

On the influence of small chemical changes upon the supramolecular association in substituted 2-(phenoxy)-1,4-naphthoquinones

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Abstract. X-ray crystallography reveals the common feature of the title compounds is a 1,4-naphthoquinone ring system with a substituted phenoxy residue adjacent to an oxo-group to give **1** (H), **2** (3-Br), **3** (3-CF₃), **4** (4-CN) and **5** (4-NO₂). To a first approximation the fused ring system along with the two oxo substituents is planar with the major difference between the molecules relating to the relative orientations of the pendant phenoxy residues: dihedral angles range from 56.56(4)° (**3**) to 87.52(10)° (**2**). The presence of intermolecular C–H···O interactions is the common feature of the supramolecular association in the crystals of **1-5**. In each of **1** and **5**, these extend in three-dimensions but, only to supramolecular dimers in **4**, chains in **2** and layers in **3**. Each crystal also features C=O···π interactions, pointing to the importance of these points of contact in this series di-oxo-compounds. In **2**, these, along with C–Br···π interactions lead to a three-dimensional architecture. For **3**, the C=O···π and π···π interactions occur within the layers which stack without directional interactions between them. In **4**, C–H···O and C=O···π interactions combine to give a supramolecular layer, which also stack without directional interactions in the inter-layer region. Further analysis of the molecular packing was conducted by a Hirshfeld surface analysis (HSA). This points to the significant role of H···H, C···H/H···C and O···H/H···O contacts in the packing of **1**. Notably different roles for these contacts are found in the other crystals correlating with the participation of the respective substituents in the molecular packing. The HSA suggests the association between layers in **3** (weak F...F and H...F interactions) and **4** (weak H...N interactions) is contributed by the phenoxy-substituents.

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Introduction

Quinones, both naturally occurring and synthetic derivatives, continue to be intensely investigated due to their bright colours, their biological properties [1,2] and, as a consequence of their redox properties, their potential in materials chemistry [3-10]. Specifically, the structural skeleton of 2-(phenoxy)-1,4-naphthoquinone derivatives is found in a number of natural products that include Rubicolins [11], Newbouldiaquinones [12-14], Rubipodanones [15] and Lawsonol [16]; see Figure 1 for chemical structural formulae. The documented anti-trypanosomal [17-24] and anti-leishmanial activity [18] as well as the anti-tumour [15,23,25-29] and anti-fungal activity [30-32] of natural and synthetic derivatives of 2-(phenoxy)-1,4-naphthoquinones further highlights the significant chemical interest in this skeletal motif.

Fig. 1: Chemical structural formulae of natural products having a similar skeleton to that of 2-phenoxy-1,4-naphthoquinone skeleton.

As part of on-going studies [33-38] into the synthesis, structural characterisation and photochemistry of quinones, a series of new 2-(phenoxy)-1,4-naphthoquinone derivatives were prepared. The present study details the synthesis, characterisation and crystal structure determinations of **1-5**; see Figure 2 for chemical structural formulae.

Fig. 2: Chemical structural formulae of the substituted (phenoxy)-1,4-naphthoquinones **1-5** studied herein.

Beyond the chemical interest in the title compounds as outlined above, are crystal engineering considerations in that it is of interest to systematically evaluate the influence of small chemical changes in molecules upon the molecular packing in their crystals. The primary objective of crystal engineering endeavours is to control the manner by which molecules assemble in the condensed phase so that physiochemical properties can be tailored – by and large this objective has yet to be achieved even though considerable progress is being made in assembling specific aggregates within crystals [39]. For example, a very recent contribution in this area showed how six-molecular hetero-aggregates could be rationally assembled based on propensities to form non-covalent interactions and shape similarities [40]. There are increasing numbers of systematic studies whereby the molecular packing of series of molecules varying typically by one substituent, e.g. halide for halide, increasing sizes of alkyl groups, etc. [41-53] are evaluated. Usually some systematic trends can be discerned suggesting remote substituents are non-innocent, providing specific points of contact between molecules but, not always. For example, when studying molecular packing in a series of benzenesulfonyl asparagine derivatives, Harrison et al. concluded that the nature of the substituent did not matter [46]. On the other hand, in a systematic study of monosubstituted salicylic acids, Montis and Hursthouse concluded the substituents were very important in dictating supramolecular assembly [43]. In continuation of systematic studies whereby small chemical changes are introduced into series of molecules [41,44,45], the crystal and molecular structures of **1-5** are described along with an analysis of the calculated Hirshfeld surfaces. **From the chemistry, Figure 2, the molecular packing will be devoid of conventional hydrogen bonding interactions. Under these circumstances, it was**

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thought of interest to ascertain whether any dominant supramolecular synthon would emerge in the crystals of this series closely related molecules. In the same way, do the remote substituents exert any significant influence upon the molecular packing.

Experimental

Instrumentation

Melting points were determined with a Mel. Temp. II apparatus and are uncorrected. IR spectra were measured on a Nicolet 505 Magma FT-IR spectrophotometer. ^1H and $^{13}\text{C}\{^1\text{H}\}$ spectra were recorded using Bruker 200, 300 or 500 MHz spectrometers. High resolution mass spectra (HRMS) were recorded on a micro-TOF-II Bruker instrument.

Synthesis and crystal growth

The commercially available reagents and solvents were used without further purification. Analytical thin layer chromatography (TLC) was performed on pre-coated silica gel 60 F254 aluminum plates (Merck) with visualisation under UV light at 254 and 366 nm. The reactions were performed following a literature procedure [54]. In a typical procedure, phenol (2.2 mmol) and K_2CO_3 (3.0 mmol) were combined in DMF (3 ml) in a round bottomed flask (10 ml). The mixture was stirred at room temperature for 15 mins then 2-bromo-1,4-naphthoquinone (2.0 mmol) was added. The reaction was followed by TLC (hexane:EtOAc, 3:1 v/v) and reactions were observed to be complete within 1 h. The reaction was hydrolysed by the addition of aqueous KHSO_4 (1 mol.L $^{-1}$, 10 ml) and the mixture extracted with EtOAc (3 x 20 ml). The organic phase was back washed with water (30 ml) and then dried over Na_2SO_4 , filtered and concentrated under reduced pressure to give a yellow solid. The products were recrystallised from EtOH/H $_2$ O unless otherwise indicated.

2-Phenoxy-1,4-naphthoquinone (1)

Yellow crystals (0.498 g, 99%). m.p. 377–378 K (lit. [54] 374 K). IR (KBr, cm^{-1}): 3071, 1686, 1658, 1652, 1615, 1594, 1587, 1484, 1213, 979. ^1H NMR (500 MHz, CDCl_3): δ 8.21–8.15 (m, 1H), 8.08–8.03 (m, 1H), 7.77–7.71 (m, 2H), 7.45 (t, J = 8.0 Hz, 2H), 7.30 (t, J = 7.5 Hz, 1H), 7.13 (d, J = 7.7 Hz, 2H), 5.94 (s, 1H). ^{13}C NMR (126 MHz, CDCl_3): δ 185.0 (C_q), 180.0 (C_q), 160.6 (C_q), 152.7 (C_q), 134.5 (CH), 133.6 (CH), 132.0 (C_q), 131.1 (C_q), 130.5 (CH), 126.9 (CH), 126.7 (CH), 126.3 (CH), 121.2 (CH), 113.4 (CH). HR-MS (ESI): m/z calcd. for $\text{C}_{16}\text{H}_{10}\text{O}_3$ [$\text{M}+\text{H}$] $^+$ 251.0702, found 251.0701.

