RSC Advances

PAPER

Cite this: *RSC Adv.*, 2020, **10**, 8586

The synthesis of quinolines *via* denitrogenative palladium-catalyzed cascade reaction of *o*-aminocinnamonitriles with arylhydrazines†

Jing Xie,[a] Hang Huang,[b] Tong Xu,[c] Renhao Li,[d] Jiuxi Chen *[c] and Xueting Ye*[b]

Received 3rd February 2020
Accepted 20th February 2020

DOI: 10.1039/d0ra01043j

rsc.li/rsc-advances

The first example of the palladium-catalyzed cascade reaction of *o*-aminocinnamonitriles with arylhydrazines has been achieved, providing an efficient synthetic pathway to access quinolines with moderate to good yields. Preliminary mechanistic experiments indicate that this cascade process involves sequential denitrogenative addition followed by an intramolecular cyclization.

Introduction

Quinoline derivatives have become increasingly popular in the past few years due to their ubiquity in natural products, bioactive compounds, and other functional molecules. For example, quinoline scaffolds are privileged structures in medicinal chemistry, and therapeutic agents with such cores on the market or in clinical trials for the treatment of urological malignancies such as renal cell carcinoma (*e.g.*, lenvatinib,[1] cabozantinib[2]) and the treatment of head and neck cancer (*e.g.*, camptothecin[3]) (Fig. 1). Therefore, the development of the effective methods for the synthesis of quinolines has been actively pursued during the past several decades.[4] However, less attention has been paid to the preparation of quinolines from nitriles.

Nitriles are well-known as solvents or ligands in organometallic reactions because of the inherently inert nature of the C≡N bond.[5] For example, acetonitrile or benzonitrile are usually used as solvents or ligands in many transition-metal-catalyzed reactions.[6] The development of transition-metal-catalyzed inert C≡N bond activation and further transformation has received significant attention from organic chemists because nitriles are normally very stable and abundant and cheap feedstock chemicals. Substantial progress towards this goal made in recent years, the transition-metal-catalyzed transformation of nitriles offers an attractive route for the synthesis of arylketones or further cyclization products by several other groups.[7] Our group also developed transition-metal-catalyzed a series of tandem addition/cyclization reaction of nitriles with organoboron reagents for the synthesis of structurally diverse 5-membered, 6-membered, and 7-membered *N*-heterocycles.[8] In addition, arylhydrazines are used as an important class of molecular building blocks in both synthetic and medicinal chemistry for preparing various nitrogen-containing compounds because of their high reactivity, low cost, and ready availability.[9] Recent progresses in the development of using arylhydrazines as aryl source by denitrogenation have been documented.[10] Despite the remarkable advances in transition-metal-catalyzed addition reactions of nitriles with arylating reagents into a valuable array of products to date, less attention has been paid to the using arylhydrazines as aryl sources by denitrogenation presumably due to the high dissociation energy from direct activation of the C–N bond.[11] To our knowledge, only two examples of denitrogenative palladium-catalyzed reaction of nitriles with arylhydrazines for the synthesis of aryl ketones have been reported (Scheme 1a).[12]

We envisioned that a Pd-catalyzed sequential denitrogenative addition followed by an intramolecular dehydrative cyclization of readily available *o*-aminocinnamonitriles with arylhydrazines would result in a tandem procedure for the preparation of 2-arylquinolines (Scheme 1b). It is worth noting that the amino group cannot approach the carbonyl group to achieve the intramolecular cyclization because of the steric configuration. Recently, Cheon group developed the synthesis of 2-substituted quinolines by the dehydrative cyclization of 2-aminostyryl ketones.[13] These strategies involve the change of unreactive (*E*)-2-aminostyryl ketones into the unstable but reactive *Z*-configuration intermediate to undergo dehydrative cyclization reaction by using iodide[13a] or benzylamine[13b] as the nucleophilic catalyst. Recently, we reported the Pd-catalyzed tandem reaction of 2-aminostyryl nitriles with arylboronic acids for the synthesis of 2-arylquinolines.[14] As part of the continuing efforts in our laboratory toward the development of novel transformations of nitriles,[8,14] we herein report the first example of the denitrogenative Pd-catalyzed cascade reaction of

---

[a] Department of Stomatology, The First Affiliated Hospital of Wenzhou Medical University, Wenzhou 325000, China

[b] Department of Urology, The First Affiliated Hospital of Wenzhou Medical University, Wenzhou 325000, China. E-mail: yexueting001@163.com

[c] College of Chemistry & Materials Engineering, Wenzhou University, Wenzhou 325000, China. E-mail: jiuxichen@wzu.edu.cn

[d] School of Pharmaceutical Sciences, Wenzhou Medical University, Wenzhou 325000, China

† Electronic supplementary information (ESI) available: ^{1}H and ^{13}C NMR spectra for products. See DOI: 10.1039/d0ra01043j

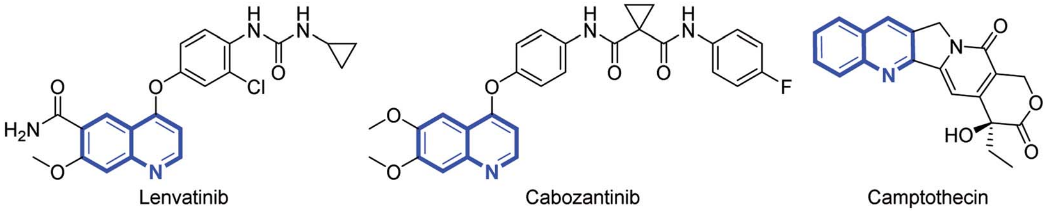
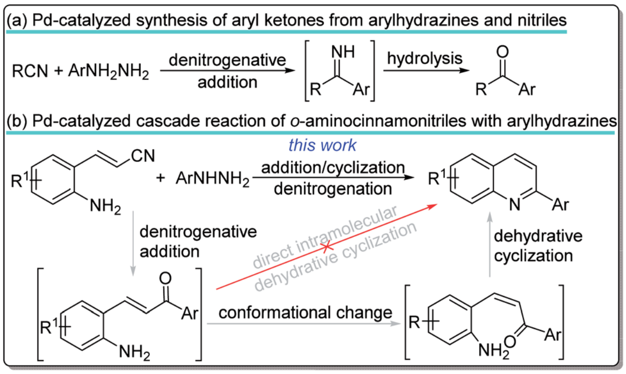


Fig. 1 Representative bioactive quinoline derivatives.



Scheme 1 Design of new approach to quinolines.

o-aminocinnamonitriles with arylhydrazines to afford 2-arylquinolines (Scheme 1b).

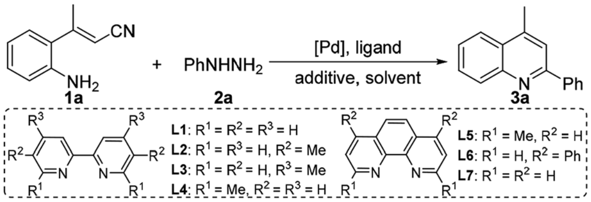
Results and discussion

We begin our investigation with readily available (*E*)-3-(2-aminophenyl)but-2-enenitrile (**1a**) and phenylhydrazine (**2a**) for the optimization of reaction conditions (Table 1).

