110	20	56
2	–	EtOH	NaOAc	–	$AgSbF_6$	110	23	45
3	$SnCl_2$	EtOH	NaOAc	5	$AgSbF_6$	110	20	60
4	$SnCl_2$	Toluene	$Cu(OAc)_2$	5	$AgSbF_6$	110	18	62
5	L- Proline	EtOH	$Cu(OAc)_2$	5	$AgSbF_6$	110	19	65
6	L-Proline	DCM	$Cu(OAc)_2$	5	$AgSbF_6$	110	21	63
7	$InCl_3$	EtOH	$Cu(OAc)_2$	5	$AgSbF_6$	110	25	70
8	$InCl_3$	DCM	$Cu(OAc)_2$	5	$AgSbF_6$	110	24	50
9	DMAP	EtOH	$Cu(OAc)_2$	5	$AgSbF_6$	110	16	68
10	DMAP	PEG-400	$Cu(OAc)_2$	5	$AgSbF_6$	110	15	75
11	[Ru (p-cymene)Cl_2]$_2$	DCM	$Cu(OAc)_2$	5	$AgSbF_6$	110	14	60
12	[Ru (p-cymene)Cl_2]$_2$	PEG-400	$Cu(OAc)_2$	5	$AgSbF_6$	110	11.30	85
13	[Ru (p-cymene)Cl_2]$_2$	EtOH	$Cu(OAc)_2$	5	$AgSbF_6$	110	13	80
14	[Ru (p-cymene)Cl_2]$_2$	Toluene	$Cu(OAc)_2$	5	$AgSbF_6$	110	14.30	78

isoquinoline 3a in low yield but better in case of $Cu(OAc)_2$ than NaOAc (Table I, entry 3.4). Therefore, from results (entry 1,2,3,4), it was concluded that $Cu(OAc)_2$ acts as better oxidizing agent than NaOAc. Gratifyingly, introduction of catalyst such as $InCl_3$, DMAP, and *L*-Proline was found to promote the reaction (Table I, entries 5–9) in solvent such as EtOH, DCM, Toluene and PEG-400. More pleasingly, when solvents were tested (Table I, entries 5–7), it was found that use of PEG-400 furnished the required isoquinoline in almost quantitative yield (Table I, entry 10).

After optimization effect of concentration of the catalyst have been studied (Table II). It was found that loading of 10mol % of catalyst gives 90% of the yield in stipulated time (Table II, entry2). Increase and decrease of catalytic concentration decreases the percentage of yield. With this optimization in our hand we also studied effect of decrease and increase of the reaction temperature resulted in a diminished yield of the product (Table II, entry 6, 7).

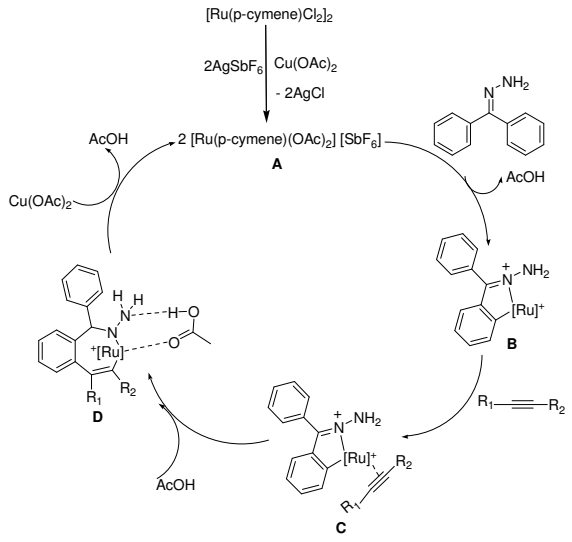
After determining the optimized condition, we investigated the scope and generality of the reaction

Table II — Effect of catalyst concentration [Ru (p-cymene)Cl_2]$_2$ in solvent PEG-400