2-(3-Bromophenoxy)-1,4-naphthoquinone (2)

Yellow crystals (0.524 g, 80%). m.p. 381–383 K. IR (KBr, cm^{-1}): 3087, 1686, 1650, 1616, 1578, 1465, 1335, 1265, 1215, 984, 779. ^1H NMR (500 MHz, CDCl_3): δ 8.18–8.16 (m, 1H), 8.06–8.04 (m, 1H), 7.78–7.73 (m, 2H), 7.45 (d, J = 8.0 Hz, 1H), 6.33 (t, J = 8.2 Hz, 1H), 7.32 (s, 1H), 7.10 (dd, J = 8.1, 1.9 Hz, 1H), 5.98 (s, 1H). ^{13}C -NMR (126 MHz, CDCl_3): δ 184.8 (C_q), 179.6 (C_q), 160.0 (C_q), 153.4 (C_q), 134.7 (CH), 133.8 (CH), 132.0 (C_q), 131.6 (CH), 131.1 (C_q), 129.9 (CH), 126.9 (CH), 126.4 (CH), 124.6 (CH), 123.4 (C_q), 120.0 (CH), 114.0 (CH). HR-MS (ESI): m/z calcd. for $\text{C}_{16}\text{H}_9\text{BrO}_3$ [$\text{M}+\text{Na}$] $^+$ 350.9627, found 350.9629.

2-(3-(Trifluoromethyl)phenoxy)-1,4-naphthoquinone (3)

Quantities: 3-trifluoromethylphenol (0.525 g, 3.24 mmol), K_2CO_3 (0.634 g, 4.59 mmol) in DMF (3 ml) with 2-bromo-1,4-naphthoquinone (0.725 g,

3.06 mmol). Yellow crystals after recrystallisation in EtOH (0.836 g, 86%). m.p. 368–370 K. IR (KBr, cm^{-1}): 3070, 1687, 1652, 1613, 1595, 1323, 1264, 1217, 1173, 1122, 983. ^1H NMR (500 MHz, CDCl_3): δ 8.20–8.18 (m, 1H), 8.07–8.06 (m, 1H), 7.80–7.75 (m, 2H), 7.63–7.58 (m, 2H), 7.43 (s, 1H), 7.36–7.34 (m, 1H), 5.96 (s, 1H). ^{13}C NMR (126 MHz, CDCl_3): δ 184.7 (C_q), 179.6 (C_q), 159.9 (C_q), 153.1 (C_q), 134.7 (CH), 133.8 (CH), 133.2 (C_q , $^2J_{\text{C-F}} = 33.3$ Hz), 132.0 (C_q), 31.3 (CH), 131.1 (C_q), 127.0 (CH), 126.5 (CH), 124.7 (CH), 123.5 (CH, $^3J_{\text{C-F}} = 3.6$ Hz), 123.3 (CF_3 , $^1J_{\text{C-F}} = 273$ Hz), 118.4 (CH, $^3J_{\text{C-F}} = 3.6$ Hz), 114.2 (CH). HR-MS (ESI): m/z calcd. for $\text{C}_{17}\text{H}_9\text{F}_3\text{O}_3$ [$\text{M}+\text{Na}$] $^+$ 341.0396, found 341.0404.

2-(4-Cyanophenoxy)-1,4-naphthoquinone (4)

Quantities: 4-cyanophenol (0.750 g, 6.3 mmol), K_2CO_3 (1.244 g, 9.0 mmol) in DMF (6 ml) with 2-bromo-1,4-naphthoquinone (1.422 g, 6.0 mmol). Yellow crystals (1.440 g, 87%). m.p. 448–450 K. IR (KBr, cm^{-1}): 3099, 3051, 2227, 1682, 1655, 1619, 1596, 1499, 1240, 1223, 982, 862, 718. ^1H NMR (500 MHz, CDCl_3): δ 8.14 (d, $J = 6.7$ Hz, 1H), 8.05 (d, $J = 6.7$ Hz, 1H), 7.78–7.75 (m, 4H), 7.25 (d, $J = 7.4$ Hz, 2H), 6.07 (s, 1H). ^{13}C NMR (126 MHz, CDCl_3): δ 184.5 (C_q), 179.4 (C_q), 158.9 (C_q), 156.7 (C_q), 134.8 (CH), 134.7 (CH), 134.7 (CH), 134.0 (CH), 131.9 (C_q), 131.0 (C_q), 127.0 (CH), 126.5 (CH), 121.7 (CH), 121.7 (CH), 117.9 (C_q), 115.8 (CH), 110.4 (C_q). HR-MS (ESI): m/z calcd. for $\text{C}_{17}\text{H}_9\text{NO}_3$ [$\text{M}+\text{Na}$] $^+$ 298.0474, found 298.0480.

2-(4-Nitrophenoxy)-1,4-naphthoquinone (5)

Quantities: 4-nitrophenol (0.918 g, 6.6 mmol), K_2CO_3 (1.244 g, 9 mmol) in DMF (5 ml) and 2-bromo-1,4-naphthoquinone (1.422 g, 6 mmol). Yellow crystals from acetone/water (1.418 g, 80%). m.p. 461–463 K. IR (KBr, cm^{-1}): 3355, 3113, 3080, 3052, 1689, 1647, 1618, 1591, 1577, 1515, 1490, 1346, 1333, 1243, 1222, 981, 897. ^1H NMR (500 MHz, CDCl_3): δ 8.34 (d, $J = 9.1$ Hz, 2H), 8.17–8.15 (m, 1H), 8.08–8.06 (m, 1H), 7.81–7.75 (m, 2H), 7.30 (d, $J = 9.1$ Hz, 2H), 6.16 (s, 1H). ^{13}C NMR (126 MHz, CDCl_3): δ 184.5 (C_q), 179.3 (C_q), 158.7 (C_q), 158.3 (C_q), 145.6 (C_q), 134.9 (CH), 134.1 (CH), 131.9 (C_q), 131.0 (C_q), 127.1 (CH), 126.6 (CH), 126.4 (CH), 126.4 (CH), 121.2 (CH), 121.2 (CH), 116.4 (CH). HR-MS (ESI): m/z calcd. for $\text{C}_{16}\text{H}_9\text{NO}_5$ [$\text{M}+\text{Na}$] $^+$ 318.0373, found 318.0372.

Crystal structure determination

Intensity data for **1-5** were measured at 100 K on a Rigaku Oxford Diffraction diffractometer (The Woodlands, Texas, USA) using graphite-mo-chromatised $\text{MoK}\alpha$ radiation ($\lambda = 0.71073$ Å). Data processing and absorption corrections were accomplished with CrysAlis PRO [55]. Unit cell data, X-ray data collection parameters and details of the structure refinement are given in Table 1. The structures were solved by Direct Methods using SHELXS [56] and full-matrix least-squares [57] refinement was on F^2 (anisotropic displacement parameters and C-bound H atoms in their idealised positions). A weighting scheme of the form $w = 1/[\sigma^2(F_o^2) + (aP)^2 + bP]$ where $P = (F_o^2 + 2F_c^2)/3$ was introduced in each case. The absolute structure of **1** could not be determined but, that of **2** was determined based on differences in Friedel pairs included in the data set.