We initially found that the desired product 2-phenylquinoline (**3a**) could be obtained in 12% yield under the combination of Pd(OAc)$_2$, trifluoroacetic acid (TFA) and 2,2′-bipyridine (**L1**) in THF under air atmosphere (entry 2). Various palladium catalysts were tested (entries 3–7) and PdCl$_2$ exhibited the highest catalytic reactivity in 31% yield (entry 5). Delightedly, the yield of **3a** could be improved to 56% using toluene as the solvent. Other solvents, including DMF, dimethylacetamide (DMA), 1,4-dioxane and H$_2$O were less efficient (entries 8–13). Replacement of **L1** with other bidentate *N*-ligands (entries 13–19), resulted in lower yields. However, trace amounts of **3a** was detected when sterically hindered ligands, such as 6,6′-dimethyl-2,2′-bipyridine (**L4**) and 2,9-dimethyl-1,10-phenanthroline (**L5**) were used (entries 16–17). An investigation of the effect of additive revealed that the yield of **3a** was greatly increased to 81% under O$_2$ atmosphere (entry 23). The product **3a** was not observed if either Pd catalyst or ligand was absent (entries 24 and 25).

Having the optimized reaction conditions in hand, we examined the substrates scope of this cascade reaction. First, the cascade reaction of (*E*)-3-(2-aminophenyl)but-2-enenitrile (**1a**) with different arylhydrazines were evaluated under optimized conditions (Table 2). The reactivities of *para*-, *meta*-, and *ortho*-tolylhydrazine were evaluated, and the results demonstrated that the steric effect of the substituent had an obvious impact on the reaction. For example, the reactions of **1a** with *para*- and *meta*-tolylhydrazine afforded 85% and 79% yields of **3b** and **3c**, respectively, while the *ortho*-tolylhydrazine gave the desired product **3d** with a diminished yield of 52%. Moderately electron-withdrawing halogens, such as fluoro (**3e**–**3f**), chloro (**3g**), and bromo (**3h**) groups, were compatible with this reaction, providing 42–76% yields. The substrate bearing

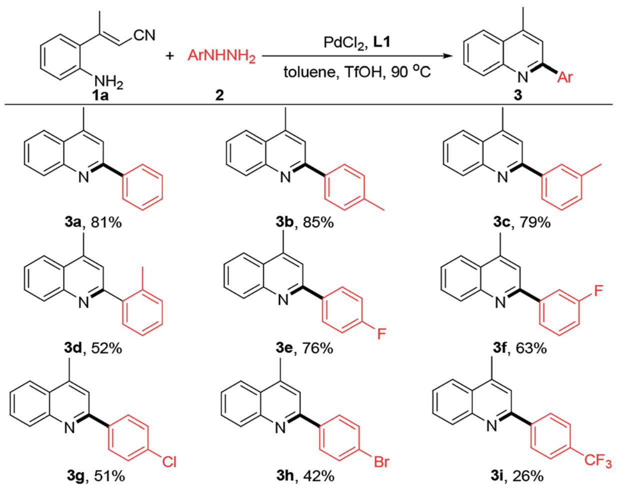
Table 1 Optimization of reaction conditions[a]



Entry	[Pd]	Ligand	Additive	Solvent	Yield[b] (%)
1	Pd(PPh$_3$)$_4$	**L1**	TFA	THF	0
2	Pd(OM)$_2$	**L1**	TFA	THF	12
3	Pd(CF$_3$CO$_2$)$_2$	**L1**	TFA	THF	19
4	Pd(PPh$_3$)$_2$Cl$_2$	**L1**	TFA	THF	17
5	PdCl$_2$	**L1**	TFA	THF	31
6	Pd$_2$(dba)$_3$	**L1**	TFA	THF	21
7	Pd(acac)$_2$	**L1**	TFA	THF	23
8	PdCl$_2$	**L1**	TFA	2-MeTHF	37
9	PdCl$_2$	**L1**	TFA	DMF	41
10	PdCl$_2$	**L1**	TFA	DMA	47
11	PdCl$_2$	**L1**	TFA	1,4-Dioxane	23
12	PdCl$_2$	**L1**	TFA	Toluene	56
13	PdCl$_2$	**L1**	TFA	H$_2$O	18
14	PdCl$_2$	**L2**	TFA	Toluene	53
15	PdCl$_2$	**L3**	TFA	Toluene	51
16	PdCl$_2$	**L4**	TFA	Toluene	Trace
17	PdCl$_2$	**L5**	TFA	Toluene	Trace
18	PdCl$_2$	**L6**	TFA	Toluene	41
19	PdCl$_2$	**L7**	TFA	Toluene	51
20	PdCl$_2$	**L1**	AcOH	Toluene	Trace
21	PdCl$_2$	**L1**	TsOH·H$_2$O	Toluene	33
22	PdCl$_2$	**L1**	MsOH	Toluene	21
23	PdCl$_2$	**L1**	TfOH	Toluene	79(81)[c]
24		**L1**	TfOH	Toluene	0
25	PdC1$_2$		TfOH	Toluene	0

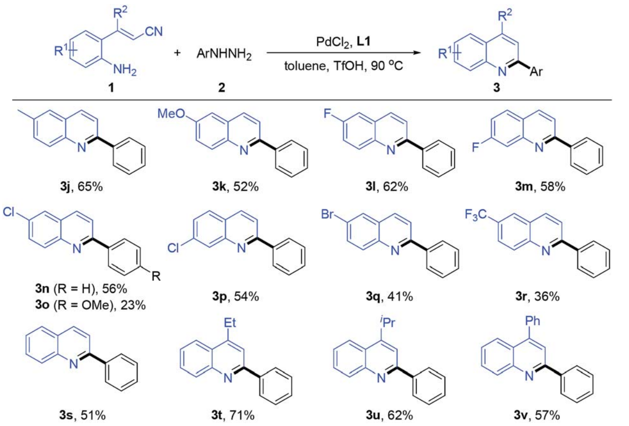
[a] Conditions: **1a** (0.3 mmol), **2a** (0.6 mmol), Pd catalyst (10 mol%), ligand (20 mol%), additive (2 equiv.), solvent (2 mL), 90 °C, 24 h, air. [b] Isolated yield. [c] Under O$_2$.

Table 2 Denitrogenative Pd-catalyzed cascade reaction of **1a** with arylhydrazines[a]



[a] Conditions: **1a** (0.3 mmol), **2** (0.6 mmol), $PdCl_2$ (10 mol%), **L1** (20 mol%), toluene (2 mL), TfOH (2 equiv.), 90 °C, 24 h, O_2, isolated yield.

Table 3 Denitrogenative Pd-catalyzed reaction of *o*-aminocinnamonitriles with arylhydrazines[a]



[a] Conditions: **1** (0.3 mmol), **2** (0.6 mmol), $PdCl_2$ (10 mol%), **L1** (20 mol%), toluene (2 mL), TfOH (2 equiv.), 90 °C, 24 h, O_2, isolated yield.

a strong electron-withdrawing group (*e.g.*, CF_3) could also be well tolerated, albeit giving the desired **3i** in a slightly lower yield.

