Organic & Biomolecular Chemistry

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/c6ob00998k

Metal free TBHP-promoted intramolecular carbonylation of arenes *via* radical cross-dehydrogenative coupling: synthesis of indenoquinolinones, 4-azafluorenones and fluorenones†

Kalpana Mishra,[a] Ashok Kumar Pandey,[b] Jay Bahadur Singh[a] and Radhey M. Singh*[a]

Received 7th May 2016,
Accepted 27th May 2016

DOI: 10.1039/c6ob00998k

www.rsc.org/obc

A metal-free, TBHP-promoted economical route is developed *via* the sp^2 C–H bond functionalization strategy for the synthesis of indenoquinolinones, 4-azafluorenones and fluorenones. Reactions provided excellent yield of the products under mild conditions. We have successfully synthesized 11*H*-indeno[1,2-*b*]quinolin-11-one, an antibacterial agent, in excellent yields.

Introduction

Quinoline derivatives are found in various alkaloids and well recognized by both synthetic and medicinal chemists because of their biological importances and use as synthetic building blocks.[1] Indenoquinolinone derivatives are another important class of molecules which possess interesting biological properties such as 5-HT-receptor binding, anti-inflammatory, anti-malarial and anti-tumor activities.[2] Indenoquinolinone scaffold **1** shows antibacterial activity against Gram-positive and Gram-negative bacteria[3] and its derivatives **2** have cytotoxic activity against HeLa cells.[4] Similarly, carboxamides **3** possess anticancer activity and inhibit topoisomerase I/II (topo I/II) enzymes (IC_{50} 35 nM–180 nM in the Jurkat human leukemia cell line)[5] (Fig. 1). Owing to their biological importance both synthetic chemists and pharmacologists are involved in developing new methodologies for their synthesis.[3–6] Recently, sp^2 C–H bond functionalization has been reported to be an important synthetic route for C–C bond formation owing to its higher atom economy and sustainability. In this context, transition metal (TM) catalyzed C–H bond functionalization has been employed in organic synthesis.[7] However, challenges for controlled C–H bond functionalization to gain regioselectivity persist.

Recently, radical chemistry is found to be an alternative route to TM-catalysis for $C(sp^2)$–$C(sp^2)$ bond formation *via* cross-dehydrogenative coupling (CDC) reaction[8] and signified its importance owing to economical and eco-friendly approaches. In this domain, carbonylation of arenes with an aldehydic group with or without a TM has been utilized in $C(sp^2)$–$C(sp^2)$ bond formation for the synthesis of complex molecular assemblies.[9] Studer *et al.* have reported a TBHP promoted intramolecular CDC reaction using a TM as an initiator for the synthesis of fluorenones and xanthones (Scheme 1).[10] Later, Glorius *et al.* have reported the CDC reaction between aldehydes and arenes using $K_2S_2O_8$ and TBAB as an oxidant and an additive respectively for the synthesis of fluorenones (Scheme 1).[11] A similar intramolecular CDC reaction using only an oxidant is not explored for the synthesis of heterocyclic and carbocyclic systems.

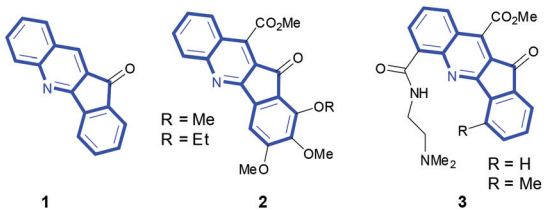
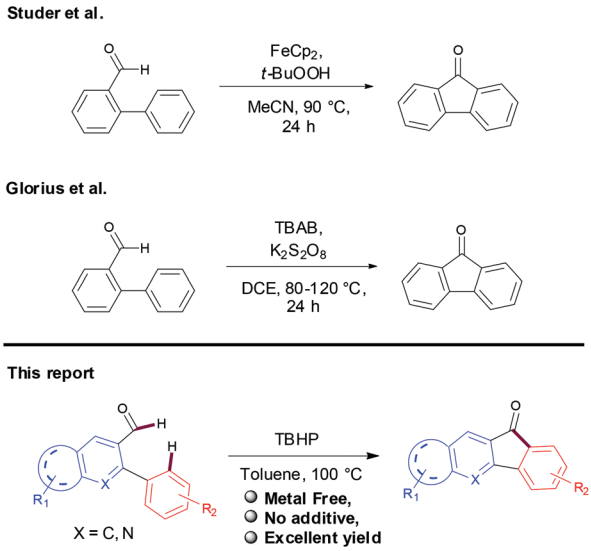


Fig. 1 Bioactive molecules with a tetracyclic indenoquinolinone ring.

In our earlier studies, 2-chloroquinolinyl-3-carboxaldehydes were used to develop new methodologies for the synthesis of various benzo or hetero fused quinoline skeletons.[12] In this study, we report an aqueous TBHP-promoted intramolecular CDC reaction for the synthesis of Indenoquinolinone, 4-azafluorenones and fluorenones from 2-arylquinolinyl-3-carboxaldehyde, 2-arylpyridenyl-3-carboxaldehyde and 2-arylbenzenyl-

[a]*Department of Chemistry, Centre of Advanced Studies, Institute of Science, Banaras Hindu University, Varanasi-221005, India. E-mail: rmohan@bhu.ac.in*
[b]*Department of Chemistry, Indian Institute of Technology Ropar, Nangal Road, Rupnagar, Punjab-140001, India. E-mail: ashokp.ansh@gmail.com*

†Electronic supplementary information (ESI) available. CCDC 1472053. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c6ob00998k



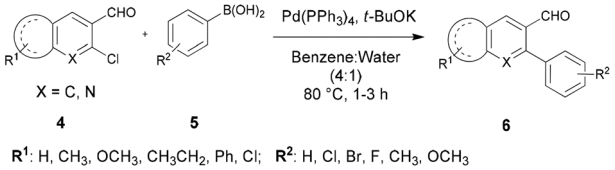
Scheme 1 Approaches for carbonylation of an aryl ring through intramolecular CDC reaction.

3-carboxaldehyde analogues respectively in good to excellent yields (Scheme 1).[13]

Results and discussion

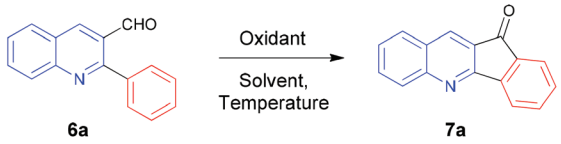
We initially optimized the Suzuki coupling reaction conditions for the preparation of **6** from precursor **4** and phenylboronic acid **5** (Scheme 2).[14] Similar conditions were also applied for the preparation of pyridine and benzene analogues.

The required precursor **6a** was examined to find the optimal annulation reaction conditions for the formation of Indenoquinolinone derivative **7a** (Table 1). Initially, the reaction of **6a** was examined under free-radical conditions using 2 equiv. of 70% *tert*-butyl hydroperoxide (TBHP)[15] in 2 mL of toluene at 100 °C under an argon atmosphere (Table 1). We were delighted that the reaction proceeded without a TM with a single spot on TLC and an annulated product **7a** was obtained in 72% yield within 17 h (entry 1). Both the rate of reaction and yield of the product improved using 3 equivalents of TBHP and gave **7a** in 81% yield within 14 h (entry 2). Inspired from the higher dosages of TBHP on the progress of the reaction and yield, we increased the number of equiv. of TBHP in different batches to see the productivity of the reaction (entries 3, 4 and 5). The reaction was found to be comparatively slow with a reduced yield of **7a** with higher equiv. of TBHP. The reaction with other oxidants such as 30% aqueous H_2O_2 in toluene was examined and found to be unsuccessful (entry 6). Further variation of solvents such as DCE, THF, DMSO, CH_3CN, and benzene (entries 7–11) and temperatures from 80 °C to 110 °C (entries 12 and 13) did not provide better yield of the product.



Scheme 2 Preparation of the starting material.