Tab: 1. Crystallographic data and refinement details for 1-5.¹

	1	2	3	4	5
Formula	C ₁₆ H ₁₀ O ₃	C ₁₆ H ₉ BrO ₃	C ₁₇ H ₉ F ₃ O ₃	C ₁₇ H ₉ NO ₃	C ₁₆ H ₉ NO ₅
Formula weight	250.24	329.14	318.24	275.25	295.24
Crystal colour, habit	Colourless, prism	Colourless, lath	Yellow, needle	Colourless, plate	Colourless, prism
Crystal size/mm	0.04 x 0.07 x 0.12	0.01 x 0.04 x 0.20	0.01 x 0.01 x 0.08	0.02 x 0.21 x 0.25	0.04 x 0.06 x 0.14
Crystal system	monoclinic	orthorhombic	monoclinic	monoclinic	monoclinic
Space group	<i>Pn</i>	<i>P2₁2₁2₁</i>	<i>I2/a</i>	<i>P2₁/c</i>	<i>P2₁/n</i>
<i>a</i> /Å	11.8027(7)	5.3247(2)	23.1971(8)	13.5903(7)	14.1790(4)
<i>b</i> /Å	5.7419(3)	15.6418(9)	6.9762(2)	16.6630(8)	5.3850(2)
<i>c</i> /Å	18.2991(9)	15.6316(9)	17.3845(5)	5.7345(2)	17.3281(7)
α /°	90	90	90	90	90
β /°	107.522(5)	90	101.132(3)	94.063(5)	105.188(3)
γ /°	90	90	90	90	90
<i>V</i> /Å ³	1182.59(11)	1301.92(12)	2760.36(15)	1295.34(10)	1276.85(8)
<i>Z</i> / <i>Z'</i>	4/2	4/1	8/1	4/1	4/1
<i>D_c</i> /g cm ⁻³	1.406	1.679	1.532	1.411	1.536
<i>F</i> (000)	520	656	1296	568	608
μ (MoK α)/mm ⁻¹	0.097	3.161	0.131	0.098	0.116
Measured data	10195	11420	27804	11337	10550
θ range/°	2.3-27.5	2.6-27.5	2.4-27.5	2.9-27.5	2.2-27.5
Unique data	4618	2924	3161	2955	2923
<i>R</i> _{int}	0.068	0.034	0.058	0.024	0.039
Observed data (<i>I</i> ≥ 2.0 σ (<i>I</i>))	3763	2672	2383	2507	2430
<i>R</i> , obs. data; all data	0.058; 0.075	0.033; 0.039	0.041; 0.061	0.039; 0.049	0.042; 0.053
<i>a</i> , <i>b</i> in wghting scheme	0.092; 0	0.035; 1.126	0.058; 1.476	0.047; 0.472	0.065; 0.329
<i>R</i> _w , obs. data; all data	0.138; 0.147	0.071; 0.073	0.100; 0.109	0.094; 0.099	0.109; 0.116
$\Delta\rho_{\max, \min}$ /e Å ⁻³	0.25, -0.38	0.55, -0.32	0.28; -0.27	0.27; -0.21	0.38; -0.23

¹ Supplementary Material: Crystallographic data for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-1847534-1847538. Copies of available material can be obtained free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK, (fax: +44-(0)1223-336033 or e-mail: deposit@ccdc.cam.ac.uk).

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In the refinement of **2**, owing to poor agreement, the (0 1 1) reflection was omitted from the final cycles of refinement. Disorder was resolved in the refinement of **3** in that the F atoms of the CF₃ group were disordered over two positions. After unconstrained anisotropic refinement, the major component had a site occupancy factor = 0.52(3) so that in the final cycles of refinement, the site occupancy for each component was fixed at 0.5. The programs WinGX [58], PLATON [59], ORTEP-3 for Windows [58], DIAMOND [60] and QMol [61] were also used in the study.

Results and discussion

Experimental molecular structures

The molecular structures of **1-5** are shown in Figure 3 and key conformational descriptors included in Table 2. The asymmetric unit of **1** comprises two independent molecules which exhibit essentially the same molecular structure. The first independent molecule is constructed about a cyclohexa-2,5-diene-1,4-dione residue that is essentially planar with the r.m.s. deviation of the C₆ atoms being 0.0126 Å; maximum deviations of 0.016(3) and 0.021(3) Å are noted for the C3 and C4 atoms, respectively. The O1-O3 atoms lie to one side of the plane and deviate by 0.022(5), 0.026(5) and 0.071(5) Å, respectively. A phenyl ring is fused to one side of the cyclohexa-2,5-diene ring, at the double bond, and is essentially co-planar, forming a dihedral angle of 1.98(2)°. To the resultant naphthalene-1,4-dione residue is connected a phenoxy substituent which is adjacent to the ketone-O1 atom. The pendant phenyl ring forms a dihedral angle of 81.03(12)° with the cyclohexadiene ring, and is inclined so that it is bisected by the approximate plane through the fused ring system. The second independent molecule of **1** presents essentially the same features as that just described as indeed do the molecular structures of **2-5**. In the case of **1**, the r.m.s. fits for the two independent molecules for bonds and angles are 0.0046 Å and 0.494°, respectively [59]. The similarity between the molecules is highlighted in the molecular overlay diagram shown in Figure 4.

Across the series, the maximum distortion of the C₆ atoms of the cyclohexa-2,5-diene-1,4-dione residue from their least-squares plane is found for **5**, having a r.m.s. deviation of 0.0261 Å. While the C3 and C4 exhibit the major deviations from this plane in the first independent molecule of **1**, for the second independent molecule the maximum deviations are found for the C4a and C5a atoms; the same is true for **2** and **3**. In each of **4** and **5**, the maximum deviations are found for the C5 and C10 atoms. No systematic patterns are noted in the deviations of the O1-O3 atoms from the central plane with all atoms lying to one side for the first independent molecule of **1**, as found for **5**. In the second independent molecule of **1** and in each of **3** and **4**, the O2 atom lies to the opposite side of the plane to the O1 and O3 atoms. In **2**, the O3 atom lies to the opposite side to the O1 and O2 atoms. In all of the above, the deviations are less than 0.11 Å and are unlikely to have chemical significance. The maximum dihedral angle formed between the individual rings in the fused-ring system is found in **5**, i.e. 3.56(8)°. The smallest dihedral angle between the central C₆ ring and pendant phenyl ring is 59.24(4)° for **3** and the greatest is 86.47(10)° for **2**; these differences are highlighted in Figure 4. Finally, in **5**, the nitro group is almost co-planar with the phenyl ring to which it is bound with the dihedral angle between the planes of 7.54(11)° indicating a small twist.

Fig. 3 The molecular structures of (a) **1**, first independent molecule, (b) **1**, second independent molecule, (c) **2**, (d) **3**, (e) **4** and (f) **5**, showing the atom-labelling schemes and displacement ellipsoids at the 50% probability level.

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Tab. 2: Summary of key conformational parameters (Å, °) for **1-5**.

Parameter	1	1a	2	3	4	5
r.m.s. deviation of the atoms from the (C1-C5, C10) plane (= plane 1)	0.0126	0.0190	0.0106	0.0204	0.0261	0.0261
Maximum deviations of from plane 1	C3: 0.016(3) C4: -0.021(3)	C4a: 0.015(3) C5a: -0.028(3)	C5: 0.016(3) C4: -0.014(3)	C5: 0.0289(9) C4: -0.0256(9)	C5: 0.0374(8) C10: -0.0239(8)	C10: 0.0365(9) C1: -0.0263(9)
Deviation of the O1, O2 and O3 atoms from plane 1	O1: -0.022(5) O2: -0.026(5) O3: -0.071(5)	O1a: 0.015(5) O2a: -0.079(5) O3a: 0.036(5)	O1: 0.002(5) O2: 0.037(5) O3: -0.065(5)	O1: -0.049(2) O2: 0.050(2) O3: -0.107(2)	O1: -0.011(2) O2: 0.059(2) O3: -0.089(2)	O1: -0.069(2) O2: -0.006(2) O3: -0.047(2)
Dihedral angle: plane 1/(C5-C10)	1.98(2)	3.4(2)	1.1(2)	3.36(7)	3.23(6)	3.56(8)
Dihedral angle: plane 1/(C11-C16)	81.03(12)	76.87(11)	86.47(10)	59.24(4)	65.02(3)	70.86(3)
Dihedral angle (C5-C10)/(C11-C16)	80.01(13)	73.81(11)	87.52(10)	56.56(4)	61.89(3)	68.91(4)

There are no direct precedents in the crystallographic literature for **1-5** [62] although the backbone of the structure is found in various cavitands. The most closely related structure is one where there are phenoxy substituents adjacent to both ketone-O atoms and with these linked by a $-O-(CH_2)_2-O-(CH_2)_2-O-$ bridge [63], i.e. a crown ether derivative.

Fig. 4: Overlay diagrams of the molecules in **1-5**: first independent molecule in **1** (red image), second independent molecule in **1** (green), **2** (blue), **3** (pink), **4** (aqua) **5** (yellow). Molecules have been overlapped so the naphthalene-phenyl rings are coincident.

