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A radical addition/cyclization of diverse ethers to 2-isocyanobiaryls under mildly basic aqueous conditions†

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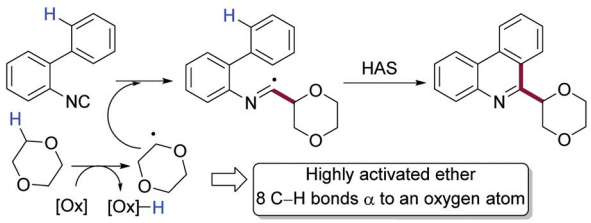
Mildly basic aqueous conditions facilitated the *tert*-butyl peroxybenzoate (TBPB) mediated dehydrogenative addition of a range of ethers, including acetals, to diverse substituted 2-isocyanobiaryls. Mechanistic studies suggest that this radical cascade is an example of base promoted homolytic aromatic substitution (BHAS).

Introduction

Phenanthridine is the scaffold of many naturally occurring products[1] that exhibit a wide range of bioactivities, such as antitumor,[2] antituberculosis,[3] antimicrobial,[4] antiviral,[5] acaricidal,[6] and fungicidal activities.[7] Some phenanthridine derivatives have also found application in biological chemistry as dyes for cytofluorometric assays[8] or even in materials science due to their optoelectronic properties.[9] Recently, the assembly of the phenanthridine framework has been elegantly achieved with a cascade that involves the addition of radicals to somophilic 2-isocyanobiphenyls, followed by intramolecular homolytic aromatic substitution.[10,11] In this context, and given the progress made in the C_α–H oxidation of ethers with peroxides to form radicals,[12] the oxidative addition of ethers to 2-isocyanobiphenyls has been successfully achieved using different conditions.[13] This transformation requires a dual selective C–H bond functionalization, and constitutes a powerful tool to increase molecular complexity with high atom-economy, where only hydrogen is lost (Scheme 1). Moreover, ethers are very important raw materials and they are also common substructures of natural and synthetic bioactive products.[14] Consequently, the development of methods that make use of relatively unreactive ethers to build complex molecules, is highly demanded by organic and medicinal chemists.

It is worth noting that 1,4-dioxane is the model substrate for C–H bond functionalization of ethers in most of the reported studies.[13] This symmetric ether presents all eight C–H bonds adjacent to an oxygen atom, which stabilizes the



Scheme 1 Oxidative addition of 1,4-dioxane to 2-isocyanobiphenyls: a radical cascade.

radical by hyperconjugation with the non-bonding electrons. Moreover, theoretical studies suggest that the release of ring strain upon radical formation is greater in 1,4-dioxane than in other cyclic ethers such as tetrahydrofuran.[15] As a matter of fact, when TBPB was used as the oxidant in the insertion of 2-isocyanobiaryls with ethers, only 1,4-dioxane was successful and THF failed.[13a] Notably, when benzoyl peroxide was used in the same transformation, another three ethers could be inserted with moderate results (40–45%).[13b] To the best of our knowledge, the greatest number of ethers tolerated in this reaction (seven examples) has been possible with the use of DTBP as the oxidant, $FeCl_3$ as the catalyst and DBU as the co-catalyst.[13c] With these precedents we decided to develop a new protocol for this reaction aimed at accommodating a range of ethers, free of transition-metal catalysts and using economical and environmentally friendly conditions (Scheme 2).

Results and discussion

To explore new reaction conditions we selected 2-isocyanobiphenyl (**1a**) and THF (**2a**) as model substrates. In a control experiment we performed the reaction using BPO as the oxidant at 100 °C and we obtained 35% yield of the desired

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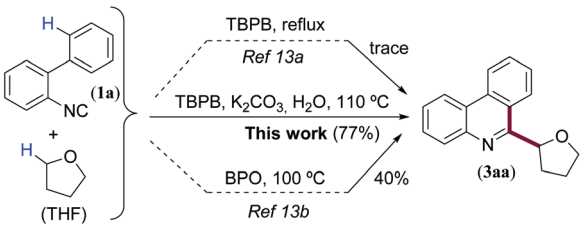
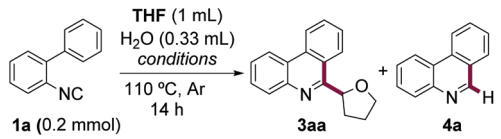


Scheme 2 Previous results and our reaction conditions for THF.

product **3aa**, a similar result to the one obtained by the Cheng group,[13b] together with byproduct **4a** (Table 1, entry 1). Surprisingly, the addition of K_2CO_3 and H_2O completely inhibited the formation of **3aa** (entry 2). Prompted by the excellent results in oxidative transformations achieved with Bu_4NI as the catalyst and TBHP,[16] we tried this combination, but **3aa** was obtained in low yield (entry 3). The use of DTBP or $(NH_4)_2S_2O_8$ in combination with Bu_4NI was also unsuccessful in this transformation (entries 4–6). It is reported that TBPB fails to afford product **3aa** in this reaction and that only compound **4a** is obtained.[13a] To our surprise, the inclusion of H_2O in this reaction mixture afforded product **3aa**, although in low yield (entry 7). We were pleased to find that the same oxidant, but in the presence of K_2CO_3 and H_2O, allowed full conversion of **1a** to obtain compound **3aa** in good yield (entry 10). While the addition of Bu_4NI had no important impact on the reaction, the amount of base and the control of the reaction temperature were crucial to obtain good and reliable results (entries 8–11). Similar results were obtained with Na_2HPO_4, and lower yields were obtained for the desired product when non-nucleophilic organic bases were used in substoichiometric amounts (entries 12–14).

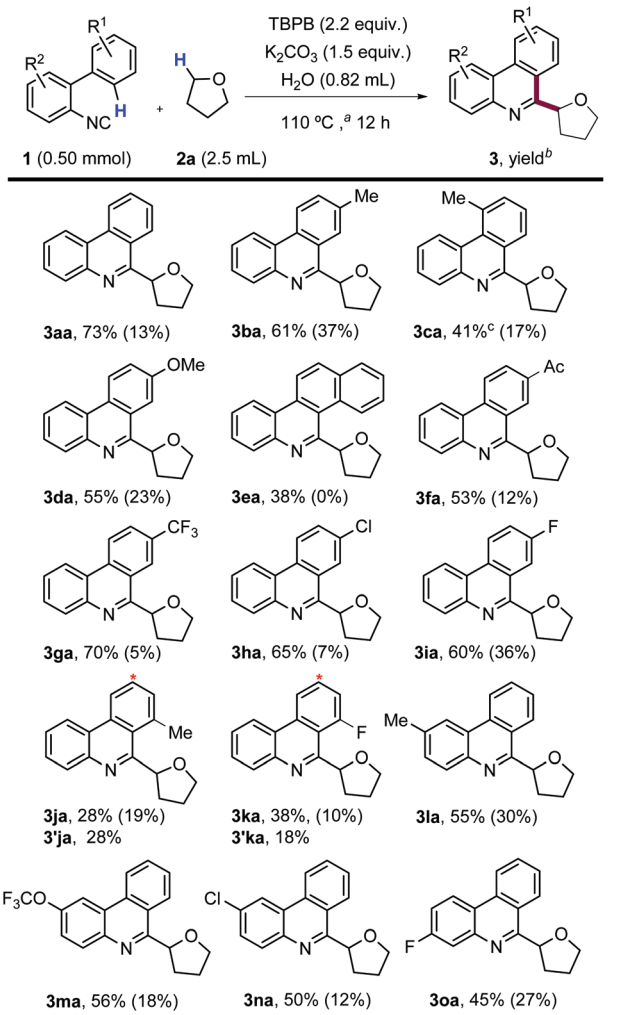
Having found very simple optimized conditions for the model reaction, we evaluated its scope using different 2-isocyanobiaryls and THF (Scheme 3). We first examined substrates with substituents on the upper aromatic ring. Methyl-substituted products **3ba** and **3ca** were obtained in good to moderate yields, without observing any benzylic oxidation. During the formation of **3ca**, some compound **3aa** was also observed (GC-MS), likely by *ipso*-homolytic aromatic substitution, and its isolated yield was affected due to difficulties in the chromatographic purification. A more electron-donating group such as methoxy was compatible with this protocol, affording compound **3da** in reasonably good yield, as well as the corresponding byproduct **4d** (detected by GC-MS and ^{1}H-NMR).