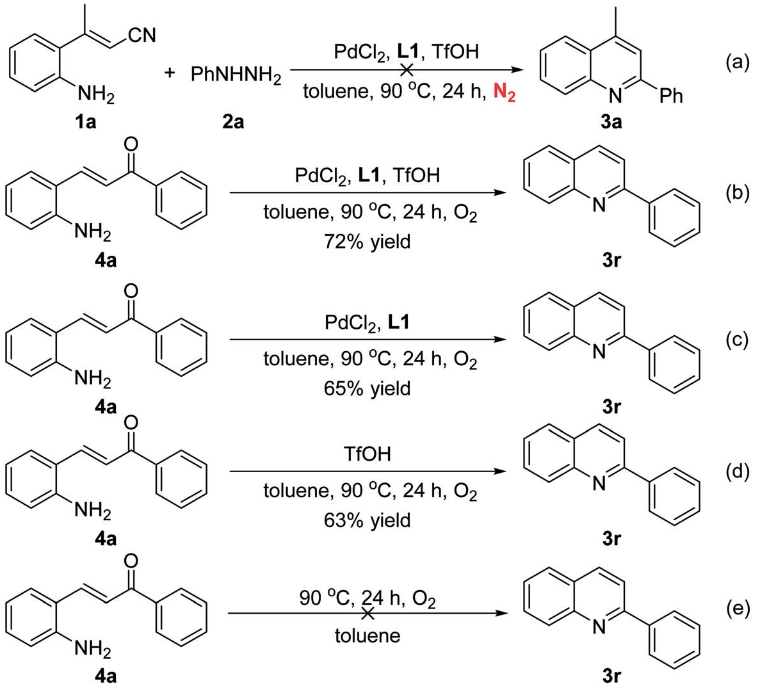
We next turned our attention to the effect of the reactions between substituted *o*-aminocinnamonitriles (**1**) and phenylhydrazine (**2a**) under standard conditions (Table 3). First, the influence of a variety of functional groups (R^1) on the phenyl ring of the 2-(benzylideneamino)benzonitriles was evaluated. Both electron-donating groups, such as methyl (**3j**) and methoxy (**3k**) moieties, and electron-withdrawing groups, such as fluoro (**3l**–**3m**), chloro (**3n**–**3p**) and bromo (**3q**) moieties, were also compatible, affording the corresponding desired products with moderate to good yields. Treatment of a strong electron-withdrawing trifluoromethyl substituent with **2a** delivered product **3r** in 36% yield. Finally, several representative examples of substituents (R^2) on the carbon–carbon double bond were investigated. The R^2-substituted products **3t**, **3u** and **3u** was obtained in 71%, 62% and 57% yields, respectively, compared to relatively low yield of the product **3s** in 51% yield. It is worth noting that the presence of the halogen in the products (*e.g.*, **3h**, **3q**) is very useful for further synthetic elaborations by cross-coupling reaction thereby broadening the diversity of the products.

To gain insight into the mechanism of this cascade reaction, several control experiments were conducted (Scheme 2). The desired product **3a** was not detected when the reaction was performed under N_2 atmosphere (Scheme 2a), which revealed that the reaction required the presence of oxygen. As expected, the reactions of (*E*)-3-(2-aminophenyl)-1-phenylprop-2-en-1-one (**4a**) under optimized conditions in the absence of phenylhydrazine achieved the product 2-phenylquinoline (**3r**) in 72% yield, indicating that **4a** was proposed as a possible intermediate for this transformation (Scheme 2b). The cyclization of **4a** gave the desired product **3r** in 65% yield in the absence of TfOH (Scheme 2c). The cyclization of **4a** could also proceed to afford **3r** in 63% yield in the absence of $PdCl_2$/**L1** (Scheme 2d). However, we attempted to perform the reaction in the absence of palladium catalyst and additive failed to give **3r** (Scheme 2e).

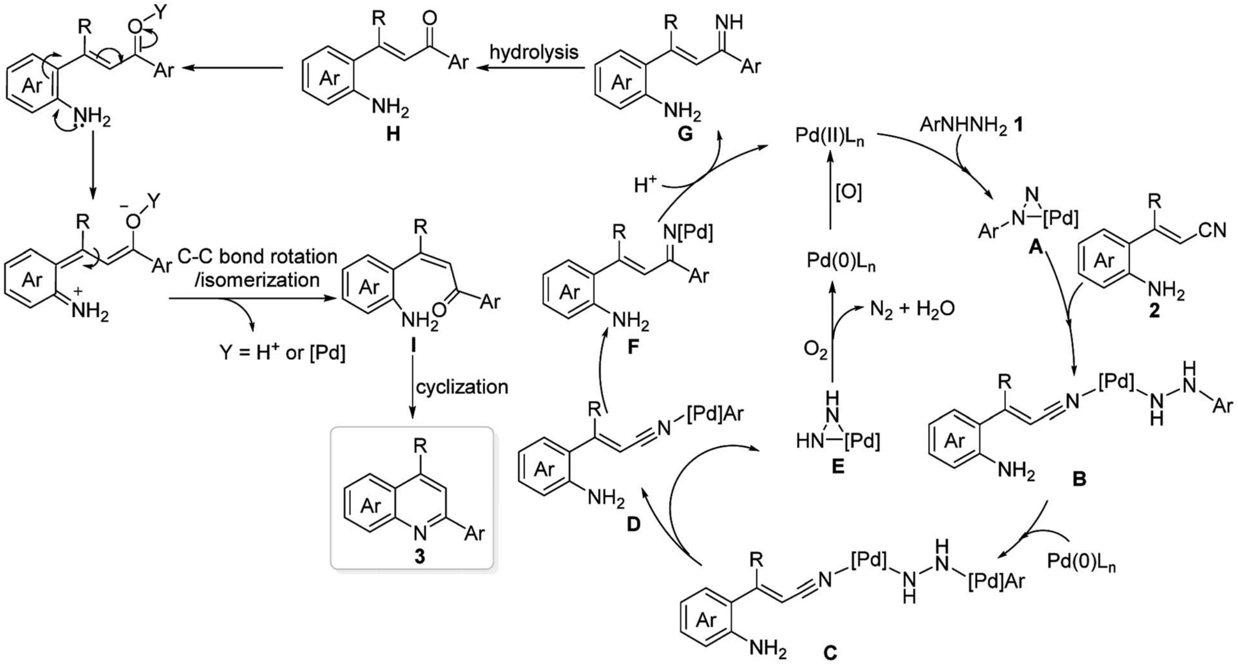
On the basis of the above experimental results and previous reports,[12a] a possible reaction mechanism for the formation of quinolines is shown in Scheme 3. The first step may involve metathesis between the palladium catalyst and arylhydrazide to form the palladiaziridine intermediate **A**, which is followed by the coordination of cyano group affording intermediate **B**. Oxidative addition of the intermediate **B** to palladium(0) species to give the corresponding two palladium(II) centered intermediate **C** *via* C–N bond cleavage. Thereafter, cracking of the intermediate **C** gives the intermediate **D** and the palladiaziridine intermediate **E**, which would be decomposed into palladium(0), N_2 and H_2O in the presence of oxygen. Then, carbopalladation of the cyano group affords the imine-Pd intermediate **F**. Protonation of **F** by TfOH gives the imine intermediate **G** and regenerates palladium(II) species. Hydrolysis of **G** under acidic conditions would deliver the ketone intermediate **H**. Finally, the ketone intermediate **H** undergoes C–C bond *E*/*Z* configurational tautomerization to give **I** in the presence of TfOH and/or palladium(II) species, which is followed by intramolecular cyclization to generate the desired quinolines **3**.