Molecular packing

The geometric parameters characterising the key interatomic interactions in the crystals of **1-5** are collated in Table 3. The molecular packing in **1** features extensive $C-H\cdots O$ interactions to consolidate the three-dimensional architecture. Thus, cyclohexadiene- $C-H\cdots O$ (ketone), phenoxy- $C-H\cdots O$ (ketone) and phenoxy- $C-H\cdots O$ (phenoxy) interactions are present, with the ketone-O3a atom accepting two contacts. In this scheme all interactions occur between the independent molecules of the asymmetric unit and no role is apparent for the ketone-O1/O1a atoms. Rather, each of the ketone-O1 atoms participates in a $C=O\cdots\pi$ (cyclohexadiene) interaction, again involving molecules derived from the independent molecules. **The latter contacts are approximately parallel with the angle subtended at the carbonyl-oxygen atom being approximately at right-angles. The criterion of significant, at least in terms of distances, is based on twice the van der Waals radii of two π -systems, i.e. 3.80 Å as opposed to 3.42 Å, being the sum of the radii of a π -system and an oxygen atom [59]. Within this architecture, each of the independent molecules forms a naphthalene-C9-H $\cdots\pi$ (cyclohexadiene) contact with the other independent molecule.** Views of the molecular packing are shown in Figure 5a, highlighting the $C-H\cdots O$ interactions, and Figure 5b, highlighting the $C=O\cdots\pi$ (cyclohexadiene) interactions.

Fig. 5: Molecular packing in **1**: views of the unit cell contents in projection down the (a) b -axis and (b) a -axis, with $C-H\cdots O$ and $C=O\cdots\pi$ interactions are indicated by orange and purple dashed lines, respectively.

In the packing of **2**, naphthalene- $C8-H\cdots O3$ (ketone) contacts assemble molecules into a helical supramolecular chain along the b -axis. Connections between chains are of the type $C=O\cdots\pi$ and $C-Br\cdots\pi$. For the former, the ketone-O1 atoms form two interactions, with cyclohexadiene and naphthalene-phenyl rings being the acceptors. In this way, the ketone-O1 atom bridges two molecules. The phenoxy-Br atom also forms an interaction with the cyclohexadiene ring so the latter also effectively acts as a bridge between two molecules. **While the $C-Br\cdots\pi$ (cyclohexadiene) might be considered long, the analysis of the calculated Hirshfeld surface indicates this contact is relatively important in providing stability to the molecular packing.** The aforementioned interactions assemble molecules in three-dimensions, Figure 6; no specific interaction is evident for the phenoxy-O2 atom in the molecular packing.

Tab. 3: Summary of intermolecular A–H···B and $\pi\cdots\pi$ point-to-point contacts (Å, °) in the crystals of **1-5**.

A	H	B	H···B	A···B	A–H...B	Symmetry operation
1						
C3a	H3a	O3	2.33	3.188(5)	150	$\frac{1}{2}+x, -y, \frac{1}{2}+z$
C13	H13	O3a	2.53	3.163(6)	124	$\frac{1}{2}+x, -y, -\frac{1}{2}+z$
C14	H14	O3a	2.58	3.186(5)	122	$\frac{1}{2}+x, -y, -\frac{1}{2}+z$
C16	H16	O2a	2.53	3.443(5)	161	x, y, z
C16a	H16a	O2	2.49	3.372(5)	154	x, -1+y, z
C1	O1	Cg(C1a-C5a, C10a)	3.328(3)	4.139(4)	124.2(3)	x, 1+y, z
C1a	O1a	Cg(C1-C5, C10)	3.347(3)	4.118(4)	121.4(3)	x, y, z
C9	H9	Cg(C5a-C10a)	2.83	3.513(4)	130	x, 1 + y, z
C9a	H9a	Cg(C5-C10)	2.94	3.589(4)	127	x, y, z
2						
C8	H8	O3	2.42	3.327(5)	158	1-x, - $\frac{1}{2}$ +y, 1 $\frac{1}{2}$ -z
C1	O1	Cg(C1-C5, C10)	3.255(3)	4.116(4)	127.9(2)	$\frac{1}{2}+x, \frac{1}{2}-y, 1-z$
C1	O1	Cg(C5-C10)	3.564(3)	4.198(4)	113.4(2)	1+x, y, z
C13	Br1	Cg(C1-C5, C10)	3.9500(17)	5.287(5)	125.95(14)	$\frac{1}{2}-x, 1-y, -\frac{1}{2}+z$
3						
C6	H6	O3	2.50	3.4409(18)	170	1-x, -y, 1-z
C12	H12	O3	2.36	3.2843(17)	164	x, 1+y, z
C15	H15	O1	2.58	3.1872(18)	122	1-x, - $\frac{1}{2}$ +y, 1 $\frac{1}{2}$ -z
C16	H16	O1	2.53	3.1554(18)	123	1-x, - $\frac{1}{2}$ +y, 1 $\frac{1}{2}$ -z
C16	H16	O2	2.58	3.5273(17)	175	1-x, - $\frac{1}{2}$ +y, 1 $\frac{1}{2}$ -z
C4	O3	Cg(C1-C5, C10)	3.2346(12)	3.2894(15)	81.67(8)	1-x, 1-y, 1-z
Cg(C1-C5,C10)	–	Cg(C11-C16)	–	3.6675(8)	–	1-x, - $\frac{1}{2}$ +y, 1 $\frac{1}{2}$ -z
Cg(C1-C5,C10)	–	Cg(C1-C5, C10)	–	3.8274(8)	–	1-x, 1-y, 1-z

4

C3	H3	O3	2.40	3.3161(15)	163	1-x, 1-y, -z
C1	O1	Cg(C1-C5, C10)	3.2726(10)	4.0797(13)	123.80(8)	x, 1½-y, ½+z
C4	O3	Cg3(C11-C16)	3.1692(11)	4.2799(13)	150.42(8)	1-x, 1-y, -z
C9	H9	Cg(C5-C10)	2.79	3.4592(13)	128	x, 1½-y, ½+z

5

C3	H3	O3	2.39	3.3309(17)	169	1-x, -y, 1-z
C15	H15	O5	2.60	3.5476(17)	176	1½-x, -½+y, ½-z
C16	H16	O1	2.35	3.2333(17)	154	½-x, -½+y, ½-z
C1	O1	Cg(C1-C5, C10)	3.4381(11)	4.3436(14)	131.74(9)	½ - x, - ½ + y, ½ -z
C1	O1	Cg(C5-C10)	3.6514(12)	4.1176(13)	103.96(8)	x, 1 + y, z
C4	O3	Cg(C11-C16)	3.2586(11)	4.3936(14)	153.39(9)	1 -x, - y, 1 - z

Fig. 6: Molecular packing in **2**: a view of the unit cell contents in projection down the *a*-axis, with C–H \cdots O, C=O \cdots π and C–Br \cdots π interactions are indicated by orange, purple and blue dashed lines, respectively.

In the crystal of **3**, a number of C–H \cdots O interactions are evident with each of the oxygen atoms participating in at least one such contact. Thus, the ketone-O1 atom accepts two contacts, from two phenoxy-C–H atoms, and similarly the ketone-O3 atom accepts one C–H \cdots O contact from a phenoxy-C–H and another from a naphthalene-C–H atom. The phenoxy-O2 atom accepts a C–H \cdots O contact from a phenoxy-C–H atom. As shown in Figure 7a, the C–H \cdots O interactions lead to the formation of supramolecular layers in the *bc*-plane. Within the layer, $\pi\cdots\pi$ interactions between cyclohexadiene and phenoxy rings and between symmetry-related cyclohexadiene rings as well as C=O3 \cdots π (cyclohexadiene) contacts are also evident and provide additional stability to the aggregation in the *bc*-plane. The supramolecular layers stack along the *a*-axis with non-directional interactions between them, Figure 7b.

Fig. 7: Molecular packing in **3**: (a) a view of the supramolecular layer in the *bc*-plane sustained by C–H \cdots O interactions and (b) a view of the unit cell contents in projection down the *b*-axis. The C–H \cdots O, C=O \cdots π and $\pi\cdots\pi$ interactions are indicated by orange, purple and green dashed lines, respectively. For clarity, only one orientation of the statistically disordered –CF₃ group is illustrated.