Table 1 Screening of reaction conditions



Entry	Oxidant (mol%)/ additive (mol%)	Base (mol%)	Conv.[a] (%)	(**3aa** : **4a**)[b]
1[c]	BPO (120)	None	100	35 : 22
2	BPO (120)	K_2CO_3 (150)	37	—
3	TBHP (300)/Bu_4NI (20)	K_2CO_3 (150)	45	20 : 5
4	DTBP (300)/Bu_4NI (20)	None	0	—
5	DTBP (300)/Bu_4NI (20)	K_2CO_3 (150)	0	—
6	$(NH_4)_2S_2O_8$ (220)	K_2CO_3 (150)	0	—
7	TBPB (220)	None	100	12 : 4[c]
8	TBPB (120)/Bu_4NI (20)	K_2CO_3 (150)	55	—
9	TBPB (220)	K_2CO_3 (100)	70	—
10[d]	**TBPB (220)**	**K_2CO_3 (150)**	**100**	**77 : 23**
11	TBPB (220)/Bu_4NI (50)	K_2CO_3 (150)	100	75 : 25
12	TBPB (220)	Na_2HPO_4 (150)	90	75 : 25
13[c]	TBPB (220)	DABCO (50)	100	18 : 0
14[c]	TBPB (220)	DBU (50)	100	40 : 0

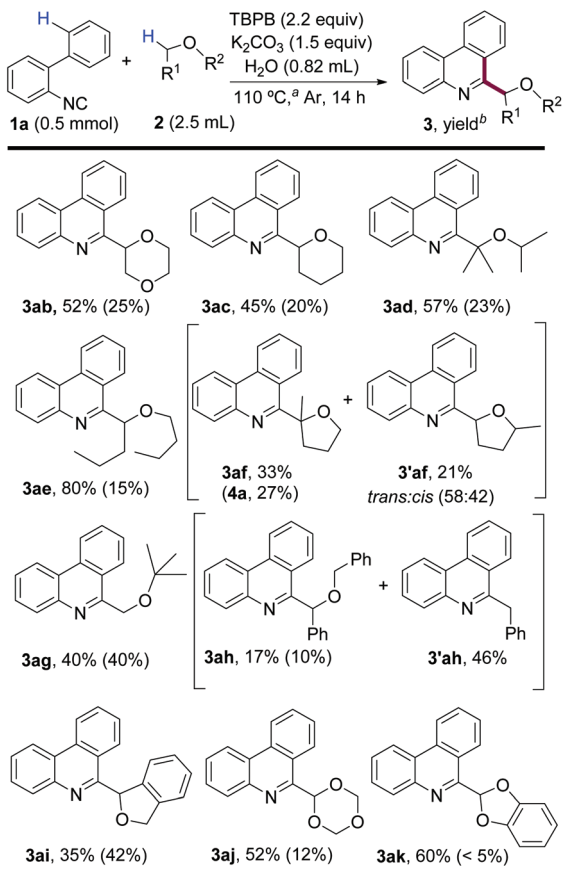
[a] By GC of the crude reaction mixture. [b] Yield calculated by ^{1}H-NMR of the crude reaction mixture using durene as the internal standard. [c] Formation of other products is observed by GC. [d] The conversion was 90% at 80 °C and 0% at 60 °C. BPO = benzoyl peroxide. DTBP = di-*tert*-butylperoxide. TBPB = *tert*-butylperoxybenzoate. DABCO = 1,4-diazabicyclo[2.2.2]octane. DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene.



Scheme 3 Scope of 2-isocyanobiaryls with THF. [a] Measured temperature of the sand bath. [b] Yields after purification of isolated products and in parentheses are yields of 6-H phenanthridines **4** estimated by GC-MS of crude reaction mixtures. [c] Product **3aa** was also formed and purification of **3ca** was more difficult. *The other regioisomer isolated (**3'**).

When 2-(2-isocyanophenyl)-naphthalene was used, compound **3ea** was the only regioisomer isolated in moderate yield, despite the steric hindrance between the ether moiety and the extra aromatic ring.[17] Electron-withdrawing groups, such as acetyl, trifluoromethyl, chloro and fluoro, were suitable substituents in the upper aromatic ring, furnishing products (**3fa**, **3ga**, **3ha** and **3ia**) in good isolated yields. Interestingly, when *meta*-substituted substrates **1j** and **1k** were used, both possible regioisomers were isolated after column chromatography. While the ratio of **3ja**/**3′ja** was 1 : 1, for **1k** the major product was the most crowded regioisomer (**3ka**).[18] We also examined isocyanobiaryls substituted in the lower aromatic ring by electron-donating and electron-withdrawing groups, obtaining uniformly moderate yields in all cases (**3la–3oa**).

We further explore the performance of different ethers using the optimized procedure (Scheme 4). 1,4-Dioxane (**2b**) and THP (**2c**) were also suitable for this protocol, obtaining products **3ab** and **3ac** in moderate yields after purification, as well as compound **4a** as the byproduct. With THP, minor amounts of regioisomers were formed (see the ESI† for GC-MS of isomers), complicating the isolation of **3ac** in a pure form. Acyclic ethers such as i-Pr_2O (**2d**), *n*-Bu_2O (**2e**) and *t*-BuOMe (**2g**) afforded the corresponding products in good to excellent yields, with linear *n*-Bu_2O providing the best yield. 2-MeTHF (**2f**) was also examined, affording the more substituted compound **3af** as the major product and regioisomer **3′af** as an inseparable *trans*/*cis* mixture. Surprisingly, when Bn_2O (**2h**) was examined, the expected product (**3ah**) was obtained in only 17% yield and the addition of a benzyl radical took place preferentially (**3′ah**). It seems reasonable that after H-abstraction from Bn_2O, a β-fragmentation gives rise to the benzyl radical, which is finally added to **1a**. The addition of phthalan (**2i**) was also possible, but compound **3ai** was obtained in lower yield. Importantly, acetals **2j** and **2k** led, respectively, to products **3aj** and **3ak** in synthetically useful yields. These compounds could be easily hydrolyzed to obtain the corresponding 6-formylphenanthridine and the acetal moiety has the potential to be transformed into other functionalities.[19]

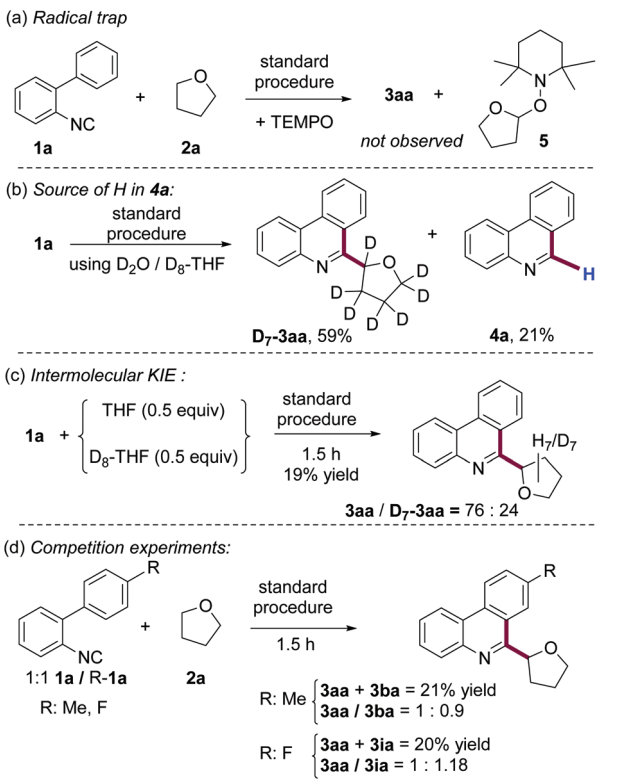


Scheme 4 Scope of ethers. [a] Measured temperature of the sand bath. [b] Yields after purification of isolated products and in parentheses are yields of **4a**.

Investigation of the reaction mechanism

To gain insight into the reaction mechanism we performed some experiments. As shown in Scheme 5a, the use of TEMPO as a radical scavenger in our model reaction, under standard conditions, completely inhibited the formation of **3aa** and the coupling product **5** was detected by MS. Since compounds **4** are consistent byproducts of the radical cyclization studied here, we were intrigued about their formation and we have not found any experimental evidence of this in the literature.[20]

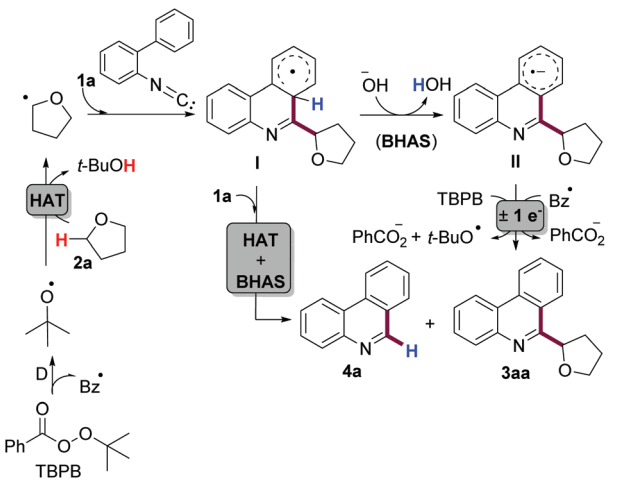
When the reaction was conducted using D_2O and D_8-THF (Scheme 5b), the expected product **D_7-3aa** was obtained,



Scheme 5 Mechanistic investigations.

accompanied by phenanthridine **4a**. Importantly, the byproduct of this reaction is not deuterated, indicating that neither THF nor H_2O is the source of hydrogen for the formation of this phenanthridine. We also studied the intermolecular kinetic isotopic effect (KIE) by competition experiments of equimolar amounts of THF and D_8-THF with **1a** at the initial stage of the reaction (Scheme 5c). The large KIE obtained (k_H/k_D = 3.16) suggests that the cleavage of the C(sp^3)–H bond is involved in the rate determining step of this reaction. In addition, we also performed competition experiments at the initial state of the reaction, using equimolar quantities of **1a** and 2-isocyanobiphenyls substituted in position 4′ by methyl or fluoro groups. The results shown in Scheme 4d suggested that electron-withdrawing substituents in the upper aromatic ring accelerate the reaction. Since this class of group stabilizes the LUMO of the upper aromatic ring, this result is also consistent with a radical cyclization pathway.[21]