Conclusions

In summary, we have developed a new and complementary strategy for the synthesis of 2-arylquinolines in moderate to good yields by palladium-catalyzed cascade denitrogenative addition and intramolecular cyclization of *o*-aminocinnamonitriles with arylhydrazines.



Scheme 2 Control experiments.



Scheme 3 Plausible reaction mechanism for the formation of quinolines.

Experimental section

General methods

Melting points are uncorrected. ^{1}H NMR and ^{13}C NMR spectra were measured on a 500 MHz spectrometer using $CDCl_3$ as the solvent with tetramethylsilane (TMS) as an internal standard at room temperature. Chemical shifts are given n δ relative to TMS, and the coupling constants *J* are given in hertz. The starting materials *o*-aminocinnamonitriles[15] and **4a**[16] were synthesized according to the method described in the literatures. Column chromatography was performed using EM silica gel 60 (300–400 mesh).

General procedure for the synthesis of quinolines

Under O_2 atmosphere, a Teflon-valve-sealed Schlenk tube was charged with *o*-aminocinnamonitriles and arylhydrazines, $PdCl_2$, **L1**, TfOH and toluene at room temperature. The reaction mixture was stirred for 10 minutes at room temperature for proper mixing of the reactants, and then heated at 90 °C (oil bath) with vigorous stirring for 24 hours. After the reaction equilibrium, the mixture was poured into ethyl acetate, which was washed with saturated $NaHCO_3$ (2×10 mL) and then brine (10 mL). The aqueous layer was extracted with ethyl acetate, the combined organic layers were dried over anhydrous Na_2SO_4 and evaporated under vacuum. The residue was purified by flash column chromatography (hexane/ethyl acetate) to afford the desired products.

4-Methyl-2-phenylquinoline (3a).[17] White solid (53.2 mg, 81%), mp 62–63 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.22 (d, $J =$ 10.5 Hz, 1H), 8.19–8.17 (m, 2H), 7.97 (d, $J =$ 10.5 Hz, 1H), 7.75–7.70 (m, 2H), 7.56–7.52 (m, 3H), 7.49–7.46 (m, 1H), 2.73 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.0, 148.2, 144.8, 139.8, 130.3, 129.3, 129.2, 128.8, 127.6, 127.3, 126.0, 123.6, 119.7, 19.0.

4-Methyl-2-(*p*-tolyl)quinoline (3b).[18] Yellow oil (59.4 mg, 85%). ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.20 (d, $J =$ 10.5 Hz, 1H), 8.09–8.07 (m, 2H), 7.98 (d, $J =$ 10.0 Hz, 1H), 7.74–7.70 (m, 2H), 7.55–7.51 (m, 1H), 7.34 (d, $J =$ 10.0 Hz, 2H), 2.74 (s, 3H), 2.45 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.0, 148.1, 144.7, 139.3, 136.9, 130.2, 129.5, 129.3, 127.4, 127.2, 125.9, 123.6, 119.6, 21.3, 19.0.

4-Methyl-2-(*m*-tolyl)quinoline (3c).[18] Yellow oil (55.2 mg, 79%). ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.22 (d, $J =$ 8.0 Hz, 1H), 8.02–7.98 (m, 2H), 7.94 (d, $J =$ 8.0 Hz, 1H), 7.74–7.70 (m, 2H), 7.56–7.52 (m, 1H), 7.44–7.41 (m, 1H), 7.29 (d, $J =$ 7.5 Hz, 1H), 2.75 (s, 3H), 2.50 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.3, 148.1, 144.7, 139.8, 138.4, 130.3, 130.0, 129.3, 128.7, 128.3, 127.3, 126.0, 124.7, 123.6, 119.9, 21.6, 19.0.

4-Methyl-2-(*o*-tolyl)quinoline (3d).[19] Yellow oil (36.3 mg, 52%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.20 (d, $J =$ 8.5 Hz, 1H), 8.04–8.03 (m, 1H), 7.76–7.73 (m, 1H), 7.60–7.57 (m, 1H), 7.51–7.49 (m, 1H), 7.39 (s, 1H), 7.37–7.31 (m, 3H), 2.76 (s, 3H), 2.43 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 160.3, 147.9, 144.3, 140.5, 136.0, 130.3, 130.0, 129.6, 129.3, 128.3, 126.0, 123.6, 123.1, 20.3, 18.8.

2-(4-Fluorophenyl)-4-methylquinoline (3e).[20] Yellow oil (54.1 mg, 76%). ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.18 (d, $J =$ 10.5 Hz, 1H), 7.99 (d, $J =$ 10.5 Hz, 1H), 7.92–7.90 (m, 2H), 7.75–7.71 (m, 1H), 7.67 (s, 1H), 7.58–7.54 (m, 1H), 7.50–7.45 (m, 1H), 7.17–7.13 (m, 1H), 2.76 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 163.8 (d, $J =$ 247.5 Hz), 155.9, 148.1, 145.0, 135.9 (d, $J =$ 2.5 Hz), 130.2, 129.4, 129.3 (d, $J =$ 7.5 Hz), 127.2, 126.1, 123.6, 119.4, 115.7 (d, $J =$ 22.5 Hz), 19.0.

2-(3-Fluorophenyl)-4-methylquinoline (3f).[21] Yellow oil (44.8 mg, 63%). ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.18 (m, 3H), 7.86–7.85 (m, 1H), 7.61–7.50 (m, 2H), 7.43–7.42 (m, 1H), 7.09–7.07 (m, 2H), 2.62 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 163.4 (d, $J =$ 243.8 Hz), 155.5 (d, $J =$ 2.5 Hz), 148.0, 145.1, 142.1 (d, $J =$ 7.5 Hz), 130.4, 130.2 (d, $J =$ 8.8 Hz), 129.5, 127.4, 126.4, 123.6, 123.0 (d, $J =$ 3.8 Hz), 119.4, 116.0 (d, $J =$ 21.3 Hz), 114.4 (d, $J =$ 22.5 Hz), 19.0.

2-(4-Chlorophenyl)-4-methylquinoline (3g).[22] White solid (38.8 mg, 51%), mp 73–74 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.16 (d, $J =$ 10.5 Hz, 1H), 8.11–8.09 (m, 2H), 7.98 (d, $J =$ 10.5 Hz, 1H), 7.74–7.70 (m, 1H), 7.65 (s, 1H), 7.57–7.53 (m, 1H), 7.49–7.47 (m, 2H), 2.74 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 155.5, 147.9, 144.9, 138.0, 135.3, 130.1, 129.4, 128.8, 128.6, 126.2, 126.1, 123.5, 119.1, 18.8.

2-(4-Bromophenyl)-4-methylquinoline (3h).[21] White solid (37.5 mg, 42%), mp 66–67 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.22–8.15 (m, 2H), 8.05–8.03 (m, 1H), 8.00–7.98 (m, 1H), 7.74–7.71 (m, 1H), 7.66–7.63 (m, 2H), 7.57–7.51 (m, 2H), 2.77–2.76 (m, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 155.3, 148.0, 145.2, 141.8, 132.1, 130.6, 130.4, 130.3, 129.6, 127.4, 126.4, 126.1, 123.7, 123.1, 119.5, 19.0.

