Facile [2+2] Cycloaddition of DDQ to an Alkyne: Synthesis of Pyrrolyl- and Indolylbicyclo[4.2.0]octadienes from *C*-Ethynylpyrroles or *C*-Ethynylindoles

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Abstract: *C*-Ethynylpyrroles or -indoles, which can be prepared by cross-coupling of pyrroles or indoles with haloalkynes on active surfaces, undergo [2+2]-cycloaddition reactions with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone to give 2-pyrrolyl- or 3-indolylbicyclooctadienes in almost quantitative yields. The adducts are charge-transfer complexes that are paramagnetic in the solid state, and therefore represent a new family of densely functionalized pyrrole and indole derivatives potentially useful as pharmaceutical candidates, highly potent building blocks, or precursors of advanced materials. The reaction contributes to the practical and basic chemistry of pyrroles, indoles, alkynes, and quinones.

Key words: pyrroles, indoles, cycloadditions, alkynes, polycycles

Pyrroles and benzopyrroles (indoles) are among the most important heterocyclic systems in that they occur widely in nature as constituents of the frameworks of natural products and because many synthetic variants of these compounds have significant pharmaceutical effects.[1] Considerable attention has therefore been devoted to the development of efficient methods for derivatizing the pyrrole nucleus. Among the most useful pyrrole building blocks are those containing alkyne moieties. Because of the rich chemistry of the alkyne function, alkynylpyrroles are widely used in syntheses of pyrrole-containing structures.[2] Of particular interest are 2-ethynylpyrroles, owing to their usefulness in the total syntheses of polyfunctional complex molecules containing the indole skeleton.[3] Because indole skeletons are present in many drugs and natural products, the search for new methods for preparing indoles with various substitution patterns has recently been the object of several research programs.[4]

Although methods for the preparation of 3-substituted indoles are well developed, the syntheses of 2-substituted indole derivatives is less well elaborated. A new, reliable, and robust method for preparing 2-functionalized indoles, particularly 2-ethynylindoles, could make a considerable contribution to the chemistry and pharmacology of indoles.

2-Ethynylpyrroles and 3-ethynylindoles bearing electron-withdrawing substituents (acyl or alkoxycarbonyl groups) adjacent to the triple bond have now became readily available as a result of the discovery of techniques for the ethynylation of the pyrrole nucleus by electrophilic haloalkynes on alumina[5] or other active surfaces.[6] Note that these functionalized ethynylpyrroles and -indoles are not accessible by common synthetic approaches, including Sonogashira couplings.[7] In particular, this new method permits the preparation of 2-acyl- and 2-(alkoxycarbonyl)ethynyl-4,5,6,7-tetrahydroindoles from readily available 4,5,6,7-tetrahydroindole.[8] These compounds, because of their possible aromatization, may be suitable as intermediates for the synthesis of 2-functionalized indoles.[9]

2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) is a particularly effective reagent for aromatization, and it is often the reagent of choice for the dehydrogenation of both simple and complex hydroaromatic compounds.[10] Some fully aromatic derivatives have been obtained in high yields by dehydrogenation of the corresponding tetrahydro heteroaromatic compounds by using DDQ.[11] It is known that treatment of dimethyl (4,7-dihydro-1*H*-indol-2-yl)fumarate with DDQ in benzene at room temperature for one hour gives the expected indole in 94% yield.[12] Consequently, we were intrigued by the possibility of applying this method to the synthesis of indoles with alkyne substituents, starting with the 2-ethynyl-4,5,6,7-tetrahydroindoles **1a–d**.

To our surprise, however, the anticipated aromatization did not occur under analogous conditions; instead, [2+2] cycloaddition at the triple bond occurred to afford 1:1 adducts, the bicyclo[4.2.0]octadienes **2a–d**, in 81–93% isolated yields (Table 1).

The adducts, which were bright or deep cherry in color, began to precipitate immediately on mixing the reactants. The adducts were stable in the solid state for months, but decomposed within hours in solution in benzene or dimethyl sulfoxide.

Signals for the indole protons were absent from the ^{1}H NMR spectra of the adducts **2a–d**, but the signals for the four methylene groups of the cyclohexano moiety and the signals for the pyrrole H-3 atom remained. The NH,H-3 coupling constants were in the range 1.7–2.0 Hz, which are typical values for 2,4,5-trisubstituted pyrroles.[5a,13] In the ^{13}C NMR spectra, the signals of the acetylenic carbons (81.8–87.9 ppm) disappeared, and cyclobutene sp^3 signals (53.8–52.2 ppm) were observed. Analysis of heteronucle-

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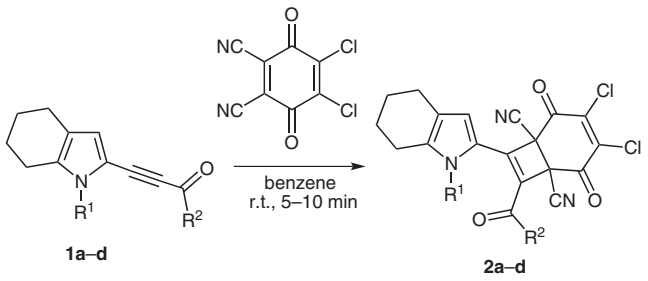
Table 1 Reactions of 2-Ethynyl-4,5,6,7-tetrahydroindoles **1a–d** with DDQ