An important feature of this protocol is the crucial role of K_2CO_3 and H_2O in a successful transformation (Table 1, entries 6 and 9). Since the seminal contribution of Studer and Curran,[22] several known reactions have been recognized as "base promoted homolytic substitutions" (BHAS) and many new transformations have been developed with this concept.[11] Based on literature precedents and our own results, we believe that this reaction is an example of BHAS. A possible reaction mechanism is depicted in Scheme 6. Firstly, homolysis of TBPB takes place upon heating. From the two generated radicals, it is reported that *t*-BuO$^{\bullet}$ abstracts a hydrogen atom from THF faster than Bz$^{\bullet}$ to generate the α-furanyl radical.[23] Addition of this intermediate to isonitrile **1a**, followed by intramolecular addition to the upper aromatic ring, is well documented in a number of examples.[11] DFT studies performed by the Studer group indicate that cyclohexadienyl radicals, such as **I**, are extremely strong acids (pK_a ~ −15 in H_2O).[24] Therefore, this radical intermediate can be deprotonated under mild basic aqueous conditions (*e.g.* K_2CO_3 in H_2O) to generate a radical anion **II**. This species is a potent reductant that can easily transfer an electron to radical Bz$^{\bullet}$ or to oxidant TBPB, while generating product **3aa**. In addition, intermediate **I** can transfer a hydrogen atom to **1a**, which after a similar BHAS process leads to the formation of byproduct **4a**. This explanation is consistent with our observation that neither THF nor H_2O was the hydrogen source of **4a**.[25]



Scheme 6 Plausible mechanism.

Conclusions

In conclusion, we have demonstrated that TBPB can be used under mildly basic aqueous conditions to promote the radical addition of a range of ethers to 2-isocyanobiaryls followed by cyclization. Mechanistic investigations suggest that this transformation is an example of BHAS and a plausible explanation is provided for the formation of byproduct **4**. Some salient features of the developed methodology are: (a) neither transition metals nor any expensive additives are needed; (b) the wastes generated are harmless inorganic salts and can be easily removed by aqueous workup; (c) the reaction medium is constituted by the reactant ethers and water.

Experimental section

General remarks

All starting isonitriles were prepared according to a reported method.[10b] TLC was performed on silica gel 60 F_{254}, using aluminium plates and visualized by exposure to ultraviolet light. Flash chromatography was carried out on hand-packed columns of silica gel 60 (230–400 mesh). Infrared (IR) spectra were recorded with a spectrophotometer equipped with an ATR component; wavenumbers are given in cm^{-1}. LRMS were obtained using a mass spectrometer coupled with a gas chromatographer (GC); the mobile phase was helium (2 mL min^{-1}); HP-1 column of 12 m was used; temperature program starts at 80 °C for 3 min, then up to 270 °C at a rate of 20 °C min^{-1}, and 17.5 min at 270 °C. HRMS analyses were carried out using Electron Impact (EI) mode at 70 eV by Q-TOF. ^{1}H NMR spectra were recorded at 300 or 400 MHz for ^{1}H-NMR and 75 or 100 MHz for ^{13}C-NMR, using $CDCl_3$ as the solvent and TMS as an internal standard (0.00 ppm). The data are being reported as (s = singlet, d = doublet, t = triplet, m = multiplet or unresolved, br s = broad signal, coupling constant(s) in Hz, integration). ^{13}C-NMR spectra were recorded with ^{1}H-decoupling at 100 MHz and referenced to $CDCl_3$ at 77.16 ppm. DEPT-135 experiments were performed to assign CH, CH_2 and CH_3.

General procedure for the synthesis of compounds 3

Into a pressure tube were added K_2CO_3 (103 mg, 0.75 mmol) and H_2O (0.82 mL). Then, to it were added sequentially the 2-isocyanobiaryl derivative **1** (0.50 mmol), ether **2** (2.5 mL) and *tert*-butyl peroxibenzoate (TBPB) (213 μL, 1.10 mmol). The reaction mixture was stirred under an Ar atmosphere for 12–14 h at 110 °C (sand bath temperature). Upon full conver-

sion of the isonitrile (TLC or GC), a saturated solution of $NaHCO_3$ (5 mL) and EtOAc (10 mL) was added to the reaction mixture. After phase separation, the aqueous phase was extracted with EtOAc (3 × 15 mL) and the combined organic layers were washed with brine (5 mL), dried over $MgSO_4$ and concentrated under reduced pressure. The residue was purified by flash column chromatography on silica gel to give the desired product.

6-(Tetrahydrofuran-2-yl)phenanthridine (3aa).[13c] Following the general procedure, compound **3aa** was obtained after column chromatography (hexane/EtOAc 9 : 1) as a yellow pale solid (91 mg, 0.36 mmol, 73%): R_f 0.23 (95 : 5 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.63 (dd, J = 8.2, 1.3 Hz, 1H), 8.55 (dd, J = 8.0, 1.5 Hz, 1H), 8.45 (dd, J = 8.7, 1.0 Hz, 1H), 8.19 (dd, J = 7.9, 1.6 Hz, 1H), 7.83 (ddd, J = 8.3, 7.0, 1.3 Hz, 1H), 7.75–7.61 (m, 3H), 5.78 (t, J = 6.9 Hz, 1H), 4.26–4.15 (m, 1H), 4.13–4.01 (m, 1H), 2.82–2.65 (m, 1H), 2.50–2.35 (m, 1H), 2.30–2.03 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 159.4 (C), 143.4 (C), 133.4 (C), 130.6 (CH), 130.4 (CH), 128.6 (CH), 127.3 (CH), 127.0 (CH), 126.6 (CH), 124.9 (C), 124.2 (C), 122.5 (CH), 122.0 (CH), 79.7 (CH), 69.1 (CH_2), 30.1 (CH_2), 26.1 (CH_2) ppm; IR ν 3073, 2981, 2881, 1583, 1444, 1300, 1057, 727 cm^{-1}; LRMS (EI) m/z (%) = 249 (M^+, 5), 220 (15), 206 (100), 193 (48), 178 (15).

8-Methyl-6-(tetrahydrofuran-2-yl)phenanthridine (3ba). Following the general procedure, compound **3ba** was obtained after column chromatography (hexane/EtOAc 93 : 7) as a yellow pale solid (80 mg, 0.31 mmol, 61%): R_f 0.20 (93 : 7 hexane/EtOAc); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.54–8.48 (m, 2H), 8.20 (br s, 1H), 8.16 (dd, J = 8.1, 1.1 Hz, 1H), 7.71–7.59 (m, 3H), 5.79–5.74 (m, 1H), 4.23–4.15 (m, 1H), 4.10–4.03 (m, 1H), 2.83–2.72 (m, 1H), 2.60 (s, 3H), 2.46–2.35 (m, 1H), 2.27–2.17 (m, 1H), 2.17–2.06 (m, 1H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 159.0 (C), 143.1 (C), 137.2 (C), 132.1 (CH), 131.2 (C), 130.5 (CH), 128.1 (CH), 126.9 (CH), 126.0 (CH), 125.1 (C), 124.3 (C), 122.3 (CH), 121.8 (CH), 79.5 (CH), 69.1 (CH_2), 30.0 (CH_2), 26.1 (CH_2), 22.1 (CH_3) ppm; IR ν 2955, 2867, 1577, 1460, 1052, 760 cm^{-1}; LRMS (EI) m/z (%) = 263 (M^+, 6), 234 (10), 220 (100), 207 (57); HRMS (EI) m/z calcd for $C_{18}H_{17}NO$ 263.1310, found 263.1307.

10-Methyl-6-(tetrahydrofuran-2-yl)phenanthridine (3ca). Following the general procedure, compound **3ca** was obtained after column chromatography (hexane/EtOAc 95 : 5–9 : 1) as a yellow pale solid (54 mg, 0.20 mmol, 41%): R_f 0.20 (95 : 5 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.77 (br d, J = 8.2 Hz, 1H), 8.35 (dd, J = 8.1, 1.6 Hz, 1H), 8.23 (dd, J = 8.1, 1.5 Hz, 1H), 7.70 (ddd, J = 8.2, 7.0, 1.4 Hz, 1H), 7.67–7.55 (m, 3H), 5.81–5.75 (t, J = 6.8 Hz, 1H), 4.25–4.15 (m, 1H), 4.10–4.01 (m, 1H), 3.11 (s, 3H), 2.84–2.67 (m, 1H), 2.48–2.32 (m, 1H), 2.27–2.00 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 159.6 (C), 144.5 (C), 135.6 (C), 134.6 (CH), 132.9 (C), 130.9 (CH), 127.8 (CH), 126.7 (CH), 126.5 (CH), 126.4 (C), 126.1 (CH), 125.6 (C), 124.9 (CH), 79.7 (CH), 69.1 (CH_2), 30.1 (CH_2), 27.1 (CH_2), 26.1 (CH_3) ppm; IR ν 3069, 2968, 2871, 1587, 1437, 1054, 760 cm^{-1}; LRMS (EI) m/z (%) = 263 (M^+, 8), 234 (18), 220 (100), 207 (59), 204 (21), 165 (18); HRMS (EI) m/z calcd for $C_{18}H_{17}NO$ 263.1310, found 263.1306.