Table 1 Optimization of reaction conditions[a]



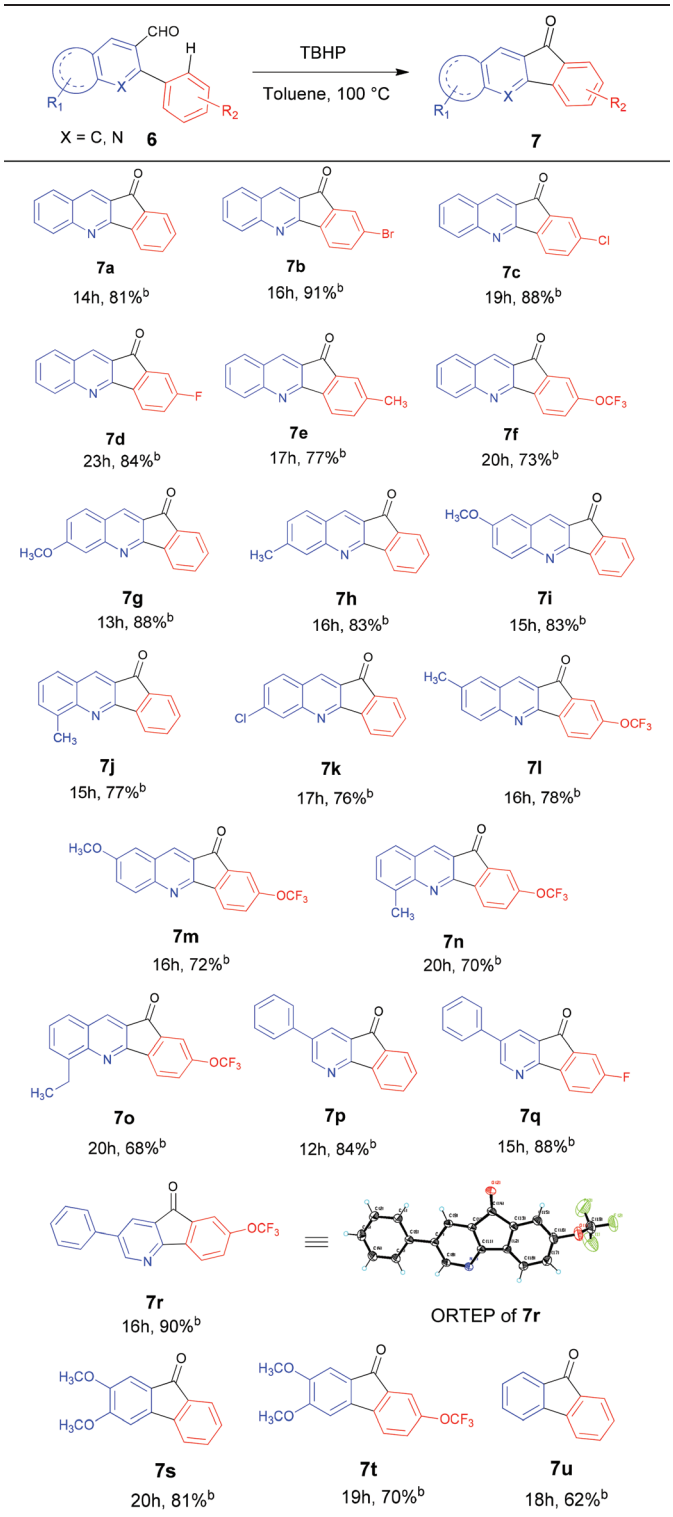
Entry	Oxidant (equiv.)	Solvent	Temp. (°C)	Time (h)	Yield[b] (%)
1	TBHP[c] (2)	Toluene	100	17	72
2	TBHP (3)	Toluene	100	14	81
3	TBHP (4)	Toluene	100	16	70
4	TBHP (6)	Toluene	100	18	65
5	TBHP (8)	Toluene	100	20	45
6	H_2O_2[d] (3)	Toluene	100	24	nr[e]
7	TBHP (3)	DCE[f]	100	18	68
8	TBHP (3)	THF[g]	100	22	40
9	TBHP (3)	DMSO[h]	100	20	51
10	TBHP (3)	CH_3CN	100	24	40
11	TBHP (3)	Benzene	100	16	71
12	TBHP (3)	Toluene	80	24	63
13	TBHP (3)	Toluene	110	16	72

[a] **6a** (1 equiv.), toluene (2 mL). [b] Isolated yield by flash column chromatography. [c] *tert*-Butyl hydroperoxide. [d] Hydrogen peroxide. [e] No reaction. [f] 1,2-Dichloroethane. [g] Tetrahydrofuran. [h] Dimethyl sulphoxide.

With the best annulation reaction conditions as 1 equiv. of **6a** with 3 equiv. of TBHP in 2 mL toluene at 100 °C in hand, the scope of this methodology was further examined with the substituent variations at the phenyl ring in substrate **6** (Table 2). All reactions afforded annulated products **7a–f** in 81–73% yields. An electron withdrawing group *e.g.* Br, Cl, and F present at the *para*-position in the phenyl ring favors higher yield of the products **7b**, **7c** and **7d**. However, electron donating groups such as methyl or trifluoromethoxy at the *para*-position in the phenyl ring reduced the yield of products **7e** and **7f** (Table 2). Increasing and decreasing yields of the product could be explained by –I and +I effects of the groups. The scope of the reaction was also examined with the substituent present in the quinoline moiety of **6** and the reaction afforded the corresponding annulated products **7g–k** in 88–76% yields (Table 2). Electron donating groups present at 6 and 7 positions enhanced the yield of annulated products (**7g–7i**). However, the methyl group at the 8-position lowered the yield of **7j**. An electron withdrawing group present at the 7-position also lowered the yield of product **7k** to 76%.

The scope of annulation reactions was further evaluated with the substrates having electron donating groups at both quinoline and phenyl rings. The reactions of the substrates with electron donating groups in the quinoline ring and the

Table 2 Substrate scope[a]



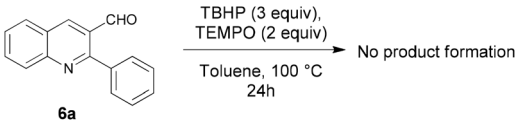
[a] 6 (1 equiv.), *tert*-butyl hydroperoxide (3 equiv.). [b] Isolated yield by flash column chromatography.

trifluoromethoxy group in the phenyl ring were examined under optimal reaction conditions and afforded the products **7l–o** in 78–68% yield (Table 2). The trifluoromethoxy group present in the phenyl ring could be responsible for lower yield of the product.

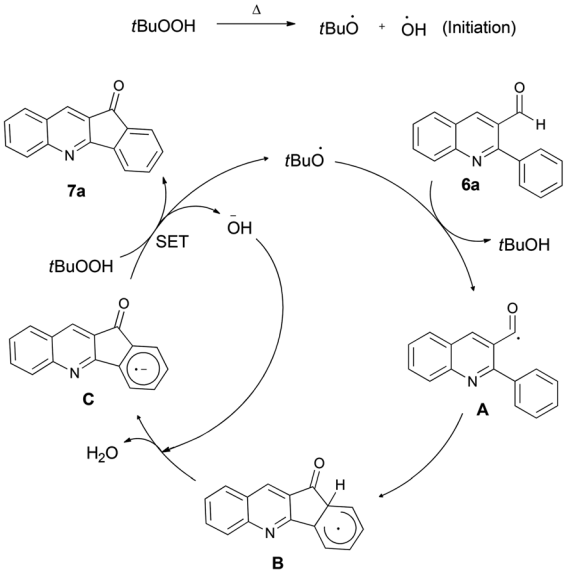
In continuation of substrate variation, pyridine analogues were also evaluated under optimal reaction conditions. 5-Phenyl-3-arylnicotinealdehyde derivatives were examined and afforded the products **7p**, **7q** and **7r** in excellent yields. The shorter reaction times and excellent yields demonstrated that the pyridine is more reactive than its benzofused analogues (quinolines). During our investigations, we obtained the single crystal structure of **7r** (Table 2, for details see the ESI†).[16] This methodology was further examined with arene analogues for the synthesis of fluorenone derivatives. All reactions proceeded smoothly and afforded the fluorenones **7s–u**, in 81–62% yield (Table 2).

We gain insight into the intramolecular CDC reaction that proceeded by a free radical mechanism. We performed the CDC reaction of **6a** in the presence of TEMPO (2 equiv.) as a free radical quencher under the optimized reaction conditions (Scheme 3). The reaction did not proceed upon prolonged heating and the starting material was isolated, which supported the free radical mechanism of the reaction.

Depending upon product formation and literature reports,[17] we proposed the free radical mechanism of the reaction in Scheme 4. Initially, upon heating *t*BuOOH could undergo O–O homolytic bond fission to produce *t*BuO and OH radicals. The *t*BuO radical might abstract hydrogen atom



Scheme 3 Intramolecular CDC reaction in the presence of TEMPO.



Scheme 4 Proposed reaction mechanism for intramolecular CDC reaction.

from aldehydic carbon of **6a** and generate the carbonyl radical intermediate **A**. Intermediate **A** underwent acylation at the *ortho*-position of the phenyl ring and generated the cyclohexadienyl radical **B**. An acidic proton in intermediate **B** might have undergone deprotonation in aqueous *t*BuOOH to produce the cyclohexadienyl radical anion **C**. Intermediate **C** underwent the single electron transfer (SET) process to reduce *t*BuOOH into a *t*BuO radical and a hydroxide anion. During this SET process intermediate **C** gave the final product **7a**. The newly generated hydroxide anion continued the propagation step of the mechanism.

Conclusions

In conclusion, we have developed a metal-free, eco-friendly and economical TBHP promoted intramolecular CDC reaction towards the synthesis of Indenoquinolinone, 4-azafluorenone and fluorenone derivatives. We have economically synthesized molecule **7a** which is known for its antibacterial activity against Gram-positive and Gram-negative bacteria. Bioactive analysis of other analogues is under investigation.