1a–d **2a–d**

Pyrrole	R^1	R^2	Yield (%)
1a	H	OEt	87
1b	Me	OEt	93
1c	Bn	OEt	81
1d	H	Ph	88

ar single quantum coherence (HSQC) and heteronuclear multiple bond correlation (HMBC) two-dimensional (2D) spectra permitted the unambiguous assignment of the ^{13}C chemical shifts of the pyrrole skeleton and the direct C-3–H-3 couplings. No C≡C stretching vibration absorption band (which should appear at 2175–2184 cm^{-1})[6b] was detected in the IR spectra of any of the adducts **2a–d**.

With regard to whether the chlorine-substituted C=C bond or the cyano-substituted C=C bond of DDQ is involved in the cycloaddition, a comparison of the ^{13}C NMR spectra of the adducts with that of DDQ[14] unambiguously favored structures **2a–d**. Indeed, the chemical shifts of the olefinic carbons C-3 and C-4 of the quinone ring (δ = 142.9–144.0 ppm and δ = 140.1–141.1 ppm, respectively) were similar to those of the chlorine-substituted carbons (δ = 141.0 ppm) in DDQ, and were significantly different from those associated with carbon atoms bound to cyano groups (δ = 125.1 ppm).

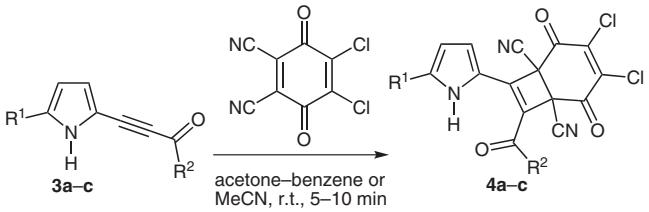
In general, DDQ is a powerful oxidizing agent. In addition, it has proved to be a versatile reagent for various organic transformations, including diene condensation.[15] It has not, however, been reported to participate in any [2+2]-cycloaddition reaction with an alkyne moiety. Moreover, it has been used to oxidize phenylalkynes to the corresponding enynes, which retain intact triple bonds.[16] Furthermore, no other [2+2]-cycloaddition reaction at the triple bond of an ethynylpyrrole has been reported.

The [2+2] cycloaddition of DDQ to the triple bond of 2-ethynyl-4,5,6,7-tetrahydroindoles **1a–d** is therefore the first example of such a reaction of an alkyne with DDQ.

Most cycloaddition reactions of benzoquinones with alkynes are photochemical, leading to either an adduct at the carbonyl group[17] or at the double bond,[18] depending on the structure of the quinone. Monitoring of the reaction of 2-ethynyl-4,5,6,7-tetrahydroindoles **1a–d** with DDQ by ^1H NMR in darkness proved that the reaction is not photochemical; in this case, the [2+2] cycloaddition was as efficient as that observed in daylight.

This new reaction was found to be general in character. Apart from 2-ethynyl-4,5,6,7-tetrahydroindoles **1a–d**, other substituted 2-ethynylpyrroles, e.g. pyrroles **3a–c** (R^1 = Ph, 4-ClC_6H_4, 4-$MeOC_6H_4$), also reacted with DDQ by the same [2+2]-cycloaddition path (Table 2), although the process took longer (one hour) or required the presence of a polar solvent (acetone, acetonitrile, or acetone–benzene). This shows the importance of donation of electrons from the pyrrole moiety to the alkyne group. (As a result of the inductive effect, the tetrahydroindolyl group releases electrons more readily than do the arylpyrrolyl substituents in **3a–c**.)

Table 2 Reactions of 2-Ethynylpyrroles **3a–c** with DDQ



3a–c **4a–c**

Pyrrole	R^1	R^2	Yield (%)
3a	Ph	Ph	82
3b	4-ClC_6H_4	Ph	76
3c	4-$MeOC_6H_4$	4-$O_2NC_6H_4$	92

The structures of the adducts **4a-c** were confirmed by their NMR spectra, which showed that the C-3 and C-4 carbons and the corresponding H-3 and H-4 protons of the pyrrole remained intact. The H-3 and the H-4 protons appeared as a doublet of doublets with typical couplings ($^4J_{H\text{-}3,NH} \approx 2.4$ Hz, $^3J_{H\text{-}3,\,H\text{-}4} \approx 4.2$ Hz, and $^4J_{H\text{-}4,NH} \approx 2.6$ Hz). Direct C-3–H-3 and C-4–H-4 couplings were observed in 2D HSQC spectra. All these values are typical of a 2,5-disubstituted pyrrole moiety. The large difference (up to 22 ppm) between the ^{13}C chemical shifts of the CN-substituted carbons in the tetrahydroindoles **2a–d** and those of the 5-aryl-substituted series **4a–c** is the result of intramolecular charge transfer (CT) from the arylpyrrole moiety (by the through-conjugation mechanism) to the dicyanocyclobutene moiety of the molecule; this was confirmed by the presence of large red shifts (up to 70 nm) and the hypochromic effect of the CT band in the UV/visible (UV/Vis) spectra of compounds **2a–d** and **4a–c** (Figure 1). This long-range charge transfer is also manifested in the ^{13}C NMR downfield shifts (1–3 ppm) of the most remote C_{para} carbons of the aryl substituents in the adducts **4a–c** compared with those of the starting alkynes **3a–c**.[5d]