4-Methyl-2-(4-(trifluoromethyl)phenyl)quinoline (3i).[23] Yellow oil (22.4 mg, 26%). ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.27 (d, J = 8.0 Hz, 2H), 8.20 (d, $J =$ 8.5 Hz, 1H), 8.02 (d, $J =$ 8.0 Hz, 1H), 7.78–7.24 (m, 4H), 7.60–7.57 (m, 1H), 2.79 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 155.5, 148.0, 145.5, 143.0, 131.0 (d, $J =$ 32.5 Hz), 130.4, 129.7, 127.9, 127.5, 126.6, 125.7 (q, $J =$ 3.8 Hz), 124.2 (d, J = 270.0 Hz), 123.7, 119.6, 19.0.

6-Methyl-2-phenylquinoline (3j).[24] White solid (42.7 mg, 65%), mp 68–69 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.18–8.16 (m, 2H), 8.10 (d, $J =$ 11.0 Hz, 2H), 7.82 (d, $J =$ 11.0 Hz, 1H), 7.57–7.52 (m, 4H), 7.48–7.45 (m, 1H), 2.55 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 156.5, 146.8, 139.8, 136.2, 136.1, 132.0, 129.4, 129.2, 128.8, 127.5, 127.2, 126.3, 119.0, 21.6.

6-Methoxy-2-phenylquinoline (3k).[25] White solid (36.7 mg, 52%), mp 125–126 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.15–8.14 (m, 1H), 8.13 (s, 1H), 8.11 (d, $J =$ 6.0 Hz, 1H), 8.08 (d, $J =$ 6.0 Hz, 1H), 7.83 (d, $J =$ 11.5 Hz, 1H), 7.52 (dd, $J_1 =$ 9.5 Hz, $J_2 =$ 9.0 Hz, 2H), 7.45 (d, $J =$ 9.5 Hz, 1H), 7.39 (dd, $J_1 =$ 3.5 Hz, $J_2 =$ 11.5 Hz, 1H), 7.08 (d, $J =$ 3.5 Hz, 1H), 3.94 (s, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.8, 155.0, 144.4, 139.8, 135.5, 131.2, 128.9, 128.8, 128.2, 127.3, 122.3, 119.2, 105.1, 55.5.

6-Fluoro-2-phenylquinoline (3l).[16] White solid (41.5 mg, 62%), mp 94–95 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.21–8.19 (m, 2H), 8.17–8.15 (m, 2H), 7.91 (d, $J =$ 10.5 Hz, 1H), 7.56–7.44 (m, 5H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 160.4 (d, $J =$ 248.0 Hz), 156.7 (d, $J =$ 2.8 Hz), 145.3, 139.2, 136.2 (d, $J =$ 5.2 Hz), 132.1 (d, $J =$ 9.1 Hz), 129.5, 128.9, 127.7 (d, $J =$ 10.0 Hz), 127.5, 119.9 (d, $J =$ 25.7 Hz), 119.7, 110.5 (d, $J =$ 21.7 Hz).

7-Fluoro-2-phenylquinoline (3m).[25] White solid (38.8 mg, 58%), mp 88–89 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.22 (d, $J =$ 8.0 Hz, 1H), 8.16 (d, $J =$ 7.5 Hz, 2H), 7.86–7.80 (m, 3H), 7.56–7.53 (m, 2H), 7.50–7.47 (m, 1H), 7.34–7.30 (m, 1H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 163.3 (d, $J =$ 249.6 Hz), 158.3, 149.3 (d, $J =$ 12.9 Hz), 139.3, 136.6, 129.6, 129.4 (d, $J =$ 10.0 Hz), 128.9, 127.6, 124.2, 118.3 (d, $J =$ 2.5 Hz), 116.7 (d, $J =$ 25.5 Hz), 113.3 (d, $J =$ 20.2 Hz).

6-Chloro-2-phenylquinoline (3n).[26] White solid (40.3 mg, 56%), mp 109–110 °C. ^{11}H-NMR (500 MHz, $CDCl_3$) δ 8.16–8.11 (m, 4H), 7.89 (d, $J =$ 9.0 Hz, 1H), 7.84–7.80 (m, 1H), 7.66 (d, $J =$ 9.0 Hz, 1H), 7.55–7.52 (m, 2H), 7.49–7.47 (m, 1H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.5, 146.6, 139.2, 135.8, 132.0, 131.3, 130.6, 129.6, 128.9, 127.7, 127.5, 126.1, 119.8.

6-Chloro-2-(*p*-methoxyphenyl)quinoline (3o).[27] Pale yellow solid (18.6 mg, 23%), mp 156–158 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.14 (d, $J = 8.5$ Hz, 2H), 8.08 (d, $J = 8.5$ Hz, 2H), 7.85 (d, $J = 8.5$ Hz, 1H), 7.77 (s, 1H), 7.64 (d, $J = 9.0$ Hz, 1H), 7.05 (d, $J = 8.5$ Hz, 2H), 3.89 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 161.1, 157.1, 146.6, 135.7, 131.5, 131.0, 130.5, 128.9, 127.5, 126.1, 119.3, 114.3, 55.4.

7-Chloro-2-phenylquinoline (3p).[28] White solid (38.8 mg, 54%), mp 106–107 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.21–8.15 (m, 4H), 7.89–7.87 (m, 1H), 7.77–7.75 (m, 1H), 7.56–7.48 (m, 4H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 158.2, 148.5, 139.0, 136.7, 135.6, 129.7, 128.9, 128.7, 128.6, 127.6, 127.4, 125.5, 119.2.

6-Bromo-2-phenylquinoline (3q).[27] White solid (34.9 mg, 41%), mp 113–114 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.15 (d, $J = 8.0$ Hz, 2H), 8.10–8.09 (m, 1H), 8.04 (d, $J = 8.0$ Hz, 1H), 7.96 (s, 1H), 7.88–7.86 (m, 1H), 7.79–7.77 (m, 1H), 7.55–7.52 (m, 2H), 7.50–7.47 (m, 1H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.6, 146.8, 139.1, 135.8, 133.1, 131.4, 129.6, 129.5, 128.9, 128.2, 127.5, 120.0, 119.7.

2-Phenyl-6-(trifluoromethyl)quinoline (3r).[29] White solid (29.5 mg, 36%), mp 118–119 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.26 (d, $J = 10.0$ Hz, 2H), 8.20–8.17 (m, 2H), 8.12 (s, 1H), 7.94 (d, $J = 10.0$ Hz, 1H), 7.90–7.88 (m, 1H), 7.58–7.51 (m, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 159.3, 149.3, 138.9, 137.4, 130.9, 130.0, 129.0, 128.2, 127.9, 127.7, 126.1, 125.4 (q, $J = 3.8$ Hz), 125.3 (q, $J = 3.8$ Hz), 123.1, 120.0.