Experimental

General information

^{1}H NMR and ^{13}C NMR spectra were recorded at ambient temperature using a JEOL spectrometer operating at 300 MHz and 75 MHz respectively. ^{19}F NMR spectra were recorded at 500 MHz. Data are reported as follows: chemical shifts in ppm from internal tetramethylsilane (TMS) on the δ scale, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet), coupling constants (Hz) and integration. Melting points were measured using a Buchi melting-point apparatus in an open capillary tube and are uncorrected. IR spectra were recorded on Varian 3300 FTIR spectrophotometers in cm^{-1} units. High resolution mass spectra (HRMS) were obtained on TOF/6500 Series QTOF B.05.00 (B5042.0). Thin-layer chromatography (TLC) was performed on glass plates (7.5 × 2.5 and 7.5 × 5.0 cm) coated with silica gel GF 254 and various combinations of ethyl acetate and hexane were used as eluents. Boronic acids and TBHP are commercially available. Solvents were purified according to standard procedures. The developed chromatogram was analyzed by UV light. Column chromatography was performed using silica gel (mess size 100–200). Data of compounds **6a**, **6e**, **6i** and **6j** are reported[18] in the literature.

General procedure for synthesis of starting materials 6

A solution of 2-chloroquinoline-3-carbaldehyde (1 equiv.), arylboronic acid (1.2 equiv.), $Pd(PPh_3)_4$ (2 mol%) and potassium *tert*-butoxide (1 equiv.) in benzene : water (4 : 1, 3 mL) was heated at 80 °C under a nitrogen atmosphere for 2 h. Benzene was evaporated under reduced pressure. Water (20 mL) was added to the reaction mixture and extracted with ethyl acetate (4 × 5 mL). The collected organic phase was washed with water, brine and dried over anhydrous Na_2SO_4. The solvent was removed under reduced pressure and the obtained residue was purified by column chromatography (hexane : ethyl acetate = 18 : 2) to afford starting materials **6**.

2-Phenylquinoline-3-carbaldehyde (6a). 2-Chloroquinoline-3-carbaldehyde (0.19 g, 1.00 mmol), phenylboronic acid (0.15 g, 1.20 mmol), *t*BuOK (0.11 g, 1.00 mmol), reaction time: 2 h, yield: 0.21 g, 92%, white solid, mp: 98 °C, IR (KBr): ν 1693, 1156, 753 cm^{-1}, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.17 (s, 1H), 8.84 (s, 1H), 8.21 (d, J = 8.7 Hz, 1H), 8.00 (d, J = 8.1 Hz, 1H), 7.86 (t, J = 7.2 Hz, 1H), 7.69–7.54 (m, 6H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.4, 160.2, 149.6, 138.1, 138.0, 137.7, 132.5, 130.2, 129.5, 129.4, 129.3, 128.8, 128.7, 127.6, 127.4, 126.3.

2-(4-Bromophenyl)quinoline-3-carbaldehyde (6b). 2-Chloroquinoline-3-carbaldehyde (0.09 g, 0.47 mmol), (4-bromophenyl)boronic acid (0.12 g, 0.57 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 3 h, yield: 0.14 g, 95%, white solid, mp: 150 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.17 (s, 1H), 8.85 (s, 1H), 8.20 (d, J = 8.1 Hz, 1H), 8.02 (d, J = 8.1 Hz, 1H), 7.89 (t, J = 7.8 Hz, 1H), 7.76–7.56 (m, 5H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 190.9, 158.9, 149.6, 138.6, 136.7, 132.8, 131.9, 131.8, 130.9, 129.6, 129.4, 128.8, 127.7, 127.3, 126.4, 124.14.

2-(4-Chloro-phenyl)quinoline-3-carbaldehyde (6c). 2-Chloroquinoline-3-carbaldehyde (0.19 g, 1.00 mmol), (4-chlorophenyl)boronic acid (0.19 g, 1.20 mmol), *t*BuOK (0.11 g, 1.00 mmol), reaction time: 3 h, yield: 0.25 g, 94%, white solid; mp: 114 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.17 (s, 1H), 8.85 (s, 1H), 8.21 (d, J = 8.4 Hz, 1H), 8.11 (d, J = 7.5 Hz, 1H), 8.02 (d, J = 8.1 Hz, 1H), 7.89 (t, J = 6.9 Hz, 1H), 7.64 (d, J = 8.4 Hz, 2H), 7.56–7.45 (m, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.0, 171.5, 158.9, 149.5, 138.7, 136.2, 133.7, 132.9, 131.5, 130.2, 129.5, 128.0, 128.4, 127.8, 127.6, 126.5.

2-(4-Fluoro-phenyl)quinoline-3-carbaldehyde (6d). 2-Chloroquinoline-3-carbaldehyde (0.19 g, 1.00 mmol), (4-fluorophenyl) boronic acid (0.17 g, 1.20 mmol), *t*BuOK (0.11 g, 1.00 mmol), reaction time: 2 h, yield: 0.23 g, 92%; white solid, mp: 96 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.18 (s, 1H), 8.85 (s, 1H), 8.20 (d, J = 8.7 Hz, 1H), 8.03 (d, J = 8.1 Hz, 1H), 7.89 (t, J = 8.4 Hz, 1H), 7.71–7.63 (m, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.1, 165.3, 162.0, 159.1, 149.5, 138.54, 138.5, 133.9, 133.8, 132.8, 132.2, 132.1, 129.5, 129.4, 127.6, 127.6, 126.4, 116.2, 115.98, 115.7.

2-*p*-Tolylquinoline-3-carbaldehyde (6e). 2-Chloro-quinoline-3-carbaldehyde (0.19 g, 1.00 mmol), (*p*-tolylphenyl)boronic acid (0.16 g, 1.20 mmol), *t*BuOK (0.11 g, 1.00 mmol), reaction time: 2 h, yield 0.22 g, 90%, white solid, mp: 116 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.18 (s, 1H), 8.82 (s, 1H), 8.19 (d, J = 8.4 Hz, 1H), 8.00 (d, J = 8.1 Hz, 1H), 7.85 (t, J = 7.5 Hz, 1H), 7.62–7.57 (m, 3H), 7.36 (d, J = 6.9 Hz, 2H), 2.46 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.7, 160.3, 149.7, 139.5, 138.1, 138.0, 134.9, 132.5, 130.2, 129.6, 129.4, 127.7, 127.3, 126.3, 21.3.

2-(4-Trifluoromethoxyphenyl)quinoline-3-carbaldehyde (6f). 2-Chloroquinoline-3-carbaldehyde (0.09 g, 0.50 mmol), (4-trifluoromethoxyphenyl)boronic acid (0.12 g, 0.60 mmol), *t*BuOK

(0.05 g, 0.50 mmol), reaction time: 2 h, yield: 0.13 g, 90%, white solid, mp: 116 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.19 (s, 1H), 8.86 (s, 1H), 8.20 (d, J = 8.4 Hz, 1H), 8.03 (d, J = 8.1 Hz, 1H), 7.90 (t, J = 8.1 Hz, 1H), 7.75–7.64 (m, 3H), 7.42 (d, J = 8.1 Hz, 2H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 190.8, 158.7, 150.2, 149.5, 138.7, 138.6, 136.4, 132.9, 132.8, 131.7, 131.7, 129.5, 129.4, 127.8, 127.5, 126.5, 121.1.

7-Methoxy-2-phenylquinoline-3-carbaldehyde (6g). 2-Chloro-7-methoxyquinoline-3-carbaldehyde (0.11 g, 0.51 mmol), phenylboronic acid (0.07 g, 0.62 mmol), *t*BuOK (0.06 g, 0.51 mmol), reaction time: 3 h, yield: 0.12 g, 92%, white solid, mp: 130 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.12 (s, 1H), 8.75 (s, 1H), 7.87 (d, J = 9 Hz, 1H), 7.65 (d, J = 5.7 Hz, 2H), 7.53 (t, J = 6 Hz, 3H), 7.27 (s, 1H), 3.98 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.3, 163.5, 161.1, 151.8, 137.9, 137.4, 130.5, 130.2, 129.3, 128.6, 125.8, 121.7, 121.2, 107.2, 55.8.

7-Methyl-2-phenylquinoline-3-carbaldehyde (6h). 2-Chloro-7-methylquinoline-3-carbaldehyde (0.20 g, 1.00 mmol), phenylboronic acid (0.15 g, 1.20 mmol), *t*BuOK (0.11 g, 1.00 mmol), reaction time: 2 h, yield: 0.22 g, 90%, white solid, mp: 108 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.15 (s, 1H), 8.73 (s, 1H), 8.09 (d, J = 8.4 Hz, 1H), 7.74 (s, 1H), 7.70–7.65 (m, 3H), 7.54 (d, J = 6 Hz, 3H), 2.57 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.6, 159.4, 148.3, 137.9, 137.5, 137.3, 137.2, 135.0, 130.2, 129.2, 128.6, 128.0, 127.6, 126.4, 21.5.