The 3-ethynylindoles **5a** and **5b** reacted similarly with DDQ, undergoing [2+2] cycloaddition to give the corresponding cycloadducts **6a** and **6b** in 84 and 87% yields, respectively. These reactions proceeded as smoothly as those of the 2-ethynylpyrroles **3a–c**, and were complete in

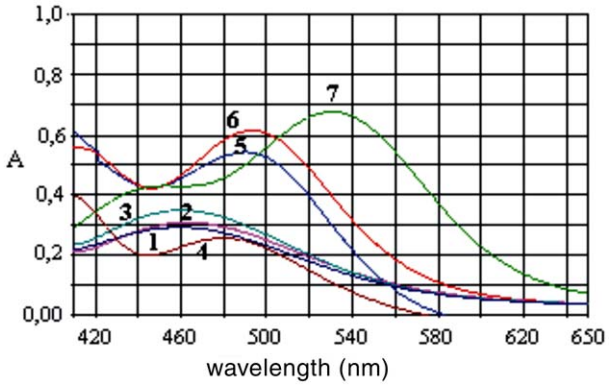


Figure 1 CT bands in the UV/Vis spectra of the cycloadducts: 1, **2a**; 2, **2b**; 3, **2c**; 4, **2d**; 5, **4a**; 6, **4b**; 7, **4c**

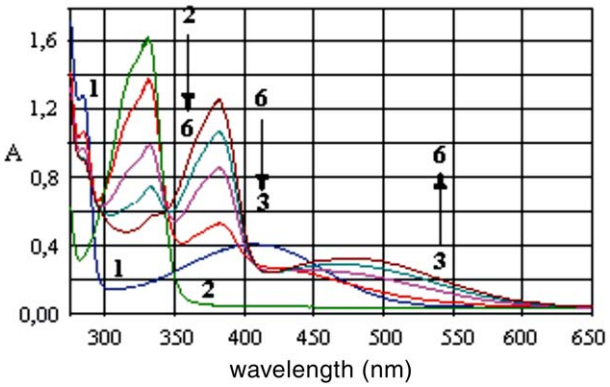
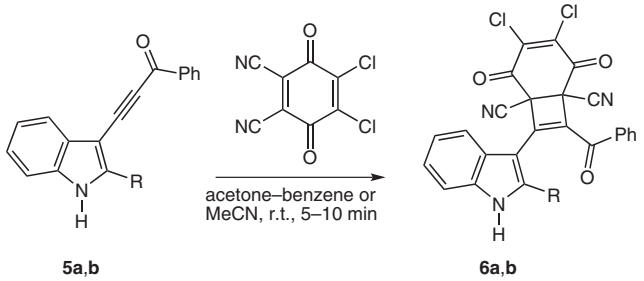


Figure 2 UV/Vis spectra of a mixture of pyrrole **1a** (0.025 mM) and DDQ (0.025 mM) in benzene at r.t.; 1, DDQ; 2, pyrrole **1a**; 3, after 2 min; 4, after 10 min; 5, after 25 min; 6, after 60 min

Table 3 Reaction of 3-Ethynylindoles **5a** and **5b** with DDQ



5a,b **6a,b**

Indole	R	Yield (%)
5a	H	87
5b	Me	84

5–10 min in acetone–benzene or acetonitrile at room temperature (Table 3).

Reactions of quinones often proceed with electron transfer and can therefore be monitored by UV[19] or ESR[19a,c,20] spectroscopy. Indeed, our experimental results from these techniques could be tentatively rationalized as providing evidence for electron transfer in the cycloaddition reaction. When monitored by UV/Vis spectroscopy (Figure 2), two sharp and intense peaks at 330 and 381 nm, along with a broad absorption band in the region 400–600 nm were observed immediately after mixing reactant **1a** with DDQ in benzene. After 60 minutes, the intensity of the band at 330 nm decreased whereas the intensities of the band at 381 nm and the broad absorption in the region 400–600 nm increased, and a peak at 477 nm appeared. The final spectrum corresponded to that of the adduct **2a**, the isosbestic point at 431 nm indicating the conversion **1a** + DDQ → **2a**.

In MeCN at about –30 °C, an absorption band at 1082 nm (which disappeared at room temperature) was observed (Figure 3).