Entry	Catalyst (mole %)	Time (h)	Temp °C	Yield[a] (%)
1	5	11.30	110	85
2	10	10	110	90
4	15	15	110	86
5	20	18	110	80
6	10	13	100	70
7	10	09	120	75

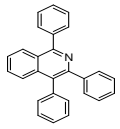
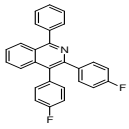
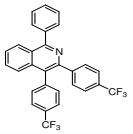
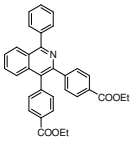
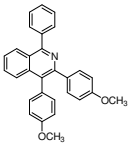
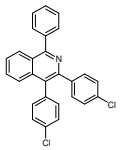
[a] Isolated yield

using different internal alkynes (Scheme II). It was found that diarylalkyne having an electron-donating functional group on the aromatic ring furnished the corresponding isoquinoline in good yield (Table III). Interestingly, disubstituted alkyne also participated in the annulation reaction, producing the corresponding product in moderate yield. The alkynes bearing electron-withdrawing groups such as Cl,F, CF_3, and ester on the aromatic ring also furnished the corresponding isoquinolines in good to excellent yields. When *meta*-substituted diarylalkynes were employed, the reaction also delivered the products in high yields. The sterically hindered *o*-substituted



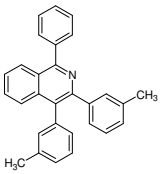
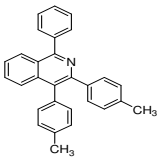
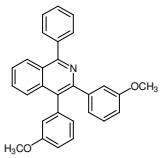
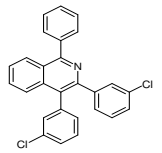
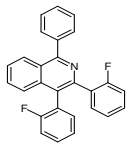
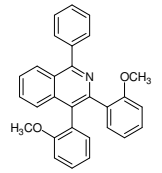
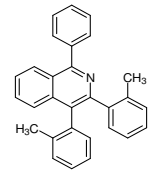
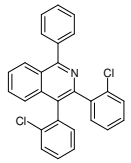
Scheme II — Plausible mechanism

Table III — Exploration of the substrate scope for the synthesis of isoquinoline derivatives

Compd	Substituted Phenyl acetylene	Time (h)	Product	m.p. (°C.	Yield[a] (%)
3a	H	10		187-191[18a]	90
3b	4-F	11		183-185[18a]	88
3c	4-CF_3	12		208-210[9]	85
3d	4-COOEt	11		173-175[9]	86
3e	4-OMe	10		175-177[18b]	91
3f	4-Cl	10.5		189-191[18a]	90

(*Contd*.)

Table III — Exploration of the substrate scope for the synthesis of isoquinoline derivatives

Compd	Substituted Phenyl acetylene	Time (h)	Product	m.p. (°C.	Yield[a] (%)
3g	3-CH_3	10		224-226[18a]	88
3h	4-CH_3	10		218-220	92
3i	3-OCH_3	11.5		194-196[19]	95
3j	3-Cl	12		213-215[9]	87
3k	2-F	11		203-206	88
3l	2-OCH_3	10.5		208-210[19]	90
3m	2-CH_3	10		194-196	87
3n	2-Cl	11		233-235	89

[a] Isolated yield

diarylalkyne was also found to be companionable under our reaction conditions. Analytical data for all the synthesised isoquinoline derivatives have been matched with literature value.[9]

On the basis of the organize experiments described above and related Ru(II)-catalyzed annulations reactions, a plausible mechanism is proposed as outlined in Scheme II. Initially, [Ru (p-cymene)Cl_2]$_2$

reacts with $AgSbF_6$ in the presence of $Cu(Ac)_2$ to generate catalytically active complex A. Then complex A undergoes cyclometalation with 1a to generate B. This is followed by migratory insertion of alkyne 2a into B to form seven-membered Ru-cyclic intermediate C, which upon acetic acid-assisted proton transfer generates intermediate D, which eventually undergoes intramolecular substitution resulting in the formation of a C–N bond and the breakage of a N–N bond to furnish isoquinoline 3a with attendant regeneration of catalytically active Ru(II) species A.