6-Methoxy-2-phenylquinoline-3-carbaldehyde (6i). 2-Chloro-6-methoxyquinoline-3-carbaldehyde (0.11 g, 0.50 mmol), phenylboronic acid (0.07 g, 0.60 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time 3 h, yield: 0.12 g, 94%, white solid, mp: 130 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.16 (s, 1H), 8.71 (s, 1H), 8.09 (d, J = 9.3 Hz, 1H), 7.66 (d, J = 5.7 Hz, 2H), 7.56–7.48 (m, 5H) 3.96 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.7, 158.4, 158.1, 146.0, 137.9, 136.4, 131.0, 130.2, 129.1, 128.7, 127.8, 127.5, 125.8, 105.9, 55.7.

8-Methyl-2-phenylquinoline-3-carbaldehyde (6j). 2-Chloro-8-methylquinoline-3-carbaldehyde (0.20 g, 1.00 mmol), phenylboronic acid (0.15 g, 1.20 mmol), *t*BuOK (0.11 g, 1.00 mmol), reaction time: 2 h, yield: 0.22 g, 92%, white solid, mp: 84 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.22 (s, 1H), 8.80 (s, 1H), 7.84 (d, J = 8.1 Hz, 1H), 7.76–7.70 (m, 3H), 7.57–7.49 (m, 4H), 2.86 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$) δ 191.8, 158.6, 148.6, 138.3, 138.2, 138.1, 137.7, 132.5, 130.6, 129.2, 128.5, 127.2, 127.1, 126.2, 17.9.

7-Chloro-2-phenylquinoline-3-carbaldehyde (6k). 2-Chloro-7-chloroquinoline-3-carbaldehyde (0.11 g, 0.50 mmol), phenylboronic acid (0.07 g, 0.60 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 2 h, yield: 0.12 g, 88%, white solid, mp: 142 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.15 (s, 1H), 8.81 (s, 1H), 8.22 (d, J = 9 Hz, 1H), 7.94 (d, J = 8.4 Hz, 1H), 7.69–7.65 (m, 3H), 7.59–7.55 (m, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.1, 161.3, 149.8, 138.8, 137.9, 137.3, 135.4, 132.2, 130.5, 130.2, 129.7, 128.8, 128.7, 127.7, 124.7, 117.4.

6-Methyl-2-(4-trifluoromethoxyphenyl)quinoline-3-carbaldehyde (6l). 2-Chloro-6-methylquinoline-3-carbaldehyde (0.10 g, 0.50 mmol), 4-trifluoromethoxyphenylboronic acid (0.10 g, 0.60 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 3 h, yield: 0.15 g, 94%, white solid, mp: 160 °C, ^{1}H NMR (300 MHz, $CDCl_3$), δ 10.17 (s, 1H), 8.76 (s, 1H), 8.09 (d, J = 8.4 Hz, 1H), 7.78–7.71 (m, 4H), 7.41 (d, J = 8.1 Hz, 2H), 2.59 (s, 2H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.0, 157.9, 150.0, 150.0, 148.2, 138.0, 137.8, 136.6, 135.3, 131.7, 129.2, 128.0, 127.5, 126.5, 121.1, 21.6.

6-Methoxy-2-(4-trifluoromethoxy-phenyl)-quinoline-3 carbaldehyde (6m). 2-Chloro-6-methoxyquinoline-3-carbaldehyde (0.11 g, 0.50 mmol), 4-trifluoromethoxyphenylboronic acid (0.10 g, 0.60 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 3 h, yield: 0.15 g, 92%, white solid, mp: 134 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.17 (s, 1H), 8.73 (s, 1H), 8.08 (d, J = 9 Hz, 1H), 7.71 (d, J = 8.7 Hz, 2H), 7.55–7.51 (m, 2H), 7.40 (d, J = 8.1 Hz, 2H), 7.23 (s, 1H) 3.98 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.2, 158.6, 156.4, 149.9, 145.9, 136.8, 136.5, 131.7, 130.9, 130.6, 127.6, 127.6, 126.2, 121.1, 105.9, 55.8.

8-Methyl-2-(4-trifluoromethoxy-phenyl)-quinoline-3-carbaldehyde (6n). 2-Chloro-8-methylquinoline-3-carbaldehyde (0.10 g, 0.50 mmol), 4-trifluoromethoxyphenylboronic acid (0.10 g, 0.60 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 2 h, yield: 0.14 g, 90%, white solid, mp: 80 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.22 (s, 1H), 8.80 (s, 1H), 7.85 (d, J = 8.1 Hz, 1H), 7.80–7.72 (m, 3H), 7.53 (t, J = 7.5 Hz, 3H), 7.41 (d, J = 8.1 Hz, 2H), 2.85 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.2, 157.1, 150.1, 148.6, 138.8, 137.8, 136.9, 132.8, 132.1, 127.5, 127.3, 126.4, 122.2, 120.9, 118.8, 17.8.

8-Ethyl-2-(4-trifluoromethoxyphenyl)-quinoline-3-carbaldehyde (6o). 2-Chloro-8-ethylquinoline-3-carbaldehyde (0.10 g, 0.50 mmol), 4-trifluoromethoxyphenylboronic acid (0.10 g, 0.50 mmol), *t*BuOK (0.56 g, 0.60 mmol), reaction time: 2 h, yield: 0.15 g, 88%, white solid, mp: 88 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.21 (s, 1H), 8.80 (s, 1H), 7.84 (d, J = 8.4 Hz, 1H), 7.78–7.71 (m, 3H), 7.56 (t, J = 7.5 Hz, 1H), 7.41 (d, J = 8.1 Hz, 2H), 3.38–3.31 (q, 2H), 1.40 (t, J = 7.8 Hz, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.2, 156.9, 150.1, 148.0, 143.5, 138.9, 138.9, 136.9, 132.0, 131.2, 127.7, 127.2, 127.2, 126.4, 120.9, 24.5, 15.0.

2,5-Diphenylpyridine-3-carbaldehyde (6p). 2-Chloro-5-phenylnicotinaldehyde (0.10 g, 0.46 mmol), phenylboronic acid (0.67 g, 0.55 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time 3 h, yield 0.11 g, 90%, light yellow, mp: 90 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.13 (s, 1H), 9.12 (s, 1H), 8.50 (s, 1H), 7.70–7.63 (m, 4H), 7.55–7.43 (m, 6H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.8, 160.8, 160.7, 151.8, 136.8, 136.3, 135.5, 133.7, 130.4, 129.6, 129.3, 129.3, 128.7, 127.1.

2-(4-Fluorophenyl)-5-phenylpyridine-3-carbaldehyde (6q). 2-Chloro-5-phenylnicotinaldehyde (0.10 g, 0.46 mmol), 4-fluorophenylboronic acid (0.08 g, 0.55 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 3 h, yield: 0.11 g, 90%, white solid, mp: 94 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.12 (s, 1H), 9.10 (s, 1H), 8.49 (s, 1H), 7.69–7.62 (m, 4H), 7.56–7.4 (m, 3H), 7.28–7.22 (m, 1H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.4, 165.4, 162.1, 159.5, 151.8, 136.2, 135.7, 133.9, 133.0, 132.9, 132.3, 132.2, 129.3, 129.2, 128.8, 127.1, 116.0, 115.7.

5-Phenyl-2-(4-trifluoromethoxyphenyl)pyridine-3-carbaldehyde (6r). 2-Chloro-5-phenylnicotinaldehyde (0.10 g, 0.46 mmol),

4-trifluoromethoxyphenylboronic acid (0.12 g, 0.55 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 2 h, yield: 0.14 g, 88%, white solid, mp: 92 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.14 (s, 1H), 9.12 (s, 1H), 8.51 (s, 1H), 7.69 (d, J = 8.4 Hz, 4H), 7.56–7.47 (m, 3H), 7.41 (d, J = 8.1 Hz, 2H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.1, 159.1, 151.8, 136.1, 136.0, 135.5, 133.9, 131.9, 131.9, 129.3, 129.3, 128.9, 128.9, 127.1, 121.0.

4,5-Dimethoxybiphenyl-2-carbaldehyde (6s). 2-Bromo-4,5-dimethoxybenzaldehyde (0.12 g, 0.49 mmol), phenylboronic acid (0.07 g, 0.58 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 2 h, yield: 0.11 g, 95%, brown solid, mp: 80 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 9.81 (s, 1H), 7.54 (s, 1H), 7.46–7.42 (m, 3H), 7.38 (d, J = 6.6 Hz, 2H), 6.86 (s, 1H), 3.97 (s, 6H), ^{13}C NMR (75 MHz, $CDCl_3$) δ 191.1, 153.4, 148.7, 141.5, 137.5, 130.1, 128.3, 127.9, 126.8, 112.6, 108.6, 56.1, 56.1.