According to Polyakov,[19a] this band can be assigned to a radical cation species, in this case, possibly **7a**. It is known that CT-complexes or ion-radical pairs such as **7** dissociate in polar solvents such as acetonitrile, in this

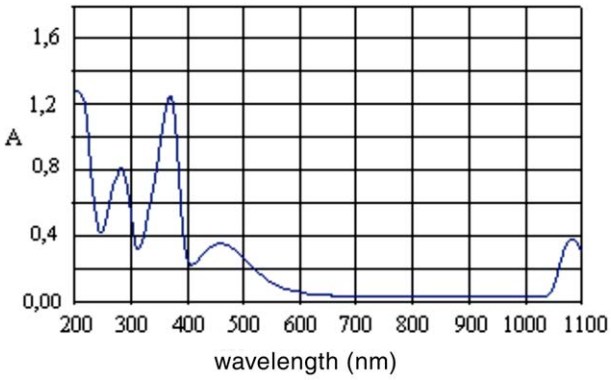
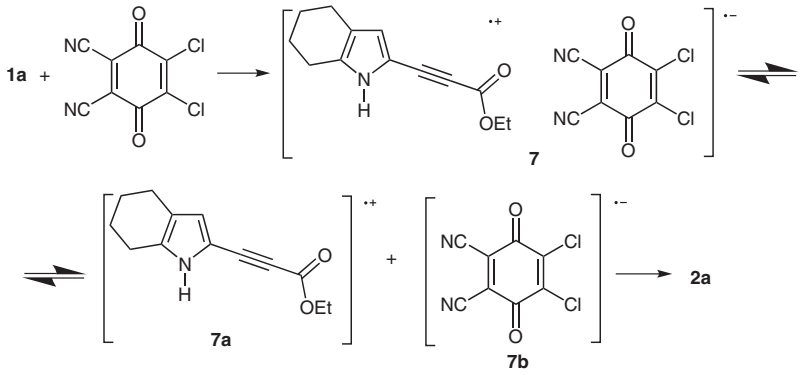


Figure 3 UV/Vis spectra of a mixture of pyrrole **1a** (0.025 mM) and DDQ (0.025 mM) in MeCN at –30 °C to r.t.

case giving the radical cation **7a** and the radical anion **7b** (Scheme 1).

Thus, UV/Vis monitoring of the course of the cycloaddition reaction shows that the starting alkynes **1a–d** are transformed rapidly on contact with DDQ to give the cycloadducts **2a–d**, a major feature of which is strong intramolecular charge transfer. At a low temperature (–30 °C), the intermediate radical cation possibly became discernible (1082 nm). Note that for adducts **4a–c**, which are derived from 2-ethynyl-5-arylpyrroles, the CT band was significantly red-shifted (up to 70 nm) with a simultaneous hypochromic effect (Δlog ε = 0.53), indicating deep charge transfer with participation of the aryl substituents (Figure 1). This is accompanied by downfield shifts of C_{para} carbons of the aryl groups (see above) and a pronounced shielding of the CN-substituted carbons.

In the ESR spectrum of a 1:1 (molar) mixture of pyrrole **1a** and DDQ in benzene at room temperature, two overlap signals (g-factors 2.0052 and 2.0048, respectively) with no hyperfine structure were observed. On the basis of the value of the g-factor, the first signal was assigned to the DDQ radical anion. To check this assignment, the reaction was monitored at a low temperature. An ampoule containing the reaction mixture under argon was frozen in liquid nitrogen and then placed in the ESR spectrometer. In the spectrum, a signal with hyperfine structure (five lines,



Scheme 1

aN = 0.58 G, g = 2.0052), attributable to the DDQ radical anion[21] was registered. This was consistent with the tentative mechanism involving electron transfer from the ethynylpyrrole moiety to DDQ to form an ion-radical pair consisting of a DDQ radical anion and an ethynylpyrrole radical cation, the latter being undetectable by the ESR technique that was used because of its lower stability. [Separately, both the reactants (pyrrole **1a** and DDQ) are nonparamagnetic in benzene].

In the solid state, adducts **2a–d**, **4a–c**, **6a**, and **6b** are all paramagnetic (~10^{18} spin/g), as exemplified by the ESR spectrum of adduct **2a**, in which two overlap singlets (g_1 = 2.0052, ΔH_1 = 8.7 G; g_2 = 2.0042, ΔH_2 = 2.9 G) are observed. This paramagnetism vanishes on dissolving the adducts in, for example, benzene. It may be assumed that the paramagnetism of the solid sample results from electron transfer in associated molecules. In the future, we plan to study this phenomenon, which is of interest in relation to advanced materials science, in more depth.

In summary, the simple and efficient [2+2]-cycloaddition reaction of DDQ with 2-ethynylpyrroles or 3-ethynylindoles with electron-withdrawing substituents at the triple bond gives densely functionalized pyrrolyl- and indolyl-substituted bicyclo[4.2.0]octadienes in almost quantitative isolated yields. This reaction is likely to attract growing attention because of the widespread research efforts[2,3,22] in the area of pyrroles and indoles with acetylenic substituents. The cycloadducts that were obtained are paramagnetic in the solid state and represent a novel class of functionalized pyrroles, indoles, and cyclobutenes that have a considerable potential as pharmaceutical candidates, synthetic building blocks, and precursors for advanced materials.