In the crystal of **4**, centrosymmetrically-related molecules associate *via* cyclohexadiene-C–H \cdots O3 interactions leading to eight-membered { \cdots OC₂H}₂ synthons. The resulting two-molecule aggregates are connected into supramolecular layers in the *bc*-plane by C=O \cdots π interactions involving both ketone-O atoms, with ketone-O1 interacting with a symmetry-related cyclohexadiene ring, **in an end-on fashion rather than the parallel approach seen for the interactions described thus far, i.e. with the C=O \cdots π (cyclohexadiene) interaction approaching linearity**, and the ketone-O3 atom interacting with a phenoxy ring. In addition, naphthalene-C9–H \cdots π (naphthalene) contacts contributes to the stability of the layer, Figure 8a. The layers stack along the *a*-axis without directional interactions between them, Figure 8b.

Fig. 8: Molecular packing in **4**: (a) a view of the supramolecular layer in the *bc*-plane sustained by C–H \cdots O, C=O \cdots π and C–H \cdots π interactions and (b) a view of the unit cell contents in projection down the *c*-axis. The C–H \cdots O, C=O \cdots π and C–H \cdots π interactions are indicated by orange, purple and blue dashed lines, respectively.

As for **4**, the molecular packing of **5** cyclohexadiene-C–H \cdots O3(ketone) interactions leading to eight-membered { \cdots OC₂H}₂ synthons between centrosymmetrically-related molecules. In addition, phenoxy-C16–H \cdots O1(ketone) and phenoxy-C15–H \cdots O5(nitro) interactions are found, each leading to supramolecular chains so a three-dimensional architecture ensues. The crystal also features C=O \cdots π interactions with the ketone-O1 atom forming two such contacts, **one parallel and the other end-on, Table 3**, to link two molecules *via* their cyclohexadiene and naphthalene rings. The ketone-O3 atom forms a contact with a phenoxy ring. A view of the unit cell contents is shown in Figure 9.

Fig. 9: Molecular packing in **5**: a view of the unit cell contents in projection down the b-axis, with C–H···O and C=O··· π interactions are indicated by orange and purple dashed lines, respectively.

The common feature of the molecular packing in **1-5** is the formation of C–H···O interactions which in the cases of **1** and **5** extend in three-dimensions. In **2**, C–H···O interactions lead to chains, in **3** to layers and in **4** to dimers. Each crystal also features C=O··· π interactions. This type of interaction is known to be significant in stabilising the molecular packing of both heavy-element and organic molecules and have been shown to sustain recognisable aggregation patterns [64-68]. It is noted that while attractive, such C=O··· π interactions contribute relative small energies of stabilisation to crystals in which they are formed, i.e. probably < 10 kJ mol⁻¹, based on DFT calculations [64-69]. The persistence of these interactions in the molecular packing of **1-5** is of interest. In the present study, parallel C=O··· π interactions provide structure-directing points of contact in the three-dimensional architectures of **1** and **5**, and provide supporting roles in the remaining crystals. In **2**, a role is found for the phenoxy-substituent in that C–Br··· π interactions are found, which, with C=O··· π interactions lead to a three-dimensional architecture. In **3**, where no specific role in the molecular packing is evident for the –CF₃ group, consistent with its disordered status, but π ··· π and C=O··· π interactions lead to a supramolecular layer. In **4**, C–H···O and C=O··· π interactions lead to a supramolecular layer with no specific role for the phenoxy-cyano group. In **5**, one of the nitro-O atoms participates in a C–H···O interaction. In summary, the study proves the prevalence of both C–H···O and C=O··· π interactions in the crystals of **1-5**.

A comparison between molecular and crystal characteristics for 1-5

A summary is presented in Table 4 of some of the key physiochemical properties for **1-5**, which were calculated with PLATON [59] and Crystal Explorer [70]. The data for the individual molecules in **1** are consistent with there being only minor differences between them. The same conclusion is reached for the two components of the disorder in the crystal of **3**. As anticipated, there is a systematic increase in volume for the molecules as the size of the phenoxy-substituent increases and this correlates with small but, discernible deviations from globularity, a measure of the globular characteristics of a molecule. In general, the higher the calculated density, the greater the molecular weight but, the packing efficiencies follow the trend **2-4** < **1** < **5**. This reflects the role upon the molecular packing exerted by the substituents in **2-4** and highlights the important role the nitro group plays in the crystal of **5**. Finally, the greater packing efficiency in **5** correlates with the greatest lattice energy across the series.

Tab. 4: Physiochemical properties of the **molecules in and for the crystals of 1-5.**

Property	1– first independent molecule	1– second independent molecule	2	3 – first disorder component	3 – second disorder component	4	5
Molecular							
Volume, V (Å ³)	288.22	290.58	318.57	338.63	338.67	317.53	312.85
Surface area, A (Å ²)	276.60	276.49	300.99	315.68	315.65	303.84	299.82
Globularity, <i>G</i>	0.763	0.767	0.749	0.744	0.744	0.741	0.743
Crystal							
Density (g cm ⁻¹)	1.406	–	1.679	1.532	–	1.411	1.536
Packing index (%)	71.5	–	70.7	70.2	70.2	70.8	73.6
Lattice energy (kJ mol ⁻¹)	-134.1	–	-132.6	-138.1	-138.8	-153.7	-164.8

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Hirshfeld surface analysis

The analysis of three-dimensional Hirshfeld surfaces and two-dimensional fingerprint plots provides an easy way of comparing intermolecular contacts relative to van der Waals radii through a red-white-blue colour scheme [70]. The contacts in red highlight intermolecular interactions with distances less than sum of van der Waal radii on the Hirshfeld surface mapped over d_{norm} and the blue colouration represents longer contacts; white is used to indicate contacts at the van der Waals separation. Crystal Explorer 17 [70] was used to generate Hirshfeld surfaces for **1-3** mapped over the calculated electrostatic potential (Figure 7) and d_{norm} (Figure 8). The electrostatic potentials were calculated using TONTO [71, 72] integrated in Crystal Explorer. The two-dimensional fingerprint plots are derived from the Hirshfeld surfaces by plotting the fraction of points on the surfaces as a function of (d_i , d_e), where d_e and d_i represent the distances from a point on the surface to the nearest atoms outside and inside, respectively. The points are coloured as a function of the number of surface points ranging from blue (relatively few points) through green (moderate) to red (highest fraction) [74]. Fingerprint plots can also be delineated into individual atom-atom contacts. In the present study, the analysis of the Hirshfeld surfaces calculated for the substituted phenoxy-1,4-naphthoquinones, **1-5**, was conducted in accord with recent work on organic compounds [72] and provide additional details on the supramolecular associations operating in the crystals.

The weak intermolecular interactions instrumental in the crystal of **1**, comprising two independent molecules, appear as the diminutive/faint-red spots on the Hirshfeld surfaces mapped over d_{norm} in Figures 10a and b for each independent molecule, respectively. Among the C-H \cdots O interactions summarised in Table 3, the phenoxy-C-H \cdots O(ketone) interactions are weaker compared to the naphthalene-C-H \cdots O(ketone) and phenoxy-C-H \cdots O(phenoxy) contacts, based on distance criteria, and this is vindicated as the faint-red spots on the surface due to the former while the latter contacts appear as bright-red spots. The Hirshfeld surfaces also reflect the importance of the C-H \cdots π contacts. Thus, the diminutive-red spots near the naphthalene-C13 and phenoxy-H12a atoms on the surfaces for the first and second independent molecules, respectively, represent more effective C-H \cdots π contacts than those resulting from the interacting naphthalene atoms of both the molecules given in Table 3, which are evident as the faint-red spots near the respective atoms in Figure 10. The presence of other short interatomic contacts listed in Table 5, calculated in Crystal Explorer [70], are also apparent as the faint-red spots in Figure 10. The donors and acceptors of intermolecular interactions in the crystal are also viewed as the blue and red regions, respectively, on the Hirshfeld surfaces mapped over the calculated electrostatic potential shown in Figure 11, and serve to highlight intra- and inter-molecular C-H \cdots O, C-H \cdots π and C=O \cdots π contacts for the independent molecules comprising **1**.