Conclusion

In this study, we report an extraordinary ruthenium catalyzed homogeneous recyclable catalytic media for hydrazine with alkynes, in consideration with the advantages presented by PEG-400 as a green and sustainable solvent using $Cu(OAc)_2$ as oxidant and $AgSbF_6$ as additive at ambient temperature for the synthesis of 1-Phenyl Isoquinoline derivatives. This methodology accounts for high atom economy, efficiency, environmental impact, and elegance as it reduces the unnecessary prefunctionalization of starting material.

Supplementary Information

Supplementary information is available in the website http://nopr.niscair.res.in/handle/123456789/60.

Acknowledgment

The authors acknowledge Dr. D. R. More, L.B.S. College, Dharmabad and Shri Muktanand Mahavidyalaya, Gangapur, Dist. Aurangabad for providing necessary facilities. The authors are also grateful to CSIR-IICT, Hyderabad for providing the spectral data.

References

1 (a) Zeni G & Larock R C, *Chem Rev*, 104 (2004) 2285; (b) Nakamura I & Yamamoto Y, *Chem Rev*, 104 (2004) 2127; (c) Roesch K R & Larock R C, *J Org Chem*, 63 (1998) 5306; (d) Huang Q, Hunter J A & Larock R C, *Org Lett*, 3 (2001) 2973; (e) Roesch K R, Zhang H & Larock R C, *J Org Chem*, 66 (2001) 8042; (f) Korivi R P & Cheng C H, *Org Lett*, 7 (2005) 5179; (g) Korivi R P, Wu W J & Cheng C H, *Chem Eur J*, 15 (2009) 10727; (h) Korivi R P, Wu W J & Cheng C H, *Chem Eur J*, 16 (2010) 282.

2 (a) Colby D A, Bergman R G & Ellman J A, *Chem Rev*, 110 (2010) 624; (b) Cho S H, Kim J Y, Wak J K & Chang S, *Chem Soc Rev*, 40 (2011) 5068; (c) Ackermann L, *Chem Rev*, 111 (2011) 1315; (d) Wencel-Delord J, Dröge T, Liu T F & Glorius F, *Chem Soc Rev*, 409 (2011) 4740; (e) Arockiam P B, Bruneau C & Dixneuf P H, *Chem Rev*, 112 (2012) 5879; (f) Wencel-Delord J & Glorius F, *Nat Chem*, 5 (2013) 369; (g) Shin K, Kim H & Chang S, *Acc Chem Res*, 48 (2015) 1040; (h) Ackermann L, *Org Process Res Dev*, 19 (2015) 260.

3 He R, Huang Z T, Zheng Q T & Wang C, *Tetrahedron Lett*, 55 (2014) 5705 and references cited therein.

4 (a) Kulkarni D A, *Org Synnth*, 4087 (2009); (b) Nakao Y, *Chem Rec*, 11 (2011) 242; (c) Miao J & Ge H, *Eur J Org Chem*, 7859 (2015); (d) Liu W & Ackermann L, *ACS Catal*, 6 (2016) 3743.

5 (a) Sun B,Yoshino T, Kanai M & Matsunaga S, *Angew Chem Int Ed*, 54 (2015) 12968; (b) Wang H, Koeller J, Liu W & Ackermann L, *Chem Eur J*, 21 (2015) 15525; (c) Sen M, Kalsi D & Sundararaju B, *Chem Eur J*, 21 (2015) 15529; (d) Muralirajan K, Kuppusamy R, Prakash S & Cheng C H, *Adv Synth Catal*, 358 (2016) 774.