IR spectra were recorded on a Bruker Vertex 70 spectrometer (400–4000 cm^{-1}, KBr pellets). The UV/Vis spectra were recorded on a Perkin-Elmer Lambda 35 spectrophotometer (MeCN, 4×10^{-4} to 7×10^{-4} mol/L, d = 0.1 cm; reaction mixtures in soln were examined at a concentration 0.025 mM in benzene at 25 °C or MeCN at –30 °C. The ^{1}H (400.13 MHz) and ^{13}C NMR (101.6 MHz) spectra were recorded on a Bruker DPX-400 instrument. Concerted ^{1}H–^{1}H 2D homonuclear experiments (COSY and NOESY) and ^{1}H–^{13}C 2D heteronuclear experiments (HSQC and HMBC) were used to assign the carbon and proton resonances in all cases. CW ESR spectra were recorded on a Bruker ELEXSYS E580 spectrometer. The reactions were monitored by TLC on Silufol UV_{254} plates (CH_2Cl_2) and by ^{1}H NMR ($CDCl_3$).

2-Ethynylpyrroles **1a–d** and **3a–c** and 3-ethynylindoles **5a** and **5b** were prepared from pyrroles or indoles and haloalkynes by the methods described in the literature.[5,6]

Ethyl 3,4-Dichloro-1,6-dicyano-2,5-dioxo-8-(4,5,6,7-tetrahydro-1*H*-indol-2-yl)bicyclo[4.2.0]octa-3,7-diene-7-carboxylate (2a)

A soln of indole **1a** (0.109 g, 0.5 mmol) and DDQ (0.114 g, 0.5 mmol) in anhyd benzene (20 mL) was stirred at r.t. for 5 min. The benzene was evaporated (~5 min) and the residue was filtered on a short silica gel column (5 g) with elution by CH_2Cl_2 to give a cherry-colored solid; yield: 0.193 g (87%); mp 207–208 °C.

IR (KBr): 2246 (νCN), 1716, 1694 (νC=O), 1634, 1565, 1546, 1518 (νC=C), 1288, 1048 (νC–O), 798 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, $CDCl_3$): δ = 1.35 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.75 (m, 2 H, CH_2-6), 1.82 (m, 2 H, CH_2-5), 2.54 (m, 2 H, CH_2-4), 2.68 (m, 2 H, CH_2-7), 4.30 (m, 2 H, OCH_2), 6.73 (d, *J* = 1.7 Hz, 1 H, H-3), 10.65 (br s, 1 H, NH).

^{13}C NMR (101.6 MHz, $CDCl_3$): δ = 14.1, 22.4, 22.7, 23.0, 23.8, 52.5, 53.5, 62.4, 108.6, 111.3, 111.8, 119.4, 120.6, 125.0, 141.1, 142.4, 143.5, 144.0, 161.8, 174.7, 176.4.

UV/Vis (MeCN): λ_{max} (log ε) = sh. 267 (3.99), 285 (4.09), 369 (4.33), 459 nm (3.77).

Anal. Calcd for $C_{21}H_{15}Cl_2N_3O_4$: C, 56.77; H, 3.40; Cl, 15.96; N, 9.46. Found: C, 56.48; H, 3.40; Cl, 15.65; N, 9.50.

Ethyl 3,4-Dichloro-1,6-dicyano-2,5-dioxo-8-(1-methyl-4,5,6,7-tetrahydro-1*H*-indol-2-yl)bicyclo[4.2.0]octa-3,7-diene-7-carboxylate (2b)

A soln of indole **1b** (0.116 g, 0.5 mmol) and DDQ (0.114 g, 0.5 mmol) in anhyd benzene (20 mL) was stirred at r.t. for 5 min while the mixture thickened. The precipitate was filtered off and washed with Et_2O (5 mL) to give a cherry-colored solid; yield: 0.109 g. The benzene and Et_2O were evaporated, and the residue was filtered on a short silica gel column (5 g) with elution by CH_2Cl_2 to give a further crop of the product; yield: 0.104 g; total yield: 0.213 g (93%); mp 163–164 °C.

IR (KBr): 2250 (νCN), 1715, 1678 (νC=O), 1620, 1565, 1543, 1502 (νC=C), 1270, 1055 (νC–O), 809 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, $CDCl_3$): δ = 1.33 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.71 (m, 2 H, CH_2-5), 1.84 (m, 2 H, CH_2-6), 2.51 (m, 2 H, CH_2-4), 2.58 (m, 2 H, CH_2-7), 3.59 (s, 3 H, NMe), 4.25 (q, *J* = 7.1 Hz, 2 H, OCH_2), 6.83 (s, 1 H, H-3).

^{13}C NMR (101.6 MHz, $CDCl_3$): δ = 14.0, 22.4, 22.8, 22.8, 23.1, 33.7, 52.7, 53.1, 62.1, 111.8, 111.9, 112.1, 121.0, 123.0, 124.1, 140.3, 142.0, 143.2, 145.3, 159.7, 175.5, 177.2.

UV/Vis (MeCN): λ_{max} (log ε) = sh. 267 (3.96), 285 (4.01), 368 (4.23), 463 nm (3.71).