Tab. 5: Summary of short inter atomic contacts (Å) in the crystals of **1-5**.

Contact	Distance	Symmetry operation
1		
O1 \cdots C1a	3.116(4)	x, 1 + y, z
O1 \cdots C2a	3.155(4)	x, 1 + y, z
O1 \cdots C3	3.207(5)	x, 1 + y, z
C1 \cdots O1a	3.065(5)	x, y, z
C2 \cdots O1a	3.059(5)	x, y, z

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C9...O3	3.165(5)	$x, 1 + y, z$
O3a...H6	2.51	$\frac{1}{2} + x, -y, \frac{1}{2} + z$
C3...H12a	2.58	$-\frac{1}{2} + x, 1 - y, -\frac{1}{2} + z$
C9...H9a	2.76	x, y, z
C9a...H9	2.70	$x, -1 + y, z$
C10...H9a	2.66	x, y, z
C10a...H9	2.73	$x, -1 + y, z$
C13...H7	2.69	$1 + x, y, z$
H12...H13a	2.13	$-\frac{1}{2} + x, 1 - y, -\frac{1}{2} + z$

2

Br1...O3	3.080(3)	$\frac{1}{2} - x, 1 - y, -\frac{1}{2} + z$
O1...C1	3.087(5)	$\frac{1}{2} + x, \frac{1}{2} - y, 1 - z$
O1...C2	2.966(4)	$\frac{1}{2} + x, \frac{1}{2} - y, 1 - z$
O1...C5	3.183(5)	$1 + x, y, z$
O3...C2	3.110(4)	$-1 + x, y, z$
C8...C12	3.277(3)	$-\frac{1}{2} + x, \frac{1}{2} - y, 1 - z$
C8...H16	2.69	$2 - x, -\frac{1}{2} + y, \frac{3}{2} - z$
H9...H12	1.97	$\frac{1}{2} + x, \frac{1}{2} - y, 1 - z$

3

F2...F2	2.760(14)	$\frac{3}{2} - x, -\frac{5}{2} - y, \frac{1}{2} - z$
F3...F3	2.787(11)	$1 - x, y, \frac{1}{2} - z$
C3...C5	3.352(2)	$1 - x, 1 - y, 1 - z$
C4...C4	3.340(2)	$1 - x, 1 - y, 1 - z$
F1...H3	2.62	$x, -1 + y, z$
F2...H9	2.62	$x, -2 - y, -\frac{1}{2} + z$

4

O1...C1	3.0489(14)	$x, \frac{3}{2} - y, \frac{1}{2} + z$
O1...C2	3.1355(14)	$x, \frac{3}{2} - y, \frac{1}{2} + z$
O2...H16	2.53	$x, \frac{3}{2} - y, \frac{1}{2} + z$
C6...H12	2.67	$1 - x, 1 - y, 1 - z$
C9...H9	2.71	$x, \frac{3}{2} - y, -\frac{1}{2} + z$
C10...H9	2.68	$x, \frac{3}{2} - y, -\frac{1}{2} + z$
N1...H8	2.69	$1 - x, y, -1 + z$
N1...H13	2.73	$2 - x, 1 - y, -z$

5

O1...C2	3.1272(10)	$\frac{1}{2} - x, \frac{1}{2} + y, \frac{1}{2} - z$
O5...H8	2.50	$1 + x, y, z$
O5...N1	3.0546(16)	$\frac{3}{2} - x, -\frac{1}{2} + y, \frac{1}{2} + z$
O5...C14	3.1153(17)	$\frac{3}{2} - x, -\frac{1}{2} + y, \frac{1}{2} + z$
C3...H12	2.67	$x, -1 + y, z$
C4...H13	2.85	$1 - x, 1 - y, 1 - z$
H3...H12	2.17	$x, -1 + y, z$

Fig. 10: Different views of the Hirshfeld surface mapped over d_{norm} in the range -0.125 to +1.535 atomic units (au) for the (a) first independent molecule of **1** and (b) the second independent molecule of **1**.

Fig. 11: Different views of the Hirshfeld surface mapped over the calculated electrostatic potential in the range -0.068 to +0.039 au for the (a) first independent molecule of **1** and (b) the second independent molecule of **1**, highlighting intra- and inter-molecular C–H \cdots O, C–H \cdots π and C=O \cdots π contacts through black, red and yellow dotted lines, respectively.

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In addition to the intermolecular C=O \cdots π (cyclohexadiene, naphthalene-phenyl) contacts, the crystal of **2** also features significant naphthalene-phenyl-C8-H \cdots O3(ketone) and phenoxy-C13-Br1 \cdots π (cyclohexadiene) interactions, Table 3, as well as short interatomic Br1 \cdots O3 and H9 \cdots H12 contacts, Table 5, which are viewed as bright-red spots near the respective atoms on the Hirshfeld surfaces mapped over d_{norm} in Figure 12. The other short interatomic contacts, Table 5, representing weak interactions, are also evident as the faint-red spots on the surfaces of Figure 12. The donors and acceptors of intermolecular interactions in the crystal are also represented in the Hirshfeld surface mapped over the electrostatic potential in Figure 13.

Fig. 12: Different views of the Hirshfeld surface for **2** mapped over d_{norm} in the range -0.129 to +1.581 au.

Fig. 13: Different views of the Hirshfeld surface mapped over the calculated electrostatic potential in range -0.063 to +0.047 au for **2** highlighting intermolecular C-Br \cdots π and C=O \cdots π contacts through black and yellow dotted lines, respectively

The bright-red spots near the ketone-O3, naphthalene-H6 and phenoxy-H12 atoms on the Hirshfeld surfaces mapped over d_{norm} in Figure 14 for **3** highlight the C-H \cdots O interactions between these atoms, Table 3. The weak intermolecular C-H \cdots O interactions involving the phenoxy-C15-H15, C16-H16 and ketone-O1 atoms appear as the two groups of four faint-red spots surrounding the participating atoms. The characteristic-red spots near fluoride atoms of the -CF₃ group are indicative of short interatomic F \cdots F and F \cdots H/H \cdots F contacts as listed in Table 5 that occur in the interlayer region. The sequence of three faint-red spots near the naphthalene-C3, C4 and C5 atoms arise from short interatomic C \cdots C contacts arising from edge-to-edge $\pi\cdots\pi$ overlap between symmetry related naphthalene rings, Table 5. The C=O \cdots π and $\pi\cdots\pi$ stacking interactions involving cyclohexadiene and phenyl rings are highlighted in the views of the Hirshfeld surface mapped over the electrostatic potential in Figure 15.

Fig. 14: Different views of the Hirshfeld surface for **3** mapped over d_{norm} in the range -0.123 to +1.506 au.

Fig. 15: Different views of the Hirshfeld surface mapped over the calculated electrostatic potential in range -0.066 to +0.052 au for **3** highlighting intermolecular C=O \cdots π and $\pi\cdots\pi$ contacts through yellow and black dotted lines, respectively.

The bright-red spots near the naphthalene-H3 and ketone-O3 atoms on the Hirshfeld surface mapped over d_{norm} for **4** indicate the dominance of these intra-layer C-H \cdots O interactions on the packing, Figure 16. The pair of faint-red spots near the naphthalene-C9, C10 and H9 atoms represent short interatomic C \cdots H/H \cdots C contacts and reflect the presence of C-H \cdots π interactions involving these atoms, Table 5. Figure 17, a plot of the Hirshfeld surface mapped over the calculated electrostatic potential, illustrates the roles of the C-H \cdots O, C-H \cdots π and C=O \cdots π contacts in the molecular packing of **4**. From Figure 8b it can be discerned that the layer pack along the a-axis with the cyanophenyl groups facing each other. From the data

in Table 5, weak H \cdots N contacts serve to connect the layers, and highlighted by the red region about the cyano-nitrogen atom in Figure 17.