4,5-Dimethoxy-4′-trifluoromethoxy-biphenyl-2-carbaldehyde (6t). 2-Bromo-4,5-dimethoxybenzaldehyde (0.12 g, 0.49 mmol), 4-trifluoromethoxyphenylboronic acid (0.12 g, 0.58 mmol), *t*BuOK (0.05 g, 0.50 mmol), reaction time: 2 h, yield: 0.15 g, 92%, white solid, mp: 84 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 9.80 (s, 1H), 7.54 (s, 1H), 7.41 (d, J = 8.7 Hz, 2H), 7.31 (d, J = 8.1 Hz, 2H), 6.82 (s, 1H), 3.98 (s, 6H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 190.5, 153.5, 149.1, 149.1, 139.7, 136.3, 131.5, 127.0, 120.8, 112.5, 108.8, 56.3, 56.2.

Biphenyl-2-carbaldehyde (6u). 2-Bromobenzaldehyde (0.18 g, 1.00 mmol), phenylboronic acid (0.15 g, 1.20 mmol), *t*BuOK (0.11 g, 1.00 mmol), reaction time: 2 h, yield: 0.16 g, 90%, yellow liquid, ^{1}H NMR (300 MHz, $CDCl_3$): δ 9.98 (s, 1H), 8.02 (d, J = 7.8 Hz, 1H), 7.63 (t, J = 7.5 Hz, 1H), 7.51–7.36 (m, 6H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 192.1, 144.8, 133.8, 133.6, 131.7, 131.6, 130.8, 127.9, 127.8, 115.6, 115.3.

Procedure for the synthesis of indenoquinolinones, 4-azafluorenones, fluorenones (7)

A solution of 2-phenylquinoline-3-carbaldehyde (1 equiv.), TBHP (3 equiv.) and toluene (2 mL) was heated at 100 °C under an argon atmosphere for 14 to 24 h. After the completion of the reaction, the solvent was evaporated under reduced pressure. Water was added to the reaction mixture and extracted with EtOAc. The organic phase was washed with water, brine and dried over anhydrous Na_2SO_4. The solvent was removed under reduced pressure and the obtained residue was purified by column chromatography (hexane : ethyl acetate = 18 : 2) to afford **7a–u**.

Indeno[1,2-*b*]quinolin-11-one (7a). 2-Phenylquinoline-3-carbaldehyde (0.11 g, 0.47 mmol), TBHP (1.42 mmol), reaction time: 14 h, yield: 0.88 g, 81%, white solid, mp: 142 °C, IR (KBr): ν 1717, 1622, 775, 733 cm^{-1}, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.38 (s, 1H), 8.21 (t, J = 7.2 Hz, 2H), 7.89–7.66 (m, 4H), 7.56–7.49 (m, 2H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 190.8, 162.0, 150.6, 143.8, 137.4, 135.5, 132.4, 132.0, 131.5, 130.4, 129.8, 127.6, 127.2, 127.0, 124.1, 121.8, HRMS (ESI) exact mass calcd for $C_{16}H_9NOH$: 232.0762 $(M + H)^+$, found: 232.0768 $(M + H)^+$.

2-Bromoindeno[1,2-*b*]quinolin-11-one (7b). 2-(4-Bromophenyl)quinoline-3-carbaldehyde (0.08 g, 0.26 mmol), TBHP (0.77 mmol), reaction time: 16 h, yield: 0.07 g, 91%, light green, mp: 206 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.39 (s, 1H), 8.11 (d, J = 8.4 Hz, 1H), 7.96 (t, J = 8.1 Hz, 2H), 7.88 (d, J = 7.8 Hz, 1H), 7.82–7.76 (m, 2H), 7.55 (t, J = 7.5 Hz, 1H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 189.4, 161.2, 150.6, 142.4, 138.8, 138.2, 133.0, 132.4, 130.6, 129.8, 127.6, 127.5, 127.4, 126.6, 126.0, 123.2, HRMS (ESI) exact mass calcd for $C_{16}H_8BrNOH$: 309.9868 $(M + H)^+$, found: 309.9879 $(M + H)^+$.

2-Chloroindeno[1,2-*b*]quinolin-11-one (7c). 2-(4-Chlorophenyl)quinoline-3-carbaldehyde (0.13 g, 0.49 mmol), TBHP (1.5 mmol), reaction time: 18 h, yield: 0.11 g, 88%, light yellow, mp: 170 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.37 (s, 1H), 8.13–8.02 (m, 2H), 7.87 (d, J = 8.1 Hz, 1H), 7.80 (t, J = 8.4 Hz, 1H), 7.63 (d, J = 8.4 Hz, 1H), 7.57–7.45 (m, 2H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 189.4, 170.9, 161.1, 150.5, 141.9, 138.7, 137.9, 135.3, 133.6, 132.4, 130.6, 130.1, 128.4, 127.5, 124.4, 123.1, HRMS (ESI) exact mass calcd for $C_{16}H_8NOH$: 266.0373 $(M + H)^+$, found: 266.0377 $(M + H)^+$.

2-Fluoro-indeno[1,2-*b*]quinolin-11-one (7d). 2-(4-Fluorophenyl)quinoline-3-carbaldehyde (0.12 g, 0.49 mmol), TBHP (1.5 mmol), reaction time: 23 h, yield: 0.10 g, 84%, light yellow, mp: 148 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.37 (s, 1H), 8.09 (t, J = 8.4 Hz, 2H), 7.87 (d, J = 7.8 Hz, 1H), 7.71 (t, J = 7.8 Hz, 1H), 7.56–7.47 (m, 2H), 7.36 (t, J = 8.4 Hz, 1H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 193.0, 161.8, 150.7, 147.1, 145.0, 139.8, 138.2, 132.8, 132.3, 130.7, 130.6, 129.8, 127.3, 123.7, 123.6, 122.5, 122.2, 122.2, 111.5, 111.2, ^{19}F NMR (500 MHz, $CDCl_3$): δ −107.07, HRMS (ESI) exact mass calcd for $C_{16}H_8BrNOH$: 250.0668 $(M + H)^+$, found: 250.0661 $(M + H)^+$.

2-Methylindeno[1,2-*b*]quinolin-11-one (7e). 2-(*p*-Tolyl)quinoline-3-carbaldehyde (0.12 g, 0.49 mmol), TBHP (1.5 mmol), reaction time: 17 h, yield: 0.09 g, 77%, brown solid, mp: 166 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.29 (s, 1H), 8.06 (d, J = 8.4 Hz, 1H), 7.94 (d, J = 7.5 Hz, 1H), 7.82 (d, J = 7.8 Hz, 1H), 7.72 (t, J = 6.9 Hz, 1H), 7.60 (s, 1H), 7.50 (d, J = 8.1 Hz, 1H), 2.44 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.0, 162.2, 150.5, 142.3, 141.4, 137.7, 136.3, 132.2, 131.9, 130.4, 129.6, 127.5, 127.4, 127.0, 124.6, 121.7, 21.6, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NOH$: 246.0919 $(M + H)^+$, found: 246.0922 $(M + H)^+$.

2-Trifluoromethoxyindeno[1,2-*b*]quinolin-11-one (7f). 2-(4-Trifluoromethoxyphenyl)quinoline-3-carbaldehyde (0.08 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 20 h, yield: 0.06 g, 73%, light yellow, mp: 190 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.41 (s, 1H), 8.12 (t, J = 8.4 Hz, 2H), 7.89 (d, J = 8.1 Hz, 1H), 7.80 (t, J = 8.1 Hz, 1H), 7.66 (s, 1H), 7.61–7.45 (m, 2H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 189.3, 160.8, 151.8, 150.6, 141.9, 139.2, 133.1, 132.5, 130.6, 130.1, 129.9, 128.4, 127.6, 127.5, 127.0, 123.4, 116.3, ^{19}F NMR (500 MHz, $CDCl_3$): δ −57.69, HRMS (ESI) exact mass calcd for $C_{17}H_8F_3NO_2H$: 316.0585 $(M + H)^+$, found: 316.0594 $(M + H)^+$.

7-Methoxyindeno[1,2-*b*]quinolin-11-one (7g). 7-Methoxy-2-phenylquinoline-3-carbaldehyde (0.13 g, 0.50 mmol), TBHP (1.5 mmol), reaction time: 13 h, yield: 0.11 g, 88%, yellow solid, mp: 154 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.29 (s, 1H), 8.06 (d, J = 7.2, 1H), 7.82–7.73 (m, 2H), 7.66 (t, J = 7.2 Hz, 1H), 7.50 (s, 2H), 7.17 (d, J = 8.7 Hz, 1H), 3.99 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 190.9, 163.0, 162.9, 152.7, 143.6, 137.4,

135.2, 132.2, 132.2, 131.4, 125.1, 123.9, 122.5, 121.5, 119.6, 108.7, 55.7, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NO_2H$: 262.0868 $(M + H)^+$, found 262.0874 $(M + H)^+$.