Anal. Calcd for $C_{22}H_{17}Cl_2N_3O_4$: C, 57.66; H, 3.74; Cl, 15.47; N, 9.17. Found: C, 57.73; H, 3.94; Cl, 15.84; N, 8.82.

Ethyl 8-(1-Benzyl-4,5,6,7-tetrahydro-1*H*-indol-2-yl)-3,4-dichloro-1,6-dicyano-2,5-dioxobicyclo[4.2.0]octa-3,7-diene-7-carboxylate (2c)

A soln of indole **1c** (0.154 g, 0.5 mmol) and DDQ (0.114 g, 0.5 mmol) in anhyd benzene (20 mL) was stirred at r.t. for 5 min. The benzene was then evaporated and the residue was filtered on a short silica gel column (5 g) with elution by CH_2Cl_2 to give a cherry-colored solid; yield: 0.216 g (81%); mp 181–182 °C.

IR (KBr): 2251 (νCN), 1713 (νC=O), 1623, sh. 1592, 1565, 1543, 1502 (νC=C), 1270, 1055 (νC–O), 809 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, $CDCl_3$): δ = 1.34 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.76 (m, 2 H, CH_2-5), 1.85 (m, 2 H, CH_2-6), 2.59 (m, 4 H, CH_2-4,7), 4.28 (m, 2 H, OCH_2), 5.14 (d, *J* = 16.8 Hz, 1 H, CH_2Ph), 5.77 (d, *J* = 16.8 Hz, 1 H, CH_2Ph), 6.48 (m, 2 H, CH-2,6 Ph), 6.96 (s, 1 H, H-3), 7.18 (m, 3 H, CH-3,4,5 Ph).

^{13}C NMR (101.6 MHz, $CDCl_3$): δ = 14.1, 22.5, 22.9, 22.9, 23.0, 48.0, 52.2, 52.7, 62.1, 111.8, 111.9, 112.3, 122.1, 122.2, 124.2, 125.2, 127.8, 129.1, 136.8, 140.1, 141.9, 142.9, 145.4, 160.2, 174.8, 176.6.

UV/Vis (MeCN): λ_{max} (log ε) = sh. 267 (3.96), 285 (4.01), 368 (4.23), 462 nm (3.71).

Anal. Calcd for $C_{28}H_{21}Cl_2N_3O_4$: C, 62.93; H, 3.96; Cl, 13.27; N, 7.86. Found: C, 62.75; H, 3.92; Cl, 13.55; N, 7.53.

7-Benzoyl-3,4-dichloro-2,5-dioxo-8-(4,5,6,7-tetrahydro-1*H*-indol-2-yl)bicyclo[4.2.0]octa-3,7-diene-1,6-dicarbonitrile (2d)

A soln of indole **1d** (0.125 g, 1 mmol) and DDQ (0.114 g, 0.5 mmol) in anhyd benzene (20 mL) was stirred at r.t. for 5 min. The benzene was then evaporated and the residue was filtered on a short silica gel column (5 g) with elution by CH_2Cl_2 to give a cherry-colored solid; yield: 0.209 g (88%); mp >210 °C (dec.).

IR (KBr): 2251 (νCN), sh. 1717, 1708, 1639 (νC=O), 1598, 1583, 1556, 1530, 1454 (νC=C), 803 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, $CDCl_3$): δ = 1.78 (m, 2 H, CH_2-5), 1.86 (m, 2 H, CH_2-6), 2.61 (m, 2 H, CH_2-4), 2.78 (m, 2 H, CH_2-7), 6.92 (d, *J* = 1.7 Hz, 1 H, H-3), 7.53 (m, 2 H, CH-3,5 Ph), 7.61 (m, 1 H, CH-4 Ph), 7.77 (m, 2 H, CH-2,6 Ph), 11.80 (br s, 1 H, NH).

^{13}C NMR (101.6 MHz, $CDCl_3$): δ = 22.3, 22.9, 23.0, 24.1, 52.5, 53.8, 111.8, 113.3, 115.5, 121.2, 122.8, 127.9, 127.9, 129.0, 133.2, 136.3, 140.6, 143.2, 143.6, 144.3, 174.9, 176.4, 187.3.

UV/Vis (MeCN): λ_{max} (log ε) = 272 (4.19), 408 (4.12), 480 nm (3.96).

Anal. Calcd for $C_{25}H_{15}Cl_2N_3O_3$: C, 63.04; H, 3.17; Cl, 14.89; N, 8.82. Found: C, 63.37; H, 3.26; Cl, 15.02; N, 8.89.

7-Benzoyl-3,4-dichloro-2,5-dioxo-8-(5-phenyl-1*H*-pyrrol-2-yl)bicyclo[4.2.0]octa-3,7-diene-1,6-dicarbonitrile (4a)

A soln of DDQ (0.114 g, 0.5 mmol) in anhyd MeCN (10 mL) was added to a soln of pyrrole **3a** (0.136 g, 0.5 mmol) in anhyd MeCN (10 mL), and the mixture was stirred at r.t. for 5 min. The solvent was then evaporated and the residue was filtered on a short silica gel column (5 g) with elution by CH_2Cl_2 to give a deep cherry-colored solid; yield: 0.204 g (82%); mp 215–216 °C.