2-Phenylquinoline (3s).[30] White solid (31.4 mg, 51%), mp 84–85 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.24–8.17 (m, 4H), 7.89 (d, $J = 10.0$ Hz, 1H), 7.84 (d, $J = 10.0$ Hz, 1H), 7.76–7.72 (m, 1H), 7.56–7.52 (m, 3H), 7.49–7.46 (m, 1H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.4, 148.3, 139.6, 136.8, 129.7, 129.6, 129.4, 128.8, 127.6, 127.4, 127.2, 126.3, 119.0.

4-Ethyl-2-phenylquinoline (3t).[20] Yellow oil (49.6 mg, 71%). ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.22 (d, $J = 10.5$ Hz, 1H), 8.18–8.17 (m, 2H), 8.04 (d, $J = 10.5$ Hz, 1H), 7.74–7.70 (m, 2H), 7.56–7.52 (m, 3H), 7.49–7.46 (m, 1H), 3.17 (q, $J = 9.5$ Hz, 2H), 1.45 (t, $J = 9.5$ Hz, 3H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.3, 150.4, 148.5, 140.1, 130.6, 129.2, 128.8, 127.6, 126.4, 126.0, 123.2, 117.8, 25.4, 14.2.

4-Isopropyl-2-phenylquinoline (3u).[31] Yellow oil (45.9 mg, 62%). ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.21 (d, $J = 10.5$ Hz, 1H), 8.17–8.15 (m, 2H), 8.11 (d, $J = 10.5$ Hz, 1H), 7.79 (s, 1H), 7.73–7.70 (m, 1H), 7.57–7.52 (m, 3H), 7.49–7.45 (m, 1H), 3.84–3.77 (m, 1H), 1.48 (d, $J = 9.0$ Hz, 6H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 157.4, 154.9, 148.6, 140.3, 130.7, 129.1, 129.0, 128.8, 127.6, 125.9, 125.8, 122.9, 114.9, 28.6, 23.0.

2,4-Diphenylquinoline (3v).[32] White solid (48.1 mg, 57%), mp 104–105 °C. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 8.28 (d, $J = 10.5$ Hz, 1H), 8.21–8.19 (m, 2H), 7.92 (d, $J = 10.5$ Hz, 1H), 7.83 (s, 1H), 7.77–7.73 (m, 1H), 7.57–7.55 (m, 4H), 7.54–7.48 (m, 5H); ^{13}C-NMR (125 MHz, $CDCl_3$) δ 156.9, 149.4, 148.7, 139.6, 138.4, 130.0, 129.6, 129.4, 128.8, 128.6, 128.4, 127.6, 126.4, 125.8, 125.7, 119.4.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

We thank the National Natural Science Foundation of China (No. 21572162) and the Natural Science Foundation of Zhejiang Province (No. LY20B020015) for financial support.

References

1 H. Študentová, D. Vitáskováand and B. Melichar, Lenvatinib for the treatment of kidney cancer, *Expert Rev. Anticancer Ther.*, 2018, **18**, 511–518.

2 A. Abdelaziz and U. Vaishampayan, Cabozantinib for the treatment of kidney cancer, *Expert Rev. Anticancer Ther.*, 2017, **17**, 577–584.

3 Y. Liu, W. Li, S. L. Morris-Natschke, K. Qian, L. Yang, G. Zhu, X. Wu, A. Chen, S. Zhang, X. Nan and K. Lee, Perspectives on biologically active camptothecin derivatives, *Med. Res. Rev.*, 2015, **35**, 753–789.

4 For selected reviews, see: (*a*) J. Marco-Contelles, E. Perez-Mayoral, A. Samadi, M. C. Carreiras and E. Soriano, Recent advances in the Friedländer reaction, *Chem. Rev.*, 2009, **109**, 2652–2671; (*b*) S. M. Prajapati, K. D. Patel, R. H. Vekariya, S. N. Panchal and H. D. Patel, Recent advances in the synthesis of quinolines: a review, *RSC Adv.*, 2014, **4**, 24463–24476; (*c*) V. Kouznetsov, L. Mendez and C. Gomez, Recent progress in the synthesis of quinolines, *Curr. Org. Chem.*, 2005, **9**, 141–161; (*d*) L. M. Nainwal, S. Tasneem, W. Akhtar, G. Verma, M. F. Khan, S. Parvez, M. Shaquiquzzaman, M. Akhter and M. M. Alam, Green recipes to quinoline: a review, *Eur. J. Med. Chem.*, 2019, **164**, 121–170.

5 (*a*) F. F. Fleming and Q. Wang, Unsaturated nitriles: conjugate additions of carbon nucleophiles to a recalcitrant class of acceptors, *Chem. Rev.*, 2003, **103**, 2035–2078; (*b*) V. Y. Kukushkin and A. J. L. Pombeiro, Additions to metal-activated organonitriles, *Chem. Rev.*, 2002, **102**, 1771–1802; (*c*) D. Enders and J. P. Shilvock, Some recent applications of α-amino nitrile chemistry, *Chem. Soc. Rev.*, 2000, **29**, 359–373.

6 S. F. Rach and F. E. Kühn, Nitrile ligated transition metal complexes with weakly coordinating counteranions and their catalytic applications, *Chem. Rev.*, 2009, **109**, 2061–2080.

7 (*a*) R. C. Larock, Q. P. Tian and A. A. Pletnev, Carbocycle synthesis via carbopalladation of nitriles, *J. Am. Chem. Soc.*, 1999, **121**, 3238–3239; (*b*) C. Zhou and R. C. Larock, Synthesis of aryl ketones by the Pd-catalyzed C–H activation of arenes and intermolecular carbopalladation of nitriles, *J. Am. Chem. Soc.*, 2004, **126**, 2302–2303; (*c*) J. Lindh, P. J. R. Sjöberg and M. Larhed, Synthesis of aryl ketones by palladium(II)-catalyzed decarboxylative addition of benzoic acids to nitriles, *Angew. Chem., Int. Ed.*, 2010, **49**, 7733–7737; (*d*) X. Wang, M. Liu, L. Xu, Q. Wang, J. Chen, J. Ding and H. Wu, Palladium-catalyzed addition of potassium aryltrifluoroborates to aliphatic nitriles: synthesis of alkyl aryl ketones, diketone compounds, and 2-arylbenzo[*b*]furans, *J. Org. Chem.*, 2013, **78**, 5273–5281; (*e*)

J. T. Reeves, C. A. Malapit, F. G. Buono, K. P. Sidhu, M. A. Marsini, C. A. Sader, K. R. Fandrick, C. A. Busacca and C. H. Senanayake, Transnitrilation from dimethylmalononitrile to aryl Grignard and lithium reagents: a practical method for aryl nitrile synthesis, *J. Am. Chem. Soc.*, 2015, **137**, 9481–9488; (*f*) C. A. Malapit, J. T. Reeves, C. A. Busacca, A. R. Howell and C. H. Senanayake, Rhodium-catalyzed transnitrilation of aryl boronic acids with dimethylmalononitrile, *Angew. Chem., Int. Ed.*, 2016, **55**, 326–330; (*g*) C. A. Malapit, D. R. Caldwell, I. K. Luvaga, J. T. Reeves, I. Volchkov, N. C. Gonnella, Z. S. Han, C. A. Busacca, A. R. Howell and C. H. Senanayake, Rhodium-catalyzed addition of aryl boronic acids to 2,2-disubstituted malononitriles, *Angew. Chem., Int. Ed.*, 2017, **56**, 6999–7002; (*h*) M. Meng, L. Yang, K. Cheng and C. Qi, Pd(II)-catalyzed denitrogenative and desulfinative addition of arylsulfonyl hydrazides with nitriles, *J. Org. Chem.*, 2018, **83**, 3275–3284; (*i*) L. R. Mills, J. M. Graham, P. Patel and S. A. L. Rousseaux, Ni-catalyzed reductive cyanation of aryl halides and phenol derivatives via transnitrilation, *J. Am. Chem. Soc.*, 2019, **141**, 19257–19262.