Fig. 16: Different views of the Hirshfeld surface for **4** mapped over d_{norm} in the range -0.125 to +1.804 au.

Fig. 17: Different views of the Hirshfeld surface mapped over the calculated electrostatic potential in range -0.074 to +0.054 au for **4** highlighting intermolecular C \cdots H \cdots O (yellow dotted lines), C \cdots H \cdots π and C=O \cdots π (black) contacts.

As with **4**, the crystal of **5** also features significant phenoxy-C16–H16 \cdots O1(ketone) interactions and these are viewed as bright-red spots on the Hirshfeld surface mapped over d_{norm} in Figure 18. The diminutive-red spots near the nitro-O5 and phenoxy-H15 atoms arise from the weak contact between these atoms, Table 3. The effect of other short interatomic contacts summarised in Table 4 on the packing of **5** is also evidenced from the faint-red spots near the respective atoms. The Hirshfeld surface mapped over the electrostatic potential in Figure 19 illustrates the dominant C \cdots H \cdots O (intra-layer) and C=O \cdots π (inter-layer) interactions.

Fig. 18: Different views of the Hirshfeld surface for **5** mapped over d_{norm} in the range -0.128 to +1.568 au.

Fig. 19: Different views of the Hirshfeld surface mapped over the calculated electrostatic potential in range ± 0.066 range for **5** highlighting intermolecular C \cdots H \cdots O and C=O \cdots π contacts through black dashed and yellow dotted lines, respectively.

The distinct intermolecular interactions instrumental in the molecular packing of **1-5** are evident from the shape of their overall two-dimensional fingerprint plots and in the fingerprint plots delineated [73] into H \cdots H, O \cdots H/H \cdots O, C \cdots H/H \cdots C and C \cdots O/O \cdots C contacts, shown in Figures 20a-e, and characterise the more significant surface contacts in these crystals; the percentage contributions from the different interatomic contacts are summarised in Table 6.

The short interatomic H \cdots H contacts noted in the crystals of **1** (both independent molecules) and **2** appear as the short single peaks at $d_e + d_i \sim 2.2$ Å in the respective delineated plots shown in Figures 20a-c. The presence of similar contacts in the crystal of **5** is reflected as the pair of small peaks at $d_e + d_i \sim 2.0$ Å in the plot, Figure 20f.

In the fingerprint plots delineated into O \cdots H/H \cdots O contacts for the two independent molecules of **1**, Figure 20a and b, the prominent naphthalene-C3a–H \cdots O3(ketone) interactions, i.e. occurring between the independent molecules, are represented as a pair of narrow spikes with the tips at $d_e + d_i \sim 2.3$ Å in the acceptor and donor regions for the first and second independent molecules, respectively. Similarly, the two pairs of short and overlapping peaks with tips at $d_e + d_i \sim 2.4$ Å in the donor and acceptor regions of the independent molecules indicate the phenoxy-C16–H \cdots O2(phenoxy) interactions, whereas the points corresponding to the other specified but, weaker C \cdots H \cdots O contacts are merged within the plot. The fingerprint plots delineated into O \cdots H/H \cdots O contacts for the crystals of **2-5**, Figures 20c-f, show a pair of more or less similar spikes with their tips at $d_e + d_i \sim 2.3$ Å

indicating the most dominant intermolecular C–H \cdots O3(ketone) interactions while the merged points are ascribed to other, less prominent intermolecular C–H \cdots O contacts.

The fingerprint plots delineated into C \cdots H/H \cdots C contacts for the two independent molecules of **1** in Figures 20a and b also exhibit distinctive features. The forceps-like tip at $d_e + d_i \sim 2.6$ Å in the acceptor region of the plot for the first molecule indicates a short interatomic H \cdots C contact involving the naphthalene-C3 and phenoxy-H2 atoms, Table 5. In each plot, the pair of forceps-like peaks at $d_e + d_i \sim 2.7$ Å, where for the first independent molecule the tip in the acceptor region is merged with the peak mentioned above, together with the characteristic wings in the plots are indicative of C–H \cdots π interactions. In addition, the pair of forceps-like peaks at $d_e + d_i \sim 2.7$ Å evident in the plot for first molecule also indicates the presence of short interatomic C \cdots H/H \cdots C contacts between phenoxy-C13 and naphthalene-H7, Table 5. The short interatomic C \cdots H/H \cdots C contacts in the crystals of **2** and **5**, as summarised in Table 5, are also viewed as a pair of forceps-like tips at $d_e + d_i \sim 2.7$ Å and ~ 2.8 Å in their respective delineated plots of Figure 20c and f. The intermolecular C–H \cdots π contact involving naphthalene residues in **4** are viewed as the pair of broad tips characterising short interatomic C \cdots H/H \cdots C contacts, Table 4. In the two-dimensional fingerprint plots for the crystal of **4**, it is interesting to note that some of the carbon and hydrogen atoms are at interatomic separations greater than $d_e + d_i \sim 5.6$ Å, which result in reduced percentage contributions from these contacts than might be expected, in agreement with the values in Table 5.

The intermolecular C=O \cdots π contacts, Table 3, along with short interatomic C \cdots O/O \cdots C contacts, Table 5, are characterised from the different percentage contributions to their Hirshfeld surfaces, Table 6, and the different shape in their fingerprint plots delineated into C \cdots O/O \cdots C contacts, Figures 20a-f.

Fig. 20: The overall two-dimensional fingerprint plot and those delineated into H···H, O···H/H···O, C···H/H···C and C···O/O···C contacts for (a) **1**, first independent molecule, (b) **1**, second independent molecule, (c) **2**, (d) **3**, (e) **4** and (f) **5**.

Fig. 21: Fingerprint plots delineated into (a) Br···O/O···Br and (b) Br···C/C···Br contacts for **2**, (c) F···F, (d) F···H/H···F and (e) C···C contacts for **3**, (f) N···O/O···N contacts for **5**.

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Tab. 6: Percentage contributions from the different intermolecular contacts to the Hirshfeld surfaces of **1-5**.^a

Contact	1 – first independent molecule	1 – second independent molecule	2	3	4	5
	<i>Y</i> = H	<i>Y</i> = H	<i>Y</i> = Br	<i>Y</i> = CF ₃	<i>Y</i> = CN	<i>Y</i> = NO ₂
H··H	35.3	34.1	32.5	17.7	18.3	21.5
O··H/H··O	20.7	21.3	9.3	20.8	17.1	31.5
C··H/H··C	31.9	32.6	20.7	13.6	34.3	21.9
C··C	1.6	1.6	1.5	9.5	1.4	2.3
C··O/O··C	9.3	9.0	13.1	5.1	10.6	15.3
O··O	1.2	1.4	2.9	0.3	1.3	4.6
Y··Y	-	-	0.0	2.5	0.5	0.0
Y··H/H··Y	-	-	11.0	26.1	15.1	1.9
Y··C/C··Y	-	-	5.7	2.3	1.1	0.0
Y··O/O··Y	-	-	3.4	2.2	0.0	1.1

^a The listed values are the average determined for each of the disorder components of the CF₃ group.

In addition to above intermolecular interactions in the crystals of **1-5**, additional contacts are evident in the crystals directly related to the nature of phenoxy-bound substituent. Thus, in the crystal of **2**, the bromide substituent exerts a significant influence upon the molecular packing, including the formation of short interatomic Br \cdots O contacts, Table 5, and C–Br \cdots π contacts, Table 3. These are evident as a pair of thin spikes at $d_e + d_i \sim 3.0$ Å and a pair of saw-tooth tips at $d_e + d_i \sim 3.9$ Å from the fingerprint plots delineated into Br \cdots O/O \cdots Br and Br \cdots C/C \cdots Br contacts, shown, respectively, in Figures 21a and b.