IR (KBr): 2257 (νCN), 1713, 1631 (νC=O), 1597, 1581, 1542, 1494, 1455 (νC=C), 803 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, $CDCl_3$): δ = 6.93 (dd, ^3J = 4.4 Hz, ^4J = 2.8 Hz, 1 H, H-4), 7.27 (dd, ^3J = 4.4 Hz, ^4J = 2.5 Hz, 1 H, H-3), 7.44 (m, 1 H, CH-4 Ph), 7.50 (m, 2 H, CH-3,5 Ph), 7.56 (m, 2 H, CH-3,5 COPh), 7.65 (m, 1 H, CH-4 COPh), 7.76 (m, 2 H, CH-2,6 Ph), 7.87 (m, 2 H, CH-2,6 COPh), 12.62 (br s, 1 H, NH).

^{13}C NMR (101.6 MHz, $CDCl_3$): δ = 29.7, 31.0, 111.6, 113.1, 114.0, 118.3, 124.2, 124.4, 125.8, 128.1, 129.1, 129.2, 129.4, 129.6, 130.3, 133.6, 136.1, 143.4, 143.6, 143.8, 175.0, 176.2, 187.8.

UV/Vis (MeCN): λ_{max} (log ε) = 278 (4.43), 412 (4.14), 494 nm (4.19).

Anal. Calcd for $C_{27}H_{13}Cl_2N_3O_3$: C, 65.08; H, 2.63; Cl, 14.23; N, 8.43. Found: C, 64.81; H, 2.82; Cl, 13.97; N, 8.13.

7-Benzoyl-3,4-dichloro-8-[5-(4-chlorophenyl)-1*H*-pyrrol-2-yl]-2,5-dioxobicyclo[4.2.0]octa-3,7-diene-1,6-dicarbonitrile (4b)

A soln of DDQ (0.114 g, 0.5 mmol) in anhyd benzene (10 mL) was added to a soln of pyrrole **3b** (0.153 g, 0.5 mmol) in anhyd acetone (10 mL), and the mixture was stirred at r.t. for 5 min. The solvents were removed to give a dark-cherry-colored lustrous powder that was washed with Et_2O (5 mL); yield: 0.202 g (76%); mp >300 °C.

IR (KBr): 2260 (νCN), 1712, 1630 (νC=O), 1597, 1582, 1543, 1493, 1472 (νC=C), 803 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, $CDCl_3$): δ = 6.90 (dd, ^3J = 4.1 Hz, ^4J = 2.4 Hz, 1 H, H-4), 7.27 (dd, ^3J = 4.1 Hz, ^4J = 2.4 Hz, 1 H, H-3), 7.46 (m, 2 H, CH-3,5 Ph), 7.57 (m, 2 H, CH-3,5 COPh), 7.67 (m, 3 H, CH-2,6 Ph, CH-4 COPh), 7.87 (m, 2 H, CH-2,6 COPh), 12.63 (br s, 1 H, NH).

^{13}C NMR (101.6 MHz, C_6D_6): δ = 30.0, 30.2, 112.3, 113.5, 113.8, 119.4, 123.5, 124.5, 126.7, 129.0, 129.8, 133.6, 135.8, 136.4, 140.7, 140.8, 143.3, 144.3, 174.3, 176.1, 187.3.

UV/Vis (MeCN): λ_{max} (log ε) = 282 (4.50), 412 (4.17), 491 nm (4.24).

Anal. Calcd for $C_{27}H_{12}Cl_3N_3O_3$: C, 60.87; H, 2.27; Cl, 19.96; N, 7.89. Found: C, 60.96; H, 2.36; Cl, 19.78; N, 7.59.

3,4-Dichloro-7-[5-(4-methoxyphenyl)-1*H*-pyrrol-2-yl]-8-(4-nitrobenzoyl)-2,5-dioxobicyclo[4.2.0]octa-3,7-diene-1,6-dicarbonitrile (4c)

A soln of DDQ (0.114 g, 0. 5 mmol) in benzene (10 mL) was added to a soln of pyrrole **3c** (0.173 g, 0. 5 mmol) in acetone (10 mL), and the mixture was stirred at r.t. for 5 min. The solvents were removed. to give a dark cherry-colored lustrous powder that was washed with Et_2O (5 mL); yield: 0.263 g (92%); mp >300 °C.

IR (KBr): 2248 (νCN), 1725, 1713, 1629 (νC=O), 1603, 1575, 1545, 1493 (νC=C), 1529, 1344 (νNO_2), 1436 (δOCH), 1261, 1026 (νC–O), 803 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, $CDCl_3$): δ = 3.87 (s, 3 H, MeO), 6.93 (dd, ^3J = 4.0 Hz, ^4J = 2.4 Hz, 1 H, H-4), 7.03 (d, *J* = 8.6 Hz, 2 H, CH-3,5 4-$MeOC_6H_4$), 7.34 (dd, ^3J = 4.0 Hz, ^4J = 2.4 Hz, 1 H, H-3), 7.73 (d, *J* = 8.6 Hz, 2 H, CH-2,6 4-$MeOC_6H_4$), 7.96 (d, *J* = 8.4 Hz, 2 H, CH-3,5 4-$NO_2C_6H_4$), 8.40 (d, *J* = 8.4 Hz, 2 H, CH-2,6 4-$NO_2C_6H_4$), 12.57 (br s, 1 H, NH).