8 (*a*) L. Qi, R. Li, X. Yao, Q. Zhen, P. Ye, Y. Shao and J. Chen, Syntheses of pyrroles, pyridines, and ketonitriles via catalytic carbopalladation of dinitriles, *J. Org. Chem.*, 2020, **85**, 1097–1108; (*b*) Q. Zhen, R. Li, L. Qi, K. Hu, X. Yao, Y. Shao and J. Chen, Nickel(II)-catalyzed C–C, N–C cascade coupling of ketonitriles into substituted pyrroles and pyridines, *Org. Chem. Front.*, 2020, **7**, 286–291; (*c*) X. Yao, Y. Shao, M. Hu, Y. Xia, T. Cheng and J. Chen, Palladium-catalyzed cascade reaction of *o*-cyanobiaryls with arylboronic acids: synthesis of 5-arylidene-7-aryl-5*H*-dibenzo[*c*,*e*]azepines, *Org. Lett.*, 2019, **21**, 7697–7701; (*d*) K. Hu, Q. Zhen, J. Gong, T. Cheng, L. Qi, Y. Shao and J. Chen, Palladium-catalyzed three-component tandem process: one-pot assembly of quinazolines, *Org. Lett.*, 2018, **20**, 3083–3087; (*e*) Y. Zhang, Y. Shao, J. Gong, K. Hu, T. Cheng and J. Chen, Palladium-catalyzed tandem reaction of quinazolinone-based nitriles with arylboronic acids: synthesis of 2-(4-arylquinazolin-2-yl)anilines, *Adv. Synth. Catal.*, 2018, **360**, 3260–3265; (*f*) K. Hu, L. Qi, S. Yu, T. Cheng, X. Wang, Z. Li, Y. Xia, J. Chen and H. Wu, Efficient synthesis of isoquinolines in water by a Pd-catalyzed tandem reaction of functionalized alkylnitriles with arylboronic acids, *Green Chem.*, 2017, **19**, 1740–1750; (*g*) L. Qi, K. Hu, S. Yu, J. Zhu, T. Cheng, X. Wang, J. Chen and H. Wu, Tandem addition/cyclization for access to isoquinolines and isoquinolones via catalytic carbopalladation of nitriles, *Org. Lett.*, 2017, **19**, 218–221; (*h*) S. Yu, L. Qi, K. Hu, J. Gong, T. Cheng, Q. Wang, J. Chen and H. Wu, The development of a palladium-catalyzed tandem addition/cyclization for the construction of indole skeletons, *J. Org. Chem.*, 2017, **82**, 3631–3638; (*i*) X. Yao, Y. Shao, M. Hu, M. Zhang, S. Li, Y. Xia, T. Cheng and J. Chen, Palladium-catalyzed selective synthesis of dibenzo[*c*,*e*]azepin-5-ols and benzo[*c*]pyrido[2,3-*e*]azepin-5-ols, *Adv. Synth. Catal.*, 2019, **361**, 4707–4713; (*j*) W. Xiong, K. Hu, Y. Lei, Q. Zhen, Z. Zhao, Y. Shao, R. Li, Y. Zhang and J. Chen, Palladium-catalyzed cascade reactions of 2-(cyanomethoxy)chalcones with arylboronic acids: selective synthesis of emissive benzofuro[2,3-*c*]pyridines, *Org. Lett.*, 2020, **22**(4), 1233–1238.

9 (*a*) H. Li, S. Zhang, X. Feng, X. Yu, Y. Yamamoto and M. Bao, Rhodium(III)-catalyzed oxidative [3+2] annulation of 2-acetyl-1-arylhydrazines with maleimides: synthesis of pyrrolo[3,4-*b*]indole-1,3-diones, *Org. Lett.*, 2019, **21**, 8563–8567; (*b*) N. Lv, Z. Chen, Z. Liu and Y. Zhang, Redox-neutral rhodium(III)-catalyzed annulation of arylhydrazines with sulfoxonium ylides to synthesize 2-arylindoles, *J. Org. Chem.*, 2019, **84**, 13013–13021; (*c*) A. S. Pirzer, E.-M. Alvarez, H. Friedrich and M. R. Heinrich, Radical carbofluorination of alkenes with arylhydrazines and selectfluor: additives, mechanistic pathways, and polar effects, *Chem.–Eur. J.*, 2019, **25**, 2786–2792; (*d*) R. Li, X. Chen, S. Wei, K. Sun, L. Fan, Y. Liu, L. Qu, Y. Zhao and B. Yu, A Visible-light-promoted metal-free strategy towards arylphosphonates: organic-dye-catalyzed phosphorylation of arylhydrazines with trialkylphosphites, *Adv. Synth. Catal.*, 2018, **360**, 4807–4813; (*e*) Y. Tu, Z. Zhang, T. Wang, J. Ke and J. Zhao, A regioselective approach to trisubstituted pyrazoles via palladium-catalyzed oxidative sonogashira-carbonylation of arylhydrazines, *Org. Lett.*, 2017, **19**, 3466–3469.

10 (*a*) C. Wang, Z. Zhang, Y. Tu, Y. Li, J. Wu and J. Zhao, Palladium-catalyzed oxidative cross-coupling of arylhydrazines and arenethiols with molecular oxygen as the sole oxidant, *J. Org. Chem.*, 2018, **83**, 2389–2394; (*b*) S. Chang, L. Dong, H. Song and B. Feng, Denitrogenative palladium-catalyzed coupling of aryl halides with arylhydrazines under mild conditions, *Org. Biomol. Chem.*, 2018, **16**, 3282–3288; (*c*) T. Taniguchi, T. Naka, M. Imoto, M. Takeda, T. Nakai, M. Mihara, T. Mizuno, A. Nomoto and A. Ogawa, Transition-metal-free and oxidant-free cross-coupling of arylhydrazines with disulfides: base-promoted synthesis of unsymmetrical aryl sulphides, *J. Org. Chem.*, 2017, **82**, 6647–6655; (*d*) Y. Zhao and Q. Song, Palladium-catalyzed aerobic oxidative cross-coupling of arylhydrazines with terminal alkynes, *Chem. Commun.*, 2015, **51**, 13272–13274; (*e*) M. Ravi, P. Chauhan, R. Kant, S. K. Shukla and P. P. Yadav, Transition-metal-free C-3 arylation of quinoline-4-ones with arylhydrazines, *J. Org. Chem.*, 2015, **80**, 5369–5376; (*f*) Z. Peng, G. Hu, H. Qiao, P. Xu, Y. Gao and Y. Zhao, Palladium-catalyzed suzuki cross-coupling of arylhydrazines via C–N bond cleavage, *J. Org. Chem.*, 2014, **79**(6), 2733–2738; (*g*) J. Hofmann, H. Jasch and M. R. Heinrich, Oxidative radical arylation of anilines with arylhydrazines and dioxygen from air, *J. Org. Chem.*, 2014, **79**, 2314–2320.