In the same way, the presence of short interatomic F \cdots F and F \cdots H/H \cdots F contacts, Table 5, in the molecular packing of **3** are evident from their respective delineated fingerprint plots, Figure 21c and d, where they appear as a thin spike with the tip at $d_e + d_i \sim 2.8$ Å and as a pair of spikes at $d_e + d_i \sim 2.6$ Å, respectively. The significant contribution of 9.5 % from C \cdots C contacts to the Hirshfeld surfaces of **3**, Table 5, and an arrow-shaped distribution of points in the fingerprint plot corresponding to these contacts in Figure 20e result from $\pi\cdots\pi$ stacking interactions, Table 3. The percentage contribution arising from different interatomic contacts from the second disorder component of the disordered –CF₃ group to the Hirshfeld surfaces of **3** show minor differences as summarised in Table 5 and makes no contribution to the short interatomic F \cdots F and F \cdots H/H \cdots F contacts. The small contribution of 1.1 % from N \cdots O/O \cdots N contacts to the Hirshfeld surface of **5** indicates the presence of short interatomic N \cdots O contacts between nitro-N1 and O5 atoms, Table 5, which is viewed as a pair of conical shaped tips at $d_e + d_i \sim 3.0$ Å in Figure 21f.

The contributions from other interatomic contacts summarised in Table 6 have negligible influence on the molecular packing of **1-5**.

Conclusions

X-ray crystallography on the title substituted (phenoxy)-1,4-naphthoquinones, **1** (H), **2** (3-Br), **3** (3-CF₃), **4** (4-CN) and **5** (4-NO₂), adopt very similar molecular structures with the main differences related to the orientations of the pendant phenoxy residues to the planar, 10-membered fused ring systems. In the molecular packing, C–H \cdots O interactions is prevalent and lead to three-dimensional architectures for **1** and **5**. **In addition**, each crystal also features C=O \cdots π interactions. In bromo-substituted **2**, these along C–Br \cdots π interactions stabilise a three-dimensional architecture. Two-dimensional layers are noted in **3** and **4**. The molecular packing was also explored by a Hirshfeld surface analysis which showed notable influences exerted by the substituents in **2-5**. Notably, connections between the layer motifs in **3** were ascribed to weak H \cdots F and F \cdots F contacts, while the inter-layer in the crystal was stabilised by weak H \cdots N interactions. **Reflecting the presence of three potential oxygen acceptors and in the absence of conventional hydrogen atom donors, the common points of contact between molecules in the crystals of 1-5 are of the type C–H \cdots O and C=O \cdots π . The two substantive conclusions of the study relate i) to the clear influence of the remote substituents on the molecular packing and ii) the prevalence of C=O \cdots π interactions contacts despite their inherently weak nature.**

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References

- [1] J. Verrax, R. Beck, N. Dejeans, C. Glorieux, B. Sid, R. C. Pedrosa, J. Benites, D. Vasquez, J. A. Valderrama, P. B. Calderon, *Anti-Cancer Agents Med. Chem.* **2011**, *11*, 213.

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- [2] B. Zhao, Y. Yang, X. Wang, Z. Chong, R. Yin, S.-H. Song, C. Zhao, C. Li, H. Huang, B.-F. Sun, D. Wu, K.-X. Jin, M. Song, B.-Z. Zhu, G. Jiang, J. M. Rendtlew Danielsen, G.-L. Xu, Y.-G. Yang, H. Wang, *Nucleic Acids Res.* **2014**, *42*, 1593.
- [3] I. Pochorovski, C. Boudon, J.-P. Gisselbrecht, M.-O. Ebert, W. B. Schweizer, F. Diederich, *Angew. Chem., Int. Ed.* **2012**, *51*, 262.
- [4] I. Pochorovski, M.-O. Ebert, J.-P. Gisselbrecht, C. Boudon, W. B. Schweizer, F. Diederich, *J. Am. Chem. Soc.* **2012**, *134*, 14702.
- [5] P. I. T. Thomson, V. L. Camus, Y. Hu, C. J. Campbell, *Anal. Chem.* **2015**, *87*, 4719.
- [6] A. Jaffe, A. Saldivar Valdes, H. I. Karunadasa, *Chem. Mater.* **2015**, *27*, 3568.
- [7] J. Ma, D. He, W. Tang, P. Kovalsky, C. He, C. Zhang, T. D. Waite, *Environ. Sci. Technol.* **2016**, *50*, 13495.
- [8] K. Nueangnoraj, T. Tomai, H. Nishihara, T. Kyotani, I. Honma, *Carbon* **2016**, *107*, 831.
- [9] J. Milic, M. Zalibera, I. Pochorovski, N. Trapp, J. Nomrowski, D. Neshchadin, L. Ruhlmann, C. Boudon, O. S. Wenger, A. Savitsky, W. Lubitz, G. Gescheidt, F. Diederich, *J. Phys. Chem. Lett.* **2016**, *7*, 2470.
- [10] J. Milic, M. Zalibera, D. Talaat, J. Nomrowski, N. Trapp, L. Ruhlmann, C. Boudon, O. S. Wenger, A. Savitsky, W. Lubitz, F. Diederich, *Chem. - Eur. J.* **2018**, *24*, 1431.
- [11] Y. F. Qiao, K. Takeya, H. Itokawa, Y. Iitaka, *Chem. Pharm. Bull.* **1990**, *38*, 2896-2898.
- [12] K. O. Eyong, G. N. Folefoc, V. Kuete, V. P. Beng, K. Krohn, H. Hussain, A. E. Nkengfack, M. Saefel, S. R. Sarite, A. Hoerauf, *Phytochemistry* **2006**, *67*, 605.
- [13] V. Kuete, S. Alibert-Franco, K. O. Eyong, B. Ngameni, G. N. Folefoc, J. R. Nguemeving, J. G. Tangmouo, G. W. Fotso, J. Komguem, B. M. W. Ouahou, J. M. Bolla, J. Chevalier, B. T. Ngadjui, A. E. Nkengfack, J. M. Pages, *Int. J. Antimicrob. Agents* **2011**, *37*, 156.
- [14] K. O. Eyong, H. L. Ketsemen, S. Y. Ghansenyuy, G. N. Folefoc, *Med. Chem. Res.* **2015**, *24*, 965.
- [15] Z. Wang, S.-M. Zhao, Y.-Y. Hu, L. Feng, L.-M. Zhao, Y.-T. Di, N.-H. Tan, *Phytochemistry* **2018**, *145*, 153.
- [16] S. Akhter, S. R. Rony, M. A. Al-Mansur, C. M. Hasan, K. M. Rahman, M. H. Sohrab, *Chem. Nat. Compd.* **2018**, *54*, 26.
- [17] F. Lizzi, G. Veronesi, F. Belluti, C. Bergamini, A. Lopez-Sanchez, M. Kaiser, R. Brun, R. L. Krauth-Siegel, D. G. Hall, L. Rivas, M. L. Bolognesi, *J. Med. Chem.* **2012**, *55*, 10490.
- [18] M. L. Bolognesi, F. Lizzi, R. Perozzo, R. Brun, A. Cavalli, *Bioorg. Med. Chem. Lett.* **2008**, *18*, 2272.
- [19] K. G. Byler, M. Brito-Arias, A. Marquez-Navarro, B. Nogueta-Torres, L. G. Torres-Bustillos, K. Martinez-Mayorga, *Bioorg. Med. Chem.* **2012**, *20*, 2587.
- [20] S. Pieretti, J. R. Haanstra, M. Mazet, R. Perozzo, C. Bergamini, F. Prati, R. Fato, G. Lenaz, G. Capranico, R. Brun, B. M. Bakker, P. A. M. Michels, L. Scapozza, M. L. Bolognesi, A. Cavalli, *PLoS Neglected Trop. Dis.* **2013**, *7*, e2012.
- [21] F. Belluti, E. Uliassi, G. Veronesi, C. Bergamini, M. Kaiser, R. Brun, A. Viola, R. Fato, P. A. M. Michels, R. L. Krauth-Siegel, A. Cavalli, M. L. Bolognesi, *ChemMedChem* **2014**, *9*, 371.
- [22] K. Vazquez, C. Espinosa-Bustos, J. Soto-Delgado, R. A. Tapia, J. Varela, E. Birriel, R. Segura, J. Pizarro