7-Methyl-indeno[1,2-*b*]quinolin-11-one (7h). 7-Methyl-2-phenylquinoline-3-carbaldehyde (0.12 g, 0.50 mmol), TBHP (1.50 mmol), reaction time: 16 h, yield: 0.10 g, 83%, yellow solid, mp: 130 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.31 (s, 1H), 8.07 (d, J = 7.2 Hz, 1H), 7.90 (s, 1H), 7.82–7.74 (m, 2H), 7.66 (t, J = 7.2 Hz, 1H), 7.51 (d, J = 7.2 Hz, 1H), 7.35 (d, J = 7.8 Hz, 1H), 2.57 (s, 3H), ^{13} C NMR (75 MHz, $CDCl_3$): δ 191.0, 162.2, 150.8, 143.9, 143.0, 137.5, 135.4, 134.1, 132.2, 131.4, 130.1, 129.3, 126.4, 125.6, 124.0, 121.7, 22.0, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NOH$: 246.0919 $(M + H)^+$, found: 246.0923 $(M + H)^+$.

8-Methoxy-indeno[1,2-*b*]quinolin-11-one (7i). 6-Methoxy-2-phenylquinoline-3-carbaldehyde (0.07 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 15 h, yield: 0.06 g, 83%, yellow solid, mp: 156 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.26 (s, 1H), 8.02 (d, J = 8.7 Hz, 1H), 7.79 (d, J = 7.2 Hz, 1H), 7.64 (t, J = 6.9 Hz, 1H), 7.79–7.41 (m, 3H), 7.14 (s, 1H), 3.94 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 190.9, 159.7, 158.3, 145.7, 143.7, 135.5, 131.4, 131.0, 130.5, 128.8, 128.3, 128.0, 124.0, 121.6, 108.6, 105.3, 55.5, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NO_2H$: 262.0868 $(M + H)^+$, found: 262.0862 $(M + H)^+$.

6-Methylindeno[1,2-*b*]quinolin-11-one (7j). 8-Methyl-2-phenylquinoline-3-carbaldehyde (0.06 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 15 h, yield: 0.08 g, 77%, light green, mp: 144 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.32 (s, 1H), 8.10 (d, J = 7.5 Hz, 1H), 7.81 (d, J = 7.5 Hz, 1H), 7.71–7.59 (m, 3H), 7.49 (t, J = 7.5 Hz, 1H), 7.40 (t, J = 7.8 Hz, 1H), 2.85 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.3, 160.8, 149.4, 144.3, 138.1, 137.3, 135.4, 132.6, 132.5, 131.2, 128.4, 127.5, 126.8, 126.6, 124.0, 121.7, 17.9, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NO_2H$: 246.0919 $(M + H)^+$, found: 246.0921 $(M + H)^+$.

7-Chloroindeno[1,2-*b*]quinolin-11-one (7k). 7-Chloro-2-phenylquinoline-3-carbaldehyde (0.13 g, 0.50 mmol), TBHP (1.50 mmol), reaction time 17 h, yield: 0.10 g, 76%, light yellow solid, mp: 196 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.34 (s, 1H), 8.10 (t, J = 9.3 Hz, 2H), 7.83 (t, J = 8.1 Hz, 2H), 7.71 (t, J = 7.2 Hz, 1H), 7.57–7.49 (m, 2H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 190.4, 163.0, 151.1, 143.5, 138.1, 137.5, 135.6, 132.0, 131.9, 131.3, 129.1, 128.1, 127.2, 126.0, 124.2, 122.0, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NO_2H$: 266.0373 $(M + H)^+$, found: 266.0377 $(M + H)^+$.

8-Methyl-2-trifluoromethoxyindeno[1,2-*b*]quinolin-11-one (7l). 6-Methyl-2-(4-trifluoromethoxyphenyl)quinoline-3-carbaldehyde (0.08 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 16 h, yield: 0.06 g, 78%, light green solid, mp: 148 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.32 (s, 1H), 8.11 (d, J = 8.4 Hz, 1H), 8.02 (d, J = 8.4 Hz, 1H), 7.63 (d, J = 9.6 Hz, 3H), 7.49 (d, J = 7.8 Hz, 1H), 2.54 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 189.5, 160.1, 151.5, 149.1, 142.1, 139.0, 137.7, 134.6, 132.4, 129.7, 129.5, 129.5, 127.5, 127.5, 127.0, 123.1, 116.3, 21.4, ^{19}F NMR (500 MHz, $CDCl_3$): δ −57.69, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NO_2H$: 330.0742 $(M + H)^+$, found: 330.0739 $(M + H)^+$.

8-Methoxy-2-trifluoromethoxyindeno[1,2-*b*]quinolin-11-one (7m). 6-Methoxy-2-(4-trifluoromethoxy-phenyl)-quinoline-3-carbaldehyde (0.09 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 16 h, yield: 0.06 g, 72%, yellow solid, mp: 158 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.28 (s, 1H), 8.07–8.00 (m, 2H), 7.62 (s, 1H), 7.48–7.40 (m, 2H), 7.16 (s, 1H), 3.95 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 189.6, 158.6, 151.3, 146.4, 142.3, 138.7, 131.8, 131.0, 130.1, 128.6, 128.4, 127.6, 127.3, 124.4, 122.9, 116.4, 108.7, 55.7, ^{19}F NMR (500 MHz, $CDCl_3$): δ −57.66, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NO_2H$: 346.0691 $(M + H)^+$, found: 346.0686 $(M + H)^+$.

6-Methyl-2-trifluoromethoxyindeno[1,2-*b*]quinolin-11-one (7n). 8-Methyl-2-(4-trifluoromethoxy-phenyl)-quinoline-3-carbaldehyde (0.08 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 20 h, yield: 0.06 g, 70%, light green solid, mp: 148 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.34 (s, 1H), 8.11 (d, J = 8.1 Hz, 1H), 7.70 (d, J = 7.5 Hz, 1H), 7.63 (d, J = 6.3 Hz, 1H), 7.49–7.40 (m, 2H), 2.84 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 189.7, 159.6, 151.5, 149.5, 142.4, 139.0, 138.2, 133.1, 133.1, 132.8, 128.5, 127.4, 127.3, 127.1, 126.49, 123.1, 116.2, 17.8, ^{19}F NMR (500 MHz, $CDCl_3$): δ −57.71, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NO_2H$: 330.0742 $(M + H)^+$, found 330.0700 $(M + H)^+$.

6-Ethyl-2-trifluoromethoxyindeno[1,2-*b*]quinolin-11-one (7o). 8-Ethyl-2-(4-trifluoromethoxyphenyl)-quinoline-3-carbaldehyde (0.08 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 20 h, yield: 0.06 g, 68%, light green solid, mp: 110 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.36 (s, 1H), 8.12 (d, J = 8.1 Hz, 1H), 7.71 (d, J = 7.8, 1H), 7.65 (s, 2H), 7.47 (t, J = 7.8 Hz, 2H), 3.34 (q, J = 7.8 Hz, 2H), 1.40 (t, J = 7.2 Hz, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): 189.7, 159.5, 151.5, 148.9, 144.1, 142.5, 139.0, 133.2, 131.4, 128.5, 127.4, 127.3, 126.5, 123.1, 116.3, 24.6, 15.1, ^{19}F NMR (500 MHz, $CDCl_3$): δ −57.69, HRMS (ESI) exact mass calcd for $C_{17}H_{11}NO_2H$: 344.0898 $(M + H)^+$, found: 344.0855 $(M + H)^+$.

3-Phenylindeno[1,2-*b*]pyridin-5-one (7p). 2,5-Diphenylpyridine-3-carbaldehyde (0.13 g, 0.50 mmol), TBHP (1.5 mmol), reaction time: 12 h, yield: 0.10 g, 84%, light yellow solid, mp: 170 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.87 (s, 1H), 8.13 (t, J = 6.3 Hz, 3H), 7.92 (s, 1H), 7.77 (s, 1H), 7.62 (d, J = 6 Hz, 2H), 7.53–7.46 (m, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.6, 171.5, 163.5, 152.1, 143.1, 136.9, 135.5, 135.1, 133.6, 130.9, 130.1, 129.9, 129.2, 128.6, 128.4, 126.9, 124.3, 121.1, HRMS (ESI) exact mass calcd for $C_{18}H_{1o}NOH$: 258.0919 $(M + H)^+$, found: 258.0929 $(M + H)^+$.