6 Zhang S S, Xi G X G, Chen S Y, Tan D H, Jiang C Y, Wu J Q, Li Q & Wang H, *Adv Synth Catal*, 358 (2016) 1705.

7 Li J, Tang M, Zang L, Zhang X, Zhang Z & Ackermann L, *Org Lett*, 18 (2016) 2742.

8 Wang F, Wang Q, Bao M & Li X, *Chin J Catal*, 37 (2016) 1423.

9 Pawar A B, Darpan A & Lade D M, *J Org Chem*, 81 (2016) 11409.

10 (a) Kishor P & Jeganmohan M, *Org Lett*, 14 (2012) 1134; (b) Kishor P & Jeganmohan M, *Org Lett*, 13 (2011) 6144; (c) Ravi Kiran C G & Jeganmohan M, *Eur J Org Chem*, 417 (2012); (d) Ravi Kiran C G, Jeganmohan M, *Chem Commun*, 48 (2012) 2030.

11 (a) Thansandote P & Lautens M, *Chem Eur J*, 15 (2009) 5874; (b) Satoh T & Miura M, *Chem Eur J*, 16 (2010) 11212; (c) Satoh T & Miura M, *Synthesis*, 20 (2010) 3395; (d) Colby D A, Bergman R G & Ellman J A, *Chem Rev*, 110 (2010) 624.

12 (a) Lim S G, Lee J H, Moon C W, Hong C J W & Jun C H, *Org Lett*, 5 (2000) 2759; (b) Parthasarathy K, ,Jeganmohan M & Cheng C H, *Org Lett*, 10 (2008) 325; (c) Parthasarathy K & Cheng C H, *J Org Chem*, 74 (2009) 9359; (d) Parthasarathy K & Cheng C H, *Synthesis*, 8 (2009) 1400; (e) Colby D A, Bergman R G & Ellman J A, *J Am Chem Soc*, 130 (2008) 3645; (f) Martin R M, Bergman R G & Ellman J A, *J Am Chem Soc*, 134 (2012) 2501.

13 (a) Too P C, Wang Y F & Chiba S, *Org Lett*, 12 (2010) 5688; (b) Too P C, Chua S H, Wong S H & Chiba S J, *J Org Chem*, 76 (2011) 6159; (c) Wang Y F, Toh K K, Lee J Y & Chiba S, *Angew Chem Int Ed*, 50 (2011) 5927; (d) Zhang X, Chen D, Zhao M, Zhao J, Jia A & Li X, *Adv Synth Catal*, 353 (2011) 719; (e) Hyster T K & Rovis T, *Chem Commun*, 47 (2011) 11846.

14 (a) Ackermann L, Lygin A V & Hofmann N, *Angew Chem Int Ed*, 50 (2011) 6379; (b) Ackermann L, Lygin A V & Hofmann N, *Org Lett*, 13 (2011) 3278; (c) Ackermann L & Fenner S, *Org Lett*, 13 (2011) 6548; (d) Li B, Feng H, Xu S & Wang B, *Chem Eur J*, 17 (2011) 12573; (e) Ackermann L, Wang L & Lygin A V, *Chem Sci*, 3 (2012) 177; (f) Ackermann L & Lygin A V, *Org Lett*, 14 (2012) 764.

15 (a) Ackermann L, Pospech J, Graczyk K & Rauch K, *Org Lett*, 14 (2012) 930; (b) Hashimoto Y, Hirano K, Satoh T, Kakiuchi F & Miura M, *Org Lett*, 14 (2012) 2058.

16 Ravi Kiran C, Sandeep P & Masilamani J, *Org Lett*, 14 (2012) 12.
17 Rajendran M, Masilamani T & Masilamani J, *Org Lett*, 19 (2017) 6678.
18 Deshmukh D S & Bhanage B M, *Org Biomol Chem* (2018).
19 (a) Zhang S, Huang D, Xu G, Cao S, Wang R, Peng S & Sun J, *Org Biomol Chem*, 13 (2015) 7920; (b) Qiu L, Huang D, Xu G, Dai Z & Sun J, *Org Lett*, 17 (2015) 1810; (c) Zhang S S, Liu X G, Chen S Y, Tan D H, Jiang C Y, Wu J Q, Li Q & Wang H, *Adv Synth Catal*, 358 (2016) 1705.