11 K. Ouyang, W. Hao, W. X. Zhang and Z. Xi, Transition-metal-catalyzed cleavage of C–N single bonds, *Chem. Rev.*, 2015, **115**, 12045–12090.

12 (*a*) X. Wang, Y. Huang, Y. Xu, X. Tang, W. Wu and H. Jiang, Palladium-catalyzed denitrogenative synthesis of aryl ketones from arylhydrazines and nitriles using O_2 as sole oxidant, *J. Org. Chem.*, 2017, **82**, 2211–2218; (*b*) K. Cheng,

G. Wang, M. Meng and C. Qi, Acid-promoted denitrogenative Pd-catalyzed addition of arylhydrazines with nitriles at room temperature, *Org. Chem. Front.*, 2017, **4**, 398–403.

13 (*a*) S. Y. Lee, J. Jeon and C.-H. Cheon, Synthesis of 2-substituted quinolines from 2-aminostyryl ketones using iodide as a catalyst, *J. Org. Chem.*, 2018, **83**, 5177–5186; (*b*) S. Lee and C.-H. Cheon, On-water synthesis of 2-substituted quinolines from 2-aminochalcones using benzylamine as the nucleophilic catalyst, *J. Org. Chem.*, 2018, **83**, 13036–13044.

14 T. Xu, Y. Shao, L. Dai, S. Yu, T. Cheng and J. Chen, Pd-catalyzed tandem reaction of 2-aminostyryl nitriles with arylboronic acids: synthesis of 2-arylquinolines, *J. Org. Chem.*, 2019, **84**, 13604–13614.

15 (*a*) J. G. Harrison, O. Gutierrez, N. Jana, T. G. Driver and D. J. Tantillo, Mechanism of Rh2(II)-catalyzed indole formation the catalyst does not control product selectivity, *J. Am. Chem. Soc.*, 2016, **138**, 487–490; (*b*) L. Garanti and G. Zecchi, Thermochemical behavior of *o*-azidocinnamonitriles, *J. Org. Chem.*, 1980, **45**, 4767–4769; (*c*) J. R. Baker, J. Gilbert, S. Paula, X. Zhu, J. A. Sakoff and A. McCluskey, Dichlorophenylacrylonitriles as AhR ligands that display selective breast cancer cytotoxicity in vitro, *ChemMedChem*, 2018, **13**, 1447–1458.

16 S. Y. Lee and C.-H. Cheon, On-water synthesis of 2-substituted quinolines from 2-aminochalcones using benzylamine as the nucleophilic catalyst, *J. Org. Chem.*, 2018, **83**, 13036–13044.

17 B. Gabriele, R. Mancuso, G. Salerno, G. Ruffolo and P. Plastina, Novel and convenient synthesis of substituted quinolines by copper- or palladium-catalyzed cyclodehydration of 1-(2-aminoaryl)-2-yn-1-ols, *J. Org. Chem.*, 2007, **72**, 6873–6877.

18 P. Kumar, V. Garg, M. Kumara and A. , K. Verma, Rh(III)-catalyzed alkynylation: synthesis of functionalized quinolines from aminohydrazones, *Chem. Commun.*, 2019, **55**, 12168–12171.

19 N. Liu and Z. Wang, Kumada coupling of aryl, heteroaryl, and vinyl chlorides catalyzed by amido pincer nickel complexes, *J. Org. Chem.*, 2011, **76**, 10031–10038.

20 W. Liu, X. Yang, Z. Zhou and C. Li, Simple and clean photo-induced methylation of heteroarenes with MeOH, *Chem*, 2017, **2**, 688–702.

21 J. Yuan, L. Yang, P. Mao and L. Qu, $AgNO_3$-catalyzed direct C–H arylation of quinolines by oxidative decarboxylation of aromatic carboxylic acids, *Org. Chem. Front.*, 2017, **4**, 545–554.

22 S. S. Palimkar, S. A. Siddiqui, T. Daniel, R. J. Lahoti and K. V. Srinivasan, Ionic liquid-promoted regiospecific Friedlander annulation: novel synthesis of quinolines and fused polycyclic quinolones, *J. Org. Chem.*, 2003, **68**, 9371–9378.

23 M. S. Hofmayer, F. H. Lutter, L. Grokenberger, J. M. Hammann and P. Knochel, Practical Ni-catalyzed cross-coupling of unsaturated zinc pivalates with unsaturated nonaflates and triflates, *Org. Lett.*, 2019, **21**, 36–39.

24 G. Chakraborty, R. Sikari, S. Das, R. Mondal, S. Sinha, S. Banerjee and N. D. Paul, Dehydrogenative synthesis of quinolines, 2-aminoquinolines, and quinazolines using singlet diradical Ni(II)-catalysts, *J. Org. Chem.*, 2019, **84**, 2626–2641.

25 S. Das, D. Maiti and S. D. Sarkar, Synthesis of polysubstituted quinolines from α-2-aminoaryl alcohols via nickel-catalyzed dehydrogenative coupling, *J. Org. Chem.*, 2018, **83**, 2309–2316.

26 W. Hu, Y. Zhang, H. Zhu, D. Ye and D. Wang, Unsymmetrical triazolyl-naphthyridinyl-pyridine bridged highly active copper complexes supported on reduced graphene oxide and their application in water, *Green Chem.*, 2019, **21**, 5345–5351.

27 M. Maji, K. Chakrabarti, D. Panja and S. Kundu, Sustainable synthesis of N-heterocycles in water using alcohols following the double dehydrogenation strategy, *J. Catal.*, 2019, **373**, 93–102.

28 S. Das, S. Sinha, D. Samanta, R. Mondal, G. Chakraborty, P. Brandaõ and N. D. Paul, Metal–ligand cooperative approach to achieve dehydrogenative functionalization of alcohols to quinolines and quinazolin-4(3*H*)-ones under mild aerobic conditions, *J. Org. Chem.*, 2019, **84**, 10160–10171.

29 E. J. Cho, T. D. Senecal, T. Kinzel, Y. Zhang, D. A. Watson and S. L. Buchwald, The palladium-catalyzed trifluoromethylation of aryl chlorides, *Science*, 2010, **328**, 1679–1681.

30 M. Tobisu, I. Hyodo and N. Chatani, Nickel-catalyzed reaction of arylzinc reagents with N-aromatic heterocycles: a straightforward approach to C–H bond arylation of electron-deficient heteroaromatic compounds, *J. Am. Chem. Soc.*, 2009, **131**, 12070–12071.

31 H. Yan, Z. Hou and H. Xu, Photoelectrochemical C–H alkylation of heteroarenes with organotrifluoroborates, *Angew. Chem., Int. Ed.*, 2019, **58**, 4592–4595.

32 J. Horn, S. P. Marsden, A. Nelson, D. House and G. G. Weingarten, Convergent, regiospecific synthesis of quinolines from *o*-aminophenylboronates, *Org. Lett.*, 2008, **10**, 4117–4120.