7-Fluoro-3-phenylindeno[1,2-*b*]pyridin-5-one (7q). 2-(4-Fluorophenyl)-5-phenylpyridine-3-carbaldehyde (0.07 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 15 h, yield: 0.06 g, 88%, light yellow solid, mp: 192 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.83 (s, 1H), 8.09 (s, 1H), 7.88–7.83 (m, 1H), 7.60 (d, J = 6.9 Hz, 2H), 7.53–7.42 (m, 4H), 7.41–7.29 (m, 1H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 192.1, 165.6, 163.1, 152.7, 152.6, 142.3, 136.49, 129.9, 129.2, 128.6, 126.9, 122.7, 122.6, 122.5, 122.3, 121.9, 121.7, 121.1, 121.6, 119.4, 112.1, 111.7, ^{19}F NMR (500 MHz, $CDCl_3$): δ −108.26, HRMS (ESI) exact mass calcd for $C_{18}H_9FNOH$: 276.0825 $(M + H)^+$, found: 276.0834 $(M + H)^+$.

3-Phenyl-7-trifluoromethoxyindeno[1,2-*b*]pyridin-5-one (7r). 5-Phenyl-2-(4-trifluoromethoxyphenyl)pyridine-3-carbaldehyde (0.09 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 16 h,

yield: 0.08 g, 90%, light yellow solid, mp: 190 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.86 (s, 1H), 8.11 (s, 1H), 7.90 (d, J = 8.1 Hz, 1H), 7.6 (t, J = 7.5 Hz, 3H), 7.53–7.43 (m, 4H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 190.0, 162.6, 152.8, 151.2, 141.5, 136.9, 136.8, 136.6, 130.0, 130.0, 129.3, 129.3, 128.7, 128.7, 127.3, 126.9, 126.9, 122.2, 116.9, ^{19}F NMR (500 MHz, $CDCl_3$): δ −57.69; HRMS (ESI) exact mass calcd for $C_{19}H_8NO_2H$: 342.0742 $(M + H)^+$, found: 342.0774 $(M + H)^+$.

2,3-Dimethoxyfluoren-9-one (7s). 4,5-Dimethoxybiphenyl-2-carbaldehyde (0.06 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 20 h, yield: 0.05 g, 81%, brown solid, mp: 156 °C, ^{1}H NMR (300 MHz, $CDCl_3$): 7.47 (d, J = 6.9 Hz, 1 H), 7.30 (q, J = 7.5 Hz, 2H), 7.18 (s, 1H), 7.11 (t, J = 6.3 Hz, 1H), 6.92 (s, 1H), 3.94 (s, 3H), 3.85 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 193.1, 154.5, 149.7, 143.9, 139.4, 134.7, 134.1, 128.1, 126.8, 123.7, 119.0, 107.1, 103.4, 56.3, 56.2, HRMS (ESI) exact mass calcd for $C_{15}H_{12}O_3H$: 241.0865 $(M + H)^+$, found: 241.0829 $(M + H)^+$.

2,3-Dimethoxy-7-trifluoromethoxyfluoren-9-one (7t). 4,5-Dimethoxy-4′-trifluoromethoxy-biphenyl-2-carbaldehyde (0.08 g, 0.25 mmol), TBHP (0.75 mmol), reaction time: 19 h, yield: 0.06 g, 70%, orange solid, mp: 150 °C, ^{1}H NMR (300 MHz, $CDCl_3$): 7.36 (t, J = 8.7 Hz, 2H), 7.24 (s, 1H), 7.19 (s, 1H), 6.98 (s, 1H), 4.01 (s, 3H), 3.93 (s, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 191.2, 154.9, 149.9, 149.3, 142.2, 138.6, 136.6, 127.1, 126.1, 119.9, 116.9, 107.4, 107.3, 103.5, 56.4, 56.2, ^{19}F NMR (500 MHz, $CDCl_3$): δ −57.91, HRMS (ESI) exact mass calcd For $C_{16}H_{11}F_3O_4H$: 325.0688 $(M + H)^+$, found: 325.0685 $(M + H)^+$.

Fluoren-9-one (7u). Biphenyl-2-carbaldehyde (0.09 g, 0.50 mmol), TBHP (1.5 mmol), reaction time: 18 h, yield: 0.06 g, 62%, light green solid, mp: 60 °C, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.65 (q, J = 7.5 Hz, 1H), 7.49 (q, J = 7.5 Hz, 4H), 7.32–7.19 (m, 3H), ^{13}C NMR (75 MHz, $CDCl_3$): δ 193.8, 144.3, 134.6, 134.0, 129.0, 124.2, 120.2, HRMS (ESI) exact mass calcd for $C_{13}H_8OH$: 181.0653 $(M + H)^+$, found 181.0663 $(M + H)^+$.

Acknowledgements

KM is thankful to UGC and DRDO for a fellowship. AKP and JBS are thankful to CSIR, New Delhi for SRF. RMS is thankful to DRDO for funding ERIP/ER/1203055/M/01/1471. RMS is thankful to Prof. Ganesh Pandey, Director, CBMR, Lucknow, India for providing HRMS data of all samples.

Notes and references

1 (*a*) R. C. Elderfield, in *Heterocyclic Compounds*, ed. R. C. Elderfield, John Wiley, New York, NY, London, 1960, vol. 4, ch. 1, p. 1; (*b*) C. W. Wright, J. A. -Kyereme, A. G. Breen, J. E. Brown, M. F. Cox, S. L. Croft, Y. Gokcek, H. Kendrick, R. M. Phillips and P. L. Pollet, *J. Med. Chem.*, 2001, **44**, 3187–3194; (*c*) N. S. Sahu, C. Pal, N. B. Mandal, S. Nanerjee, M. Raha, A. P. Kundu, A. Basu, M. Ghosh, K. Roy and S. Bandyopadhyay, *Bioorg. Med. Chem.*, 2002, **10**, 1687–1693; (*d*) G. Bringman, Y. Reichert and V. Kane, *Tetrahedron*, 2004, **60**, 3539–3574; (*e*) V. V. Kournetsov, L. Y. V. Mendez and C. M. M. Gomez, *Curr. Org. Chem.*, 2005, **9**, 141–161; (*f*) P. K. Kalita, B. Baruah and P. J. Bhuyan, *Tetrahedron Lett.*, 2007, **47**, 7779–7782; (*g*) W. Zhong, F. Lin, R. Chen and W. Su, *Synthesis*, 2009, 2333–2340.

2 (*a*) S. K. Srivastava, M. Jaggi, A. T. Singh, A. Madan, N. Rani, M. Vishnoi, S. K. Agarwal, R. Mukherjee and A. C. Burman, *Bioorg. Med. Chem. Lett.*, 2007, **17**, 6660–6664; (*b*) Y. Li, J. Liang, T. Siu, E. Hu, M. A. Rossi, S. F. Barnett, D. Defeo-Jones, R. E. Jones, R. G. Robinson, K. Leander, H. E. Huber, S. Mittal, N. Cosford and P. Prasit, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 834–836; (*c*) F. Pierre, P. C. Chua, S. E. O'Brien, A. Siddiqui-Jain, P. Bourbon, M. Haddach, J. Michaux, J. Nagasawa, M. K. Schwaebe, E. Stefan, A. Vialettes, J. P. Whitten, T. K. Chen, L. Darjania, R. Stansfield, K. Anderes, J. Bliesath, D. Drygin, C. Ho, M. Omori, C. Proffitt, N. Streiner, K. Trent, W. G. Rice and D. M. Ryckman, *J. Med. Chem.*, 2011, **54**, 635–654.

3 N. Marquise, P. J. Harford, F. Chevallier, T. Roisnel, V. Dorcet, A.-L. Gagez, S. Sable, L. Picot, V. Thiery, A. E. H. Wheatley, P. C. Gros and F. Mongin, *Tetrahedron*, 2013, **69**, 10123–10133.

4 S. Chakrabarty, M. S. Croft, M. G. Marko and G. Moyna, *Bioorg. Med. Chem.*, 2013, **21**, 1143–1149.

5 (*a*) L. W. Deady, J. Desneves, A. J. Kaye, M. Thompson, G. J. Finlay, B. C. Baguley and W. A. Denny, *Bioorg. Med. Chem.*, 1999, **7**, 2801–2809; (*b*) J. Chen, L. W. Deady, J. Desneves, A. J. Kaye, G. J. Finlay, B. C. Baguley and W. A. Denny, *Bioorg. Med. Chem.*, 2000, **8**, 2461–2466; (*c*) J. Chen, L. W. Deady, A. J. Kaye, G. J. Finlay, B. C. Baguley and W. A. Denny, *Bioorg. Med. Chem.*, 2002, **10**, 2381–2386.