8-Methoxy-6-(tetrahydrofuran-2-yl)phenanthridine (3da). Following the general procedure, compound **3da** was obtained after column chromatography (hexane/EtOAc 95 : 5–75 : 25) as a white solid (78 mg, 0.28 mmol, 55%): R_f 0.20 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.53 (d, J = 9.1 Hz, 1H), 8.47–8.41 (m, 1H), 8.17–8.12 (m, 1H), 7.82 (d, J = 2.6 Hz, 1H), 7.68–7.56 (m, 2H), 7.44 (dd, J = 9.1, 2.6 Hz, 1H), 5.69 (t, J = 6.9 Hz, 1H), 4.24–4.12 (m, 1H), 4.12–4.01 (m, 1H), 3.98 (s, 3H), 2.87–2.71 (m, 1H), 2.47–2.32 (m, 1H), 2.28–2.05 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 158.6 (C), 158.4 (C), 142.5 (C), 130.5 (CH), 127.8 (C), 127.6 (CH), 127.0 (CH), 126.3 (C), 124.3 (C), 124.1(CH), 121.5 (CH), 120.8 (CH), 107.1 (CH), 80.1 (CH), 69.1 (CH_2), 55.6 (CH_3), 29.8 (CH_2), 26.2 (CH_2) ppm; IR ν 3000, 2964, 2858, 1571, 1059, 754 cm^{-1}; LRMS (EI) m/z (%) = 279 (M^+, 12), 250 (8), 236 (100), 223 (44), 207 (35); HRMS (EI) m/z calcd for $C_{18}H_{17}NO_2$ 279.1259, found 279.1261.

5-(Tetrahydrofuran-2-yl)benzo[*i*]phenanthridine (3ea). Following the general procedure, compound **3ea** was obtained after column chromatography (hexane/EtOAc 98 : 2–95 : 5) as a white solid (57 mg, 0.19 mmol, 38%): R_f 0.35 (96 : 4 hexane/EtOAc); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 9.19 (H-1, d, J = 8.5 Hz, 1H), 8.57 (H-12 + H-4, dd, J = 8.7, 5.2 Hz, 2H), 8.23 (H-7, dd, J = 8.2, 1.1 Hz, 1H), 8.10 (H-11, d, J = 8.9 Hz, 1H), 7.98 (H-10, d, J = 7.9 Hz, 1H), 7.78–7.71 (H-2 + H-8, m, 2H), 7.68–7.63 (H-3 + H-9, m, 2H), 5.91 (H-2′, t, J = 6.4 Hz, 1H), 4.47–4.38 (H-5′, m, 1H), 4.20–4.13 (H-5′, m, 1H), 2.99–2.86 (H-3′, m, 1H), 2.59–2.37 (H-4′, m, 1H), 2.27–2.07 (H-3′ + H-4′, m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 157.7 (C), 144.0 (C), 133.8 (C), 133.2 (C), 131.9(C), 130.1 (CH), 129.9 (C), 128.8 (CH), 128.7 (CH), 128.4 (CH), 127.2 (CH), 126.9 (CH), 126.7 (CH), 123.7(C), 123.0 (C), 122.5 (CH), 120.2 (CH), 80.5 (CH), 69.4 (CH_2), 31.3 (CH_2), 26.8 (CH_2) ppm; IR ν 3019, 2961, 2937, 1561, 1465, 1350, 1051, 750 cm^{-1}; LRMS (EI) m/z (%) = 299 (M^+, 14), 256 (100), 242 (28), 227 (19); HRMS (EI) m/z calcd for $C_{21}H_{17}NO$ 299.1310, found 299.1304.

1-(6-(Tetrahydrofuran-2-yl)phenanthridin-8-yl)ethan-1-one (3fa). Following the general procedure, compound **3fa** was obtained after column chromatography (hexane/EtOAc 8 : 2) as a yellow pale solid (77 mg, 0.27 mmol, 53%): R_f 0.20 (8 : 2 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 9.10 (br s, 1H), 8.65 (d, J = 8.7 Hz, 1H), 8.54 (d, J = 8.2 Hz, 1H), 8.35 (dd, 2H), 8.19 (dd, J = 8.1, 1.2 Hz, 1H), 7.77 (ddd, J = 8.3, 7.0, 1.4 Hz, 1H), 7.67 (ddd, J = 8.3, 7.1, 1.4 Hz, 1H), 5.77 (t, J = 7.0 Hz, 1H), 4.22–4.13 (m, 1H), 4.13–4.04 (m, 1H), 2.88–2.79 (m, 1H), 2.77 (s, 3H), 2.52–2.37 (m, 1H), 2.31–2.10 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 197.5 (C), 159.8 (C), 144.2 (C), 136.5 (C), 135.3 (C), 130.7 (C), 129.8 (CH), 128.8 (CH), 128.2 (CH), 127.4 (CH), 124.5 (C), 123.5 (C), 122.9 (CH), 122.6 (CH), 79.9 (CH), 69.2 (CH_2), 29.9 (CH_2), 26.9 (CH_2), 26.2 (CH_3) ppm; IR ν 2977, 2921, 2856, 1683, 1615, 1251, 1052, 760 cm^{-1}; LRMS (EI) m/z (%) = 291 (M^+, 5), 263 (20), 248 (100), 235 (65), 207 (17); HRMS (EI) m/z calcd for $C_{19}H_{17}NO_2$ 291.1259, found 291.1265.

6-(Tetrahydrofuran-2-yl)-8-(trifluoromethyl)phenanthridine (3ga). Following the general procedure, compound **3ga** was obtained after column chromatography (hexane/EtOAc 95 : 5–9 : 1) as a yellow pale solid (111 mg, 0.35 mmol, 70%):

R_f 0.25 (95 : 5 hexane/EtOAc); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.81 (s, 1H), 8.72 (d, J = 8.6 Hz, 1H), 8.54 (d, J = 8.1 Hz, 1H), 8.20 (d, J = 8.1 Hz, 1H), 8.00 (d, J = 8.6 Hz, 1H), 7.78 (t, J = 7.4 Hz, 1H), 7.69 (t, J = 7.5 Hz, 1H), 5.72 (t, J = 6.9 Hz, 1H), 4.19–4.12 (m, 1H), 4.12–4.03 (m, 1H), 2.88–2.75 (m, 1H), 2.48–2.35 (m, 1H), 2.30–2.08 (m, 2H); ^{13}C-NMR (101 MHz, $CDCl_3$) δ 159.2 (C), 144.0 (C), 135.6 (C), 130.7 (CH), 129.8 (CH), 129.1(CH), 129.0 (C-8, d, $^2J_{C-F}$ = 32.4 Hz), 127.6 (CH), 126.3 (CH, q, $^3J_{C-F}$ = 3.3 Hz), 124.5 (CH, q, $^3J_{C-F}$ = 4.3 Hz), 124.4 (CH), 124.25 (d, $^1J_{C-F}$ = 272.2 Hz), 123.5 (CH), 123.3 (C), 122.4 (CH), 80.0 (CH), 69.2 (CH_2), 29.8 (CH_2), 26.2 (CH_2) ppm; IR ν 2966, 2874, 1722, 1625, 1173, 1122, 763 cm^{-1}; LRMS (EI) m/z (%) = 317 (M^+, 4), 288 (8), 274 (100), 261 (73), 247 ([(M + 1)$^+$ − THF], 14), 226 (12); HRMS (EI) m/z calcd for $C_{14}H_8F_3N$, 247.0609, found 247.0612.

8-Chloro-6-(tetrahydrofuran-2-yl)phenanthridine (3ha). Following the general procedure, compound **3ha** was obtained after column chromatography (hexane/EtOAc 95 : 5) as an orange pale solid (92 mg, 0.32 mmol, 65%): R_f 0.25 (95 : 5 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.53 (d, J = 8.9 Hz, 1H), 8.46 (dd, J = 7.5, 1.8 Hz, 2H), 8.16 (dd, J = 8.1, 1.1 Hz, 1H), 7.78–7.68 (m, 2H), 7.64 (ddd, J = 8.4, 7.1, 1.5 Hz, 1H), 5.65 (t, J = 6.9 Hz, 1H), 4.20–4.11 (m, 1H), 4.11–4.01 (m, 1H), 2.87–2.71 (m, 1H), 2.47–2.30 (m, 1H), 2.29–2.00 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 158.3 (C), 143.3 (C), 133.3 (C), 131.8 (C), 130.9 (CH), 130.7 (CH), 128.9 (CH), 127.4 (CH), 126.2 (CH), 126.0 (C), 124.2 (CH), 123.6 (C), 121.9 (CH), 79.8 (CH), 69.1 (CH_2), 29.7 (CH_2), 26.1 (CH_2) ppm; IR ν 3063, 2939, 2839, 1617, 1460, 1220, 1038, 759 cm^{-1}; LRMS (EI) m/z (%) = 283 (M^+, 8), 254 (15), 240 ([M^+ − C_2H_3O], 100), 217 (12), 207 (65), 177 (39); HRMS (EI) m/z calcd for $C_{15}H_{11}ClN$ 240.0580, found 240.0586.

8-Fluoro-6-(tetrahydrofuran-2-yl)phenanthridine (3ia). Following the general procedure, compound **3ia** was obtained after column chromatography (hexane/EtOAc 95 : 5–8 : 2) as a yellow pale solid (80 mg, 0.30 mmol, 60%): R_f 0.21 (95 : 5 hexane/EtOAc); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.60 (H-10, dd, J_{H-F} = 9.1, 5.4 Hz, 1H), 8.46 (dd, J = 8.1, 1.1 Hz, 1H), 8.17 (dd, J = 8.1, 1.2 Hz, 1H), 8.12 (H-7, dd, J_{H-F} = 10.2, 2.6 Hz, 1H), 7.70 (ddd, J = 8.2, 7.0, 1.5 Hz, 1H), 7.64 (ddd, J = 8.3, 7.0, 1.5 Hz, 1H), 7.56 (H-9, ddd, J_{H-F} = 9.1, 8.0, 2.7 Hz, 1H), 5.63 (H-2′, t, J = 6.9 Hz, 1H), 4.20–4.13 (H-5′, m, 1H), 4.09–4.02 (H-5′, m, 1H), 2.84–2.71 (m, 1H), 2.44–2.34 (m, 1H), 2.27–2.06 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 161.33 (C-8, d, $^1J_{C-F}$ = 248.0 Hz), 158.53 (C, d, $^4J_{C-F}$ = 4.3 Hz), 142.94 (C), 130.62 (CH), 130.11 (C), 128.51 (CH), 127.43 (CH), 126.24 (C-6a, d, $^3J_{C-F}$ = 7.8 Hz), 124.93 (C-10, d, $^3J_{C-F}$ = 8.5 Hz), 123.82 (C), 121.76 (CH), 119.64 (CH, d, $^2J_{C-F}$ = 23.9 Hz), 111.59 (CH, d, $^2J_{C-F}$ = 21.8 Hz), 80.08 (CH), 69.14 (CH_2), 29.79 (CH_2), 26.08 (CH_2); IR ν 2958, 2873, 1773, 1697, 1480, 1196, 1054,759 cm^{-1}; LRMS (EI) m/z (%) = 267.1 (M^+, 5), 238 (12), 224 (100), 211 (59), 197 (19), 169 (11); HRMS (EI) m/z calcd for $C_{17}H_{14}FNO$ 267.1059, found 267.1042.

7-Methyl-6-(tetrahydrofuran-2-yl)phenanthridine (3ja). Following the general procedure, compound **3ja** was obtained after column chromatography (hexane/EtOAc 98 : 2–95 : 5) as a yellow pale solid (38 mg, 0.14 mmol, 28%): R_f 0.16 (98 : 2 hexane/EtOAc); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.53 (d, J = 8.3 Hz, 1H), 8.51 (d, J = 8.3 Hz, 1H), 8.12 (dd, J = 8.1, 1.4 Hz, 1H), 7.71–7.57 (m, 3H), 7.49 (d, J = 7.2 Hz, 1H), 5.97 (dd, J = 6.9, 5.2 Hz, 1H), 4.20–4.12 (m, 1H), 4.04–3.95 (m, 1H), 3.09 (s, 3H), 2.89–2.80 (m, 1H), 2.32–2.12 (m, 2H), 2.11–1.96 (m, 1H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 159.4 (C), 142.5 (C), 136.5 (C), 134.9 (C), 132.0 (CH), 130.2 (CH), 129.6 (CH), 128.4 (CH), 126.9 (CH), 125.4 (C), 124.4 (C), 122.2 (CH), 120.9 (CH), 80.3 (CH), 68.9(CH_2), 30.3 (CH_2), 25.8 (CH_2), 25.2 (CH_3) ppm; IR ν 2959, 2874, 1573, 1449, 1286, 1048, 749 cm^{-1}; LRMS (EI) m/z (%) = 263 (M^+, 8), 248 (6), 234 (13), 220 (100), 207 (13), 193 (19); HRMS (EI) m/z calcd for $C_{18}H_{17}NO$ 263.1310, found 263.1312.

9-Methyl-6-(tetrahydrofuran-2-yl)phenanthridine (3′ja). From the same reaction where compound **3ja** was obtained, and after column chromatography (hexane/EtOAc 95 : 5–100% EtOH), isomer **3′ja** was isolated as a yellow pale solid (37 mg, 0.14 mmol, 28%): R_f 0.19 (95 : 5 hexane/EtOAc); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.52 (dd, J = 8.1, 1.5 Hz, 1H), 8.40 (H-10, s, 1H), 8.31 (d, J = 8.4 Hz, 1H), 8.16 (dd, J = 8.1, 1.0 Hz, 1H), 7.68 (ddd, J = 8.2, 7.1, 1.4 Hz, 1H), 7.60 (ddd, J = 8.3, 7.1, 1.4 Hz, 1H), 7.50 (dd, J = 8.4, 1.4 Hz, 1H), 5.73 (t, J = 6.9 Hz, 1H), 4.23–4.16 (m, 1H), 4.11–4.00 (m, 1H), 2.76–2.65 (m, 1H), 2.62 (s, 3H), 2.46–2.32 (m, 1H), 2.27–2.04 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 159.3 (C), 143.6 (C), 140.7 (C), 133.5 (C), 130.5 (CH), 129.0 (CH), 128.4 (CH), 126.7 (CH), 126.4 (CH), 124.1 (C), 123.0 (C), 122.1 (CH), 121.9 (CH), 79.8 (CH), 69.1 (CH_2), 30.2 (CH_2), 26.1 (CH_2), 22.3 (CH_3) ppm; IR ν 2875, 2868, 1618, 1460, 1053, 760; LRMS (EI) m/z (%) = 263 (M^+, 5), 234 (13), 220 (100), 207 (51), 192 (23); HRMS (EI) m/z calcd for $C_{18}H_{17}NO$ 263.1310, found 263.1312.

7-Fluoro-6-(tetrahydrofuran-2-yl)phenanthridine (3ka). Following the general procedure, compound **3ka** was obtained after column chromatography (hexane/EtOAc 93 : 7) as a white solid (51 mg, 0.19 mmol, 38%): R_f 0.19 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.49 (d, J = 8.2 Hz, 1H), 8.45 (d, J = 8.4 Hz, 1H), 8.22 (dd, J = 8.2, 1.2 Hz, 1H), 7.82–7.70 (m, 2H), 7.64 (ddd, J = 8.3, 7.1, 1.4 Hz, 1H), 7.36 (ddd, J = 12.5, 7.9, 1.0 Hz, 1H), 6.02 (dt, J = 8.2, 4.3 Hz, 1H), 4.43–4.32 (m, 1H), 4.17–4.05 (m, 1H), 2.60–2.45 (m, 1H), 2.40–2.23 (m, 1H), 2.13–1.96 (m, 1H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 160.2 (C-7, d, $^1J_{C-F}$ = 255.2 Hz), 158.8 (C, d, $^3J_{C-F}$ = 7.9 Hz), 143.3 (CH), 136.0 (C, d, $^4J_{C-F}$ = 4.4 Hz), 131.0 (C-9, d, $^3J_{C-F}$ = 9.8 Hz), 130.8 (CH), 129.3 (CH), 127.3 (CH), 122.7 (C, d, $^5J_{C-F}$ = 2.7 Hz), 122.3 (CH), 118.7 (C-10, d, $^4J_{C-F}$ = 4.0 Hz), 114.2 (CH), 114.1 (CH), 114.0 (C-6a, d, $^2J_{C-F}$ = 24.6 Hz), 81.9 (C-2′, d, $^4J_{C-F}$ = 14 Hz), 69.3 (CH_2), 31.7 (CH_2), 25.1 (CH_2) ppm; IR ν 2970, 2870, 1581, 1451, 1240, 757 cm^{-1}; LRMS (EI) m/z (%) = 267 (M^+, 2), 224 (100), 211 (64), 197 (19), 169 (9); HRMS (EI) m/z calcd for $C_{17}H_{14}FNO$ 267.1059, found 267.1050.

9-Fluoro-6-(tetrahydrofuran-2-yl)phenanthridine (3′ka). From the same reaction where compound **3ka** was obtained, and after column chromatography (hexane/EtOAc 95 : 5), isomer **3′ka** was isolated as a white solid (24 mg, 0.09 mmol, 18%): R_f 0.27 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.52 (H-7, dd, J = 9.1, 5.8 Hz, 1H), 8.41 (H-1, dd, J = 8.2,

1.1 Hz, 1H), 8.22 (H-10, dd, J = 10.5, 2.6 Hz, 1H), 8.17 (H-4, dd, J = 8.3, 1.2 Hz, 1H), 7.74 (ddd, J = 8.3, 7.0, 1.5 Hz, 1H), 7.64 (ddd, J = 8.3, 7.0, 1.4 Hz, 1H), 7.42 (H-8, ddd, J = 9.1, 8.2, 2.6 Hz, 1H), 5.70 (H-2′, t, J = 6.9 Hz, 1H), 4.21–4.11 (H-5′, m, 1H), 4.10–4.01 (H-5′, m, 1H), 2.88–2.71 (m, 1H), 2.47–2.31 (m, 1H), 2.29–2.05 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 163.70 (C-9, d, $^1J_{C-F}$ = 251.5 Hz); 158.7 (C), 143.6 (C), 135.9 (C-10a, d, $^3J_{C-F}$ = 9.4 Hz), 130.6 (CH), 129.8 (C-7, d, $^3J_{C-F}$ = 9.3 Hz), 129.3 (CH), 127.1 (CH), 123.8 (C-6a, d, $^4J_{C-F}$ = 4.1 Hz), 122.2 (CH), 122.0 (C-6, d, $^5J_{C-F}$ = 2 Hz), 116.3 (C-10/C-8, d, $^2J_{C-F}$ = 23.7 Hz), 107.5 (C-8/C-10, d, $^2J_{C-F}$ = 22.1 Hz), 80.0 (CH), 69.1 (CH_2), 29.8 (CH_2), 26.1 (CH_2) ppm; IR ν 2962, 2877, 1619, 1496, 1195, 1052, 760 cm^{-1}; LRMS (EI) m/z (%) = 267 (M^+, 3), 238 (13), 224 (100), 211 (55), 197 (17), 169 (9); HRMS (EI) m/z calcd for $C_{17}H_{14}FNO$ 267.1059, found 267.1054.

2-Methyl-6-(tetrahydrofuran-2-yl)phenanthridine (3la). Following the general procedure, but from 0.30 mmol of **1l**, compound **3la** was obtained after column chromatography (hexane/EtOAc 94 : 6–93 : 7) as a yellow pale solid (43 mg, 0.16 mmol, 55%): R_f 0.17 (93 : 7 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.61 (d, J = 8.3 Hz, 1H), 8.42 (dd, J = 8.3, 0.7 Hz, 1H), 8.31 (s, 1H), 8.07 (d, J = 8.3 Hz, 1H), 7.79 (ddd, J = 8.3, 7.0, 1.3 Hz, 1H), 7.66 (ddd, J = 8.3, 7.0, 1.3 Hz, 1H), 7.53 (dd, J = 8.3, 1.6 Hz, 1H), 5.74 (t, J = 6.9 Hz, 1H), 4.25–4.14 (m, 1H), 4.11–4.00 (m, 1H), 2.83–2.66 (m, 1H), 2.61 (s, 3H), 2.48–2.33 (m, 1H), 2.28–2.02 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 158.3 (C), 141.7 (C), 136.8 (C), 133.1 (C), 130.3 (CH), 130.3 (CH), 130.1(CH), 127.1 (CH), 126.5 (CH), 125.0 (C), 124.0 (C), 122.4 (CH), 121.6 (CH), 79.8 (CH), 69.1 (CH_2), 30.1 (CH_2), 26.1 (CH_2), 22.1 (CH_3) ppm; IR ν 2971, 2923, 2867, 1582, 1496, 1295, 1051, 822, 729 cm^{-1}; LRMS (EI) m/z (%) = 263 (M^+, 6), 234 (12), 220 (100), 207 (47), 192 (15), 165 (12); HRMS (EI) m/z calcd for $C_{18}H_{17}NO$ 263.1310, found 263.1312.

6-(Tetrahydrofuran-2-yl)-2-(trifluoromethoxy)phenanthridine (3ma). Following the general procedure, but from 0.45 mmol of **1m**, compound **3ma** was obtained after column chromatography (hexane/EtOAc 94 : 6) as a red solid (84 mg, 0.25 mmol, 55%): R_f 0.20 (93 : 7 hexane/EtOAc); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.55 (d, J = 8.3 Hz, 1H), 8.48 (d, J = 7.9 Hz, 1H), 8.34 (d, J = 1.7 Hz, 1H), 8.21 (d, J = 8.9 Hz, 1H), 7.87 (ddd, J = 8.4, 7.1, 1.3 Hz, 1H), 7.75 (ddd, J = 8.3, 7.0, 1.2 Hz, 1H), 7.57 (ddd, J = 8.9, 2.6, 1.1 Hz, 1H), 5.77 (t, J = 6.9 Hz, 1H), 4.23–4.15 (m, 1H), 4.12–4.04 (m, 1H), 2.81–2.65 (m, 1H), 2.50–2.35 (m, 1H), 2.31–2.06 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 160.1 (C), 147.7 (C), 141.7 (C), 132.8 (C), 132.5 (CH), 130.7 (CH), 128.2 (CH), 126.8 (CH), 125.1 (C-2, d, $^3J_{C-F}$ = 10.5 Hz), 122.6 (CH), 121.9 (CH), 120.8 (q, $^1J_{C-F}$ = 257.5 Hz), 113.7 (CH), 79.6 (CH), 69.2 (CH_2), 30.1 (CH_2), 26.1 (CH_2) ppm; IR ν 2964, 2860, 1619, 1587, 1492, 1254, 1214 cm^{-1}; LRMS (EI) m/z (%) = 333 (M^+, 5), 304 (24), 290 (100), 277 (51), 263 (8); HRMS (EI) m/z calcd for $C_{18}H_{14}F_3NO_2$ 333.0977, found 333.0950.

2-Chloro-6-(tetrahydrofuran-2-yl)phenanthridine (3na). Following the general procedure, but from 0.30 mmol of **1n**, compound **3na** was obtained after column chromatography (hexane/EtOAc 94 : 6–93 : 7) as a white solid (42 mg, 0.15 mmol, 50%): R_f 0.20 (93 : 7 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.53 (d, J = 8.2 Hz, 1H), 8.48 (d, J = 2.1 Hz, 1H), 8.44 (d, J = 8.1 Hz, 1H), 8.10 (d, J = 8.7 Hz, 1H), 7.87–7.79 (m, 1H), 7.71 (ddd, J = 8.3, 7.0, 1.2 Hz, 1H), 7.64 (dd, J = 8.7, 2.3 Hz, 1H), 5.74 (t, J = 6.9 Hz, 1H), 4.24–4.14 (m, 1H), 4.11–4.01 (m, 1H), 2.79–2.65 (m, 1H), 2.49–2.34 (m, 1H), 2.28–2.03 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 159.7 (C), 141.8 (C), 132.9 (C), 132.4 (C), 132.0 (CH), 130.7 (CH), 129.1 (CH), 128.0 (CH), 126.7 (CH), 125.3 (C), 125.1 (C), 122.5 (CH), 121.7 (CH), 79.6 (CH), 69.2 (CH_2), 30.0 (CH_2), 26.1(CH_2) ppm; IR ν 2967, 2869, 1584, 1495, 1255, 1054, 822, 767 cm^{-1}; LRMS (EI) m/z (%) = 283 (M^+, 4), 254 (16), 240 ([$M^+ - C_2H_3O$], 100), 227 (51), 213 (13) 177 (29); HRMS (EI) m/z calcd for $C_{15}H_{11}ClN$ 240.0580, found 240.0576.

3-Fluoro-6-(tetrahydrofuran-2-yl)phenanthridine (3oa). Following the general procedure, but from 0.30 mmol of **1o**, compound **3oa** was obtained after column chromatography (hexane/EtOAc 96 : 4) as a brown oil (36 mg, 0.13 mmol, 45%): R_f 0.20 (93 : 7 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.54 (d, J = 8.3 Hz, 1H), 8.49 (H-1, dd, J = 9.1, 5.9 Hz, 1H), 8.43 (d, J = 8.2 Hz, 1H), 7.87–7.78 (m, 2H), 7.67 (ddd, J = 8.3, 7.0, 1.2 Hz, 1H), 7.38 (H-2, ddd, J = 8.9, 8.1, 2.7 Hz, 1H), 5.76 (t, J = 6.9 Hz, 1H), 4.24–4.14 (m, 1H), 4.11–4.01 (m, 1H), 2.78–2.64 (m, 1H), 2.48–2.34 (m, 1H), 2.29–2.03 (m, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 162.7 (C-3, d, $^1J_{C-F}$ = 247.6 Hz), 160.9 (C), 144.7 (C-4a, d, $^3J_{C-F}$ = 11.9 Hz), 133.2 (C), 130.8 (CH), 127.2 (CH), 126.7 (CH), 124.5 (C, d, $^4J_{C-F}$ = 1.0 Hz), 123.9 (C-1, d, $^3J_{C-F}$ = 9.5 Hz), 122.3 (CH), 120.9 (d, J_{C-F} = 2.1 Hz), 116.0 (CH, d, $^2J_{C-F}$ = 23.7 Hz), 115.0 (CH, d, $^2J_{C-F}$ = 20.5 Hz), 79.5 (CH), 69.2 (CH_2), 30.1 (CH_2), 26.1(CH_2) ppm; IR ν 2972, 2871, 1618, 1580, 1484, 1459, 1053, 764 cm^{-1}; LRMS (EI) m/z (%) = 267 (M^+, 5), 238 (15), 224 (100), 211 (55), 196 (17); HRMS (EI) m/z calcd for $C_{17}H_{14}FNO$ 267.1059, found 267.1048.

6-(1,4-Dioxan-2-yl)phenanthridine (3ab).[13a] Following the general procedure, compound **3ab** was obtained after column chromatography (hexane/EtOAc 85 : 15–75 : 25) as a white solid (69 mg, 0.26 mmol, 52%): R_f 0.25 (8 : 2 hexane/EtOAc). ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.66 (d, J = 8.3 Hz, 1H), 8.60–8.52 (m, 1H), 8.48–8.39 (m, 1H), 8.26–8.15 (m, 1H), 7.90–7.80 (m, 1H), 7.78–7.63 (m, 3H), 5.49 (p, J = 6.3 Hz, 1H), 4.34–4.29 (m, 2H), 4.21–4.06 (m, 2H), 3.99–3.88 (m, 2H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 156.2 (C), 143.3 (C), 133.3 (C), 130.6 (CH), 130.6 (CH), 128.7 (CH), 127.5 (CH), 127.4 (CH), 126.2 (CH), 124.6 (C), 124.1 (C), 122.6 (CH), 122.0 (CH), 76.3 (CH), 70.2 (CH_2), 67.9 (CH_2), 66.7 (CH_2) ppm; IR ν 2965, 2856, 1114, 10 856, 912, 759 cm^{-1}; LRMS (EI) m/z (%) = 265 (M^+, 4), 206 (100), 179 (24), 151 (12), 102 (5).

6-(Tetrahydro-2*H*-pyran-2-yl)phenanthridine (3ac).[13c] Following the general procedure, compound **3ac** was obtained after column chromatography (hexane/EtOAc 98 : 2–9 : 1) as a white solid (57 mg, 0.22 mmol, 43%): R_f 0.20 (95 : 5 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.62 (ddd, J = 8.2, 1.3, 0.6 Hz, 1H), 8.56–8.50 (m, 2H), 8.25–8.19 (m, 1H), 7.80 (ddd, J = 8.3, 7.0, 1.3 Hz, 1H), 7.74–7.66 (m, 2H), 7.65–7.57 (m, 1H), 5.20 (dd, J = 11.1, 2.2 Hz, 1H), 4.34–4.24 (m, 1H), 3.81 (td, J = 11.6, 2.4 Hz, 1H), 2.37–2.19 (m, 1H), 2.15–2.00 (m, 2H), 1.96–1.77

(m, 2H), 1.74–1.63 (m, 1H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 159.6 (C), 143.4 (C), 133.5 (C), 130.5 (CH), 130.3 (CH), 128.6 (CH), 127.1 (CH), 127.0 (CH), 126.8 (CH), 124.5 (C), 124.1 (C), 122.4 (CH), 121.9 (CH), 80.7 (CH), 69.6 (CH_2), 30.6 (CH_2), 26.1 (CH_2), 24.0 (CH_2) ppm; IR ν 3075, 2930, 2839, 1083, 1039, 754, 723 cm^{-1}; LRMS (EI) m/z (%) = 262 ($M^+ - 1$, 1), 235 (20), 206 (100), 193 (12).

6-(2-Isopropoxypropan-2-yl)phenanthridine (3ad).[13c] Following the general procedure, compound **3ad** was obtained after column chromatography (100% hexane to hexane/EtOAc 98 : 2) as a brown pale oil (79 mg, 0.28 mmol, 57%): R_f 0.29 (100% hexane); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 9.25 (ddd, J = 8.5, 1.4, 0.6 Hz, 1H), 8.70–8.64 (m, 1H), 8.57 (dd, J = 8.0, 1.6 Hz, 1H), 8.17–8.12 (m, 1H), 7.81 (ddd, J = 8.3, 7.0, 1.3 Hz, 1H), 7.77–7.61 (m, 3H), 3.75 (p, J = 6.1 Hz, 1H), 1.92 (s, 6H), 1.02 (d, J = 6.1 Hz, 6H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 163.7 (C), 142.9 (C), 133.9 (C), 130.6 (CH), 130.3 (CH), 129.9 (CH), 128.5 (CH), 127.0 (CH), 126.1 (CH), 124.5 (C), 124.1 (C), 122.3 (CH), 121.9 (CH), 81.8 (C), 67.0 (CH), 29.1 (CH_3), 24.8 (CH_3); IR ν 2983, 2933, 1578, 1379, 1162, 1110, 996, 760, 730 cm^{-1}; LRMS (EI) m/z (%) = 264 (M^+, 0.2), 236 (18), 221 ([$M^+ - C_5H_7O$], 100), 204 (34), 179 (54), 150 (18); HRMS (EI) m/z calcd for $C_{16}H_{14}N$ 220.1126, found 220.1128.

6-(1-Butoxybutyl)phenanthridine (3ae).[13b] Following the general procedure, compound **3ae** was obtained after column chromatography (hexane/EtOAc 99 : 1–98 : 2) as a yellow oil (123 mg, 0.40 mmol, 80%): R_f 0.65 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.94–8.89 (m, 1H), 8.69–8.64 (m, 1H), 8.57 (dd, J = 8.0, 1.6 Hz, 1H), 8.20–8.15 (m, 1H), 7.84 (ddd, J = 8.3, 7.0, 1.3 Hz, 1H), 7.77–7.62 (m, 3H), 4.98 (dd, J = 8.8, 5.4 Hz, 1H), 3.52–3.33 (m, 2H), 2.28–2.13 (m, 1H), 2.01–1.87 (m, 1H), 1.76–1.46 (m, 4H), 1.40–1.23 (m, 4H), 0.95 (t, J = 7.4 Hz, 3H), 0.83 (t, J = 7.3 Hz, 3H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 161.9 (C), 143.4 (C), 133.5 (C), 130.5 (CH), 130.2 (CH), 128.7 (CH), 127.0 (CH), 124.5 (C), 124.1 (C), 122.4 (CH), 122.0 (CH), 86.5 (CH), 69.5 (CH_2), 38.3 (CH_2), 32.2 (CH_2), 20.0 (CH_2), 19.5 (CH_2), 14.1 (CH_3), 14.0 (CH_3) ppm; IR ν 2957, 2932, 2870, 1759, 1459, 1092, 727 cm^{-1}; LRMS (EI) m/z (%) = 265 ($M^+ - C_3H_6$, 12), 250 (9), 235 (37), 206 (100), 151 (9).

6-(2-Methyltetrahydrofuran-2-yl)phenanthridine (3af). Following the general procedure, compound **3af** was obtained after column chromatography (hexane/EtOAc 99 : 1–9 : 1) as a colorless oil (43 mg, 0.16 mmol, 33%): R_f 0.75 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 9.14 (d, J = 8.4 Hz, 1H), 8.63 (d, J = 8.3 Hz, 1H), 8.53 (dd, J = 8.1, 1.5 Hz, 1H), 8.12 (d, J = 8.0 Hz, 1H), 7.78 (ddd, J = 8.1, 6.6, 1.2 Hz, 1H), 7.72–7.58 (m, 3H), 4.14–4.03 (m, 1H), 3.80–3.69 (m, 1H), 3.66–3.56 (m, 1H), 2.10–1.88 (m, 3H), 1.83 (s, 3H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 163.1, 142.9, 134.0, 130.4, 130.0, 129.3, 128.4, 126.9, 126.6, 124.4, 124.1, 122.4, 121.9, 88.7, 68.1, 37.4, 28.2, 25.2 ppm; IR ν 3065, 2970, 2930, 2872, 1570, 1097, 758 cm^{-1}; LRMS (EI) m/z (%) = 263 (M^+, 18), 235 (48), 207 (86), 179 (55), 85 (100); HRMS (EI) calcd for $C_{18}H_{17}NO$ 263.1310, found 263.1308.

6-(5-Methyltetrahydrofuran-2-yl)phenanthridine (3′af). From the same reaction where compound **3af** was obtained, and after column chromatography (hexane/EtOAc 99 : 1–9 : 1), isomer **3′af** was isolated as a white solid (26 mg, 0.10 mmol, 21%) [*trans*/*cis* mixture in a 58 : 42 ratio (^{1}H-NMR)]): R_f 0.75 (9 : 1 hexane/EtOAc); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.62 (d, J = 8.3 Hz, 1.10H), 8.53 (d, J = 8.2 Hz, 1.51H), 8.46 (d, J = 7.9 Hz, 0.6H), 8.21–8.15 (m, 1H), 7.81 (ddt, J = 8.3, 7.0, 1.3 Hz, 1.09H), 7.75–7.59 (m, 3.58H), 5.91 (t, J = 6.9 Hz, 0.58H), 5.69 (t, J = 7.1 Hz, 0.42H), 4.53–4.43 (m, 0.64H), 4.37–4.27 (m, 0.47H), 2.91–2.73 (m, 1.06H), 2.52–2.42 (m, 0.62H), 2.42–2.27 (m, 1.02H), 2.27–2.14 (m, 0.44H), 1.87–1.67 (m, 1.5H), 1.39 (dd, J = 6.1, 3.3 Hz, 3H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 159.9 (C), 159.2 (C), 143.34 (C), 143.28 (C), 133.43 (C), 133.42 (C), 130.5 (CH), 130.4 (CH), 128.6 (CH), 128.6 (CH), 127.3 (CH), 127.3 (CH), 127.0 (CH), 126.9 (CH), 126.7 (CH), 125.1 (C), 124.9 (C), 124.3 (C), 124.2 (C), 122.5 (CH), 122.4 (CH), 122.0 (CH), 80.6 (CH), 79.2 (CH), 76.1 (CH_2), 33.9 (CH_2), 33.2 (CH_2), 30.6 (CH_2), 30.0 (CH_2), 21.6 (CH_3), 21.4 (CH_3) ppm; IR ν 3074, 2971, 2929, 2877, 2861, 1583, 1444, 1073, 725 cm^{-1}; LRMS (EI) m/z (%) = 263 (M^+, 11), 220 (72), 208 (100), 179 (58); HRMS (EI): calcd for $C_{18}H_{17}NO$ 263.1310, found 263.1301.

6-(*tert*-Butoxymethyl)phenanthridine (3ag).[13c] Following the general procedure, compound **3ag** was obtained after column chromatography (hexane/EtOAc 95 : 5–93 : 2) as a yellow solid (53 mg, 0.20 mmol, 40%): R_f 0.24 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.61 (d, J = 8.3 Hz, 1H), 8.53 (td, J = 8.1, 1.3 Hz, 2H), 8.17 (dd, J = 7.8, 1.4 Hz, 1H), 7.87–7.79 (m, 1H), 7.75–7.61 (m, 3H), 5.09 (s, 2H), 1.40 (s, 9H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 158.7 (C), 143.6 (C), 133.4 (C), 130.6 (CH), 130.2 (CH), 128.6 (CH), 127.6 (CH), 127.3 (CH), 127.1 (CH), 125.7 (C), 124.5 (C), 122.2 (CH), 122.0, 74.7 (CH), 66.9 (CH_2), 27.9 ($3CH_3$) ppm; IR ν 2974, 2932, 1719, 1364, 1145, 760 cm^{-1}; LRMS (EI) m/z (%) = 265 ([$(M + 1)^+ - CH_3$], 1), 235 (37), 208 (100), 192 (48), 180 (51), 165 (25).

6-((Benzyloxy)(phenyl)methyl)phenanthridine (3ah). Following the general procedure, compound **3ah** was obtained after column chromatography (hexane/EtOAc 99 : 1–98 : 2) as a yellow solid (32 mg, 0.08 mmol, 17%): R_f 0.5 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.65–8.55 (m, 3H), 8.30–8.25 (m, 1H), 7.81–7.66 (m, 3H), 7.57–7.43 (m, 3H), 7.39–7.25 (m, 7H), 7.24–7.19 (m, 1H), 6.27 (s, 1H), 4.73 (d, J = 11.7 Hz, 1H), 4.64 (d, J = 11.7 Hz, 1H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 159.9 (C), 143.4 (C), 140.8 (C), 138.3 (C), 133.9 (C), 130.5 (CH), 130.5 (CH), 128.8 (CH), 128.4 (CH), 128.3 (CH), 128.0 (CH), 127.7 (CH), 127.4 (CH), 127.1 (CH), 126.3 (CH), 124.5 (C), 124.3 (C), 122.3 (CH), 122.1 (CH), 86.5 (CH), 71.7 (CH_2) ppm; IR ν 3060, 3029, 2915, 2850, 1572, 1449, 1067, 722 cm^{-1}. LRMS (EI-DIP) m/z (%) = 284 ($M^+ - C_7H_7$, 52), 269 (100), 268 (52), 178 (16), 91 (32); HRMS (EI) calcd for $C_{27}H_{21}NO$ 375.1623, found 375.1605.

6-Benzylphenanthridine (3′ah).[26] From the same reaction where compound **3ah** was obtained, and after column chromatography (hexane/EtOAc 99 : 1–98 : 2), compound **3′ah** was isolated as a yellow solid (62 mg, 0.23 mmol, 46%): R_f 0.5 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.56 (br d, J = 8.3 Hz, 1H), 8.51 (dd, J = 8.2, 1.4 Hz, 1H), 8.18 (ddd, J = 9.7, 8.1, 1.3 Hz, 2H), 7.72 (ddd, J = 8.2, 7.0, 1.4 Hz, 2H), 7.61 (ddd,

J = 8.3, 7.0, 1.4 Hz, 1H), 7.53 (ddd, J = 8.3, 7.0, 1.2 Hz, 1H), 7.33–7.28 (m, 2H), 7.26–7.10 (m, 4H), 4.74 (s, 2H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 160.2 (C), 143.8 (C), 139.2 (C), 133.3 (C), 130.4 (CH), 129.9 (CH), 128.7 (CH), 128.6 (2CH), 127.4 (CH), 127.1 (CH), 126.7 (CH), 126.4 (CH), 125.4 (C), 124.0 (C), 122.5 (CH), 122.0 (CH), 43.2 (CH_2) ppm; IR ν 3062, 3025, 1684, 1581, 1362, 723 cm^{-1}. LRMS (EI-DIP) m/z (%) = 269 (M^+, 41), 268 ($M^+ - 1$, 100), 254(6), 134 (11), 57 (6).

6-(1,3-Dihydroisobenzofuran-1-yl)phenanthridine (3ai). Following the general procedure, compound **3ai** was obtained after column chromatography (hexane/EtOAc 99 : 1–98: 2) as a yellow crystalline solid (52 mg, 0.17 mmol, 35%): R_f 0.4 (9 : 1 hexane/EtOAc); mp 120–121 °C (3 : 1 EtOAc/MeOH); ^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.65 (br d, J = 8.3 Hz, 1H), 8.56 (dd, J = 8.1, 1.4 Hz, 1H), 8.25 (br d, J = 8.3 Hz, 1H), 8.17 (dd, J = 8.0, 1.2 Hz, 1H), 7.80 (s, 1H), 7.72 (ddd, J = 8.2, 7.0, 1.6 Hz, 1H), 7.66 (ddd, J = 8.4, 7.0, 1.5 Hz, 1H), 7.59 (ddd, J = 8.3, 7.0, 1.2 Hz, 1H), 7.41–7.37 (m, 1H), 7.35–7.30 (m, 1H), 7.23–7.13 (m, 2H), 6.97 (t, J = 2.5 Hz, 1H), 5.59 (dd, J = 12.3, 2.7 Hz, 1H), 5.42 (dd, J = 12.3, 2.0 Hz, 1H) ppm; ^{13}C-NMR (101 MHz, $CDCl_3$) δ 158.8 (C), 143.4 (C), 140.9 (C), 139.2 (C), 133.9 (C), 130.7 (CH), 130.4 (CH), 128.7 (CH), 128.0 (CH), 127.5 (CH), 127.3 (CH), 127.3 (CH), 126.6 (CH), 124.6 (C), 124.4 (C), 122.8 (CH), 122.6 (CH), 122.0 (CH), 121.3(CH), 87.8 (CH), 73.8 (CH_2) ppm; IR ν 3074, 2851, 1572, 1027, 720 cm^{-1}. LRMS (EI) m/z (%) = 297 (M^+, 2), 268 (100), 251 (3), 119 (12); HRMS (EI) calcd for $C_{21}H_{15}NO$ 297.1154, found 297.1141.

6-(1,3,5-Trioxan-2-yl)phenanthridine (3aj). Following the general procedure, compound **3aj** was obtained after column chromatography (100% hexane to hexane/EtOAc 8 : 2) as a white solid (96 mg, 0.26 mmol, 52%): R_f 0.2 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 9.10–9.04 (m, 1H), 8.64 (d, J = 8.3 Hz, 1H), 8.60–8.55 (m, 1H), 8.23–8.18 (m, 1H), 7.90–7.83 (m, 1H), 7.79–7.67 (m, 1H), 6.48 (s, 1H), 5.50 (q, J = 6.5 Hz, 4H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 153.6 (C), 142.8 (C), 134.0 (C), 131.0 (CH), 130.6 (CH), 128.9 (CH), 128.3 (CH), 128.1 (CH), 127.4 (CH), 125.0 (C), 123.7 (C), 122.2 ($_2$CH), 106.1(CH), 94.2 (2CH_2) ppm; IR ν 3037, 2884, 1418, 1199, 1100, 1047, 944, 750, 723 cm^{-1}; LRMS (EI) m/z (%) = 267 (M^+, 1), 208 (67), 179 (100), 151 (31); HRMS (EI) calcd for $C_{16}H_{13}NO_3$ 267.0895, found 267.0879.

6-(Benzo[*d*][1,3]dioxol-2-yl)phenanthridine (3ak). Following the general procedure, compound **3ak** was obtained after column chromatography (hexane/EtOAc 99 : 1–98 : 2) as a white crystalline solid (90 mg, 0.3 mmol, 60%): R_f 0.49 (9 : 1 hexane/EtOAc); mp 105–107 °C (MeOH); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 8.64 (br d, J = 8.3 Hz, 1H), 8.56 (dd, J = 8.0, 1.4 Hz, 1H), 8.30–8.21 (m, 2H), 7.82 (ddd, J = 8.4, 7.0, 1.3 Hz, 1H), 7.79–7.66 (m, 2H), 7.60 (ddd, J = 8.3, 7.0, 1.2 Hz, 1H), 7.43 (s, 1H), 7.04–6.91 (m, 4H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 152.5 (C), 147.5 (2C), 142.9 (C), 133.9 (C), 130.9 (2CH), 129.0 (CH), 128.4 (CH), 127.7 (CH), 125.9 (CH), 125.0 (C), 123.8 (C), 122.6 (CH), 122.3 (2CH), 122.1 (CH), 112.2 (CH), 109.4 (2CH) ppm; IR ν 3078, 2909, 1479, 1338, 1229, 724 cm^{-1}; LRMS (EI) m/z (%) = 299 (M^+, 2), 270 (100), 241 (9), 178 (7); HRMS (EI) calcd for $C_{20}H_{13}NO_2$ 299.0946, found 299.0949.

Phenanthridine (4a).[13a] This compound was obtained as the by-product of **3aa** and of all compounds represented in Scheme 3. After purification by column chromatography (hexane/EtOAc 9 : 1), it was isolated as a white solid. R_f 0.25 (9 : 1 hexane/EtOAc); ^{1}H-NMR (300 MHz, $CDCl_3$) δ 9.28 (s, 1H), 8.63–8.54 (m, 1H), 8.20 (dd, J = 8.1, 1.3 Hz, 1H), 8.03 (br d, J = 7.9 Hz, 1H), 7.84 (ddd, J = 8.4, 7.1, 1.4 Hz, 1H), 7.78–7.63 (m, 2H) ppm; ^{13}C-NMR (75 MHz, $CDCl_3$) δ 153.7 (CH), 144.6 (C), 132.7 (C), 131.1 (CH), 130.3 (CH), 128.9 (CH), 128.8 (CH), 127.6 (CH), 127.2 (CH), 126.5 (C), 124.2 (C), 122.3 (CH), 122.0 (CH) ppm; IR ν 2924, 2851, 1457, 1245, 890, 745 cm^{-1}; LRMS (EI) m/z (%) = 179 (M^+, 100), 151 (13), 76(100), 179 (8).

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Notes and references

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