^{13}C NMR (101.6 MHz, C_6D_6): δ = 29.7, 54.6, 112.2, 113.7, 113.9, 114.7, 114.9, 115.4, 121.3, 123.7, 124.5, 124.7, 140.8, 141.1, 143.0, 143.1, 143.6, 149.9, 161.6, 173.8, 173.9, 175.6, 185.2.

UV/Vis (MeCN): λ_{max} (log ε) = 278 (4.34), 447 (3.93), 530 nm (4.13).

Anal. Calcd for $C_{28}H_{14}Cl_2N_4O_6$: C, 58.66; H, 2.46; Cl, 12.37; N, 9.77. Found: C, 58.96; H, 2.36; Cl, 12.54; N, 9.59.

7-Benzoyl-3,4-dichloro-8-(1*H*-indol-3-yl)-2,5-dioxobicyclo[4.2.0]octa-3,7-diene-1,6-dicarbonitrile (6a)

A soln of DDQ (0.114 g, 0.5 mmol) in anhyd benzene (10 mL) was added to a soln of indole **5a** (0.123 g, 0.5 mmol) in anhyd acetone (10 mL), and the mixture was stirred at r.t. for 5 min. The solvents were removed to give a lustrous red powder that was washed with Et_2O (5 mL); yield: 0.205 g (87%); mp >300 °C.

IR (KBr): 3391 (νNH), 2247 (νCN), 1712, 1699, sh. 1628 (νC=O), 1607, 1598, 1580, 1557, 1496 (νC=C), 806 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, acetone-d_6): δ = 6.83 (m, 1 H, H-7), 6.94 (m, 1 H, H-6), 7.15 (m, 1 H, H-5), 7.40 (m, 2 H, CH-3 Ph), 7.55 (m, 2 H, CH-4 Ph, H-2), 7.95 (m, 2 H, CH-2 Ph), 8.07 (m, 1 H, H-4), 11.53 (br s, 1 H, NH).

^{13}C NMR (101.6 MHz, acetone-d_6): δ = 53.9, 54.3, 106.6, 112.7, 113.1, 113.4, 120.5, 121.8, 123.8, 123.9, 125.9, 129.1, 129.2, 133.4, 134.5, 136.0, 137.0, 139.7, 142.0, 144.0, 176.6, 177.9, 187.6.

UV/Vis (MeCN): λ_{max} (log ε) = sh. 262 (4.72), 273 (4.73), 375 (4.21), 437 nm (3.77).

Anal. Calcd for $C_{25}H_{11}Cl_2N_3O_3$: C, 63.58; H, 2.35; Cl, 15.01; N, 8.90. Found: C, 63.76; H, 2.36; Cl, 14.78; N, 8.59.

7-Benzoyl-3,4-dichloro-8-(2-methyl-1*H*-indol-3-yl)-2,5-dioxobicyclo[4.2.0]octa-3,7-diene-1,6-dicarbonitrile (6b)

A soln of DDQ (0.114 g, 0.5 mmol) in anhyd benzene (10 mL) was added to a soln of indole **5b** (0.130 g, 0.5 mmol) in anhyd acetone (10 mL), and the mixture was stirred at r.t. for 5 min. The solvents were removed to give a lustrous red solid that was washed with Et_2O (5 mL); yield: 0.204 g (84%); mp >300 °C.

IR (KBr): 3372 (νNH), 2262, sh. 2254 (νCN), 1602, 1574, 1568, 1523, 1485, 1457 (νC=C), 1729, 1717, sh. 1625 (νC=O), 795 cm^{-1} (νC–Cl).

^{1}H NMR (400.13 MHz, acetone-d_6): δ = 2.28 (s, 3 H, Me), 7.08, 7.15 (m, 2 H, H-5,6), 7.31 (m, 1 H, H-7), 7.40 (m, 2 H, CH-3 Ph), 7.53 (m, 1 H, CH-4 Ph), 7.61 (m, 1 H, H-4), 7.91 (m, 2 H, CH-2 Ph), 11.11 (br s, 1 H, NH).

^{13}C NMR (101.6 MHz, acetone-d_6): δ = 13.7, 54.7, 56.4, 105.0, 112.2, 113.3, 114.3, 120.1, 122.2, 123.6, 126.5, 129.4, 129.4, 132.0, 135.1, 135.9, 136.4, 139.4, 142.0, 143.4, 147.9, 177.3, 177.6, 188.4.

UV/Vis (MeCN): λ_{max} (log ε) = sh. 262 (4.35), 273 (4.36), 380 (3.70), 453 nm (3.62).

Anal. Calcd for $C_{26}H_{13}Cl_2N_3O_3$: C, 64.21; H, 2.69; Cl, 14.58; N, 8.64. Found: C, 63.96; H, 2.56; Cl, 14.78; N, 8.59.

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