6 (*a*) L. W. Deady, A. J. Kaye, G. J. Finlay, B. C. Baguley and W. A. Denny, *J. Med. Chem.*, 1997, **40**, 2040–2046; (*b*) L. W. Deady, J. Desneves, A. J. Kaye, G. J. Finlay, B. C. Baguley and W. A. Denny, *Bioorg. Med. Chem.*, 2000, **8**, 977–984; (*c*) N. Malecki, P. Carato, B. Rigo, J.-F. Goossens, R. Houssin, C. Bailly and J.-P. Henichart, *Bioorg. Med. Chem.*, 2004, **12**, 641–647; (*d*) C.-H. Tseng, Y.-L. Chen, P.-J. Lu, C.-N. Yang and C.-C. Tzeng, *Bioorg. Med. Chem.*, 2008, **16**, 3153–3162; (*e*) C.-H. Tseng, C.-C. Tzeng, C.-L. Yang, P.-J. Lu, H.-L. Chen, H.-Y. Li, Y.-C. Chuang, C.-N. Yang and Y.-L. Chen, *J. Med. Chem.*, 2010, **53**, 6164–6179; (*f*) C.-H. Tseng, Y.-L. Chen, C.-L. Yang, C.-M. Cheng, C.-H. Han and C.-C. Tzeng, *Bioorg. Med. Chem.*, 2012, **20**, 4397–4404; (*g*) F. Shirini, S. S. Beigbaghlou, S. V. Atghia and S. A.-R. Mousazadeh, *Dyes Pigm.*, 2013, **97**, 19–25; (*h*) R. R. Rajawinslin, S. D. Gawande, V. Kavala, Y.-H. Huang, C.-W. Kuo, T.-S. Kuo, M.-L. Chen, C.-H. He and C.-F. Yao, *RSC Adv.*, 2014, **4**, 37806–37811.

7 Reviews: (*a*) S. Murai, F. Kakiuchi, S. Sekine, Y. Tanaka, A. Kamatani, M. Sonoda and N. Chatani, *Nature*, 1993, **366**, 529–531; (*b*) J. A. Labinger and J. E. Bercaw, *Nature*, 2002, **417**, 507–514; (*c*) V. Ritleng, C. Sirlin and M. Pfeffer, *Chem. Rev.*, 2002, **102**, 1731–1769; (*d*) M. Lersch and M. Tilset,

Chem. Rev., 2005, **105**, 2471–2526; (*e*) X. Chen, K. M. Engle, D.-H. Wang and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2009, **48**, 5094–5115; (*f*) D. A. Colby, R. G. Bergman and J. A. Ellman, *Chem. Rev.*, 2010, **110**, 624–655; (*g*) J. Wencel-Delord, T. Drooge, F. Liu and F. Glorius, *Chem. Soc. Rev.*, 2011, **40**, 4740–4761; (*h*) P. B. Arockiam, C. Bruneau and P. H. Dixneuf, *Chem. Rev.*, 2012, **112**, 5879–5918; (*i*) B. Li and P. H. Dixneuf, *Chem. Soc. Rev.*, 2013, **42**, 5744–5767; (*j*) X.-X. Guo, D.-W. Gu, Z. Wu and W. Zhang, *Chem. Rev.*, 2015, **115**, 1622–1651.

8 (*a*) S. Murarka, S. Wetz and A. Studer, *Chimia*, 2012, **66**, 413–417; (*b*) E. Shirakawa and T. Hayashi, *Chem. Lett.*, 2012, **41**, 130–134; (*c*) X.-F. Wu, J.-L. Gong and X. Qi, *Org. Biomol. Chem.*, 2014, **12**, 5807–5817; (*d*) M. Szostak, N. J. Fazakerley, D. Parmar and D. J. Procter, *Chem. Rev.*, 2014, **114**, 5959–6039; (*e*) C.-L. Sun and Z.-J. Shi, *Chem. Rev.*, 2014, **114**, 9219–9280; (*f*) F. Jin and W. Han, *Chem. Commun.*, 2015, **51**, 9133–9136.

9 Reviews and examples: (*a*) C. Chatgilialoglu, D. Crich, M. Komatsu and I. Ryu, *Chem. Rev.*, 1999, **99**, 1991–2069; (*b*) J. Barluenga, M. Trincado, E. Rubio and J. M. Gonzalez, *Angew. Chem., Int. Ed.*, 2006, **45**, 3140–3143; (*c*) M. Alessi, A. L. Larkin, K. A. Ogilvie, L. A. Green, S. Lai, S. Lopez and V. Snieckus, *J. Org. Chem.*, 2007, **72**, 1588–1594; (*d*) V. S. Thirunavukkarasu, K. Parthasarathy and C.-H. Cheng, *Angew. Chem., Int. Ed.*, 2008, **47**, 9462–9465; (*e*) S. Paul, S. Samanta and J. K. Ray, *Tetrahedron Lett.*, 2010, **51**, 5604–5608; (*f*) V. S. Thirunavukkarasu and C.-H. Cheng, *Chem. – Eur. J.*, 2011, **17**, 14723–14726; (*g*) S. Dhara, A. Ahmed, S. Nandi, S. Baitalik and J. K. Ray, *Tetrahedron Lett.*, 2013, **54**, 63–65; (*h*) S. Zhang, L.-Y. Liao, F. Zhang and X.-F. Duan, *J. Org. Chem.*, 2013, **78**, 2720–2725; (*i*) Q. Y. Toh, A. McNally, S. Vera, N. Erdmann and M. J. Gaunt, *J. Am. Chem. Soc.*, 2013, **135**, 3772–3775; (*j*) S. Sarkar and N. Tadigoppula, *RSC Adv.*, 2014, **4**, 40964–40968; (*k*) T. Fukuyama, S. Maetani, K. Miyagawa and I. Ryu, *Org. Lett.*, 2014, **16**, 3216–3219; (*l*) S. K. Manna, S. L. K. Manda and G. Panda, *Tetrahedron Lett.*, 2014, **55**, 5759–5763; (*m*) H. Li, C. Liu, Y. Zhang, Y. Sun, B. Wang and W. Liu, *Org. Lett.*, 2015, **17**, 932–935.

10 S. Wertz, D. Leifert and A. Studer, *Org. Lett.*, 2013, **15**, 928–931.

11 Z. Shi and F. Glorius, *Chem. Sci.*, 2013, **4**, 829–833.

12 (*a*) J. B. Singh, K. C. Bharadwaj, T. Gupta and R. M. Singh, *RSC Adv.*, 2016, **6**, 26993–26999; (*b*) M. Asthana, J. B. Singh and R. M. Singh, *Tetrahedron Lett.*, 2016, **57**, 615–618; (*c*) M. Asthana, R. Kumar, T. Gupta and R. M. Singh, *Tetrahedron Lett.*, 2015, **56**, 907–912; (*d*) M. Asthana, N. Sharma, R. Kumar, J. B. Singh and R. M. Singh, *Tetrahedron Lett.*, 2014, **55**, 4378–4381; (*e*) D. Nandini, M. Asthana, K. Mishra, R. P. Singh and R. M. Singh, *Tetrahedron Lett.*, 2014, **55**, 6257–6262; (*f*) R. M. Singh, A. Chandra, N. Sharma, B. Singh and R. Kumar, *Tetrahedron*, 2012, **68**, 9206–9210; (*g*) A. Srivastava and R. M. Singh, *Indian J. Chem., Sect. B: Org. Chem. Incl. Med. Chem.*, 2005, **44**, 1868–1875.

13 During the preparation of this manuscript one example appeared in the literature as "scope of successive C–H functionalizations of the methyl group in 3-picolines: intramolecular carbonylation of arenes to the metal-free synthesis of 4-azafluorenones": J. K. Laha, K. P. Jethava and S. Patel, *Org. Lett.*, 2015, **17**, 5890–5893.

14 (*a*) A. Pinter, M. Nyerges, A. Viranyi and L. Toke, *Tetrahedron Lett.*, 2003, **44**, 2343–2346; (*b*) W. Hamaguchi, N. Masuda, S. Miyamoto, Y. Shiina, S. Kikuchi, T. Mihara, H. Moriguchi, H. Fushiki, Y. Murakami, Y. Amano, K. Honbou and K. Hottori, *Bioorg. Med. Chem.*, 2015, **23**, 297–313.

15 (*a*) C. Walling and L. Heaton, *J. Am. Chem. Soc.*, 1965, **87**, 38–47, and refs cited therein; (*b*) K. B. Sharpless and T. R. Verhoeven, *Aldrichimica Acta*, 1979, **12**, 52–63.

16 CCDC no. of **7r** is 1472053 and details of XRD data are given in the ESI.†

17 (*a*) A. Studer and D. P. Curran, *Angew. Chem., Int. Ed.*, 2011, **50**, 5018–5022; (*b*) A. Studer and D. P. Curran, *Nat. Chem.*, 2014, **6**, 765–773; (*c*) D. Leifert and A. Studer, *Org. Lett.*, 2015, **17**, 386–389; (*d*) A. Studer and D. P. Curran, *Angew. Chem., Int. Ed.*, 2016, **55**, 58–102.

18 (*a*) A. Pinter, M. Nyerges, A. Viranyi and L. Toke, *Tetrahedron Lett.*, 2003, **44**, 2343–2346; (*b*) C. A. Fleckenstein and H. Plenio, *Green Chem.*, 2009, **7**, 1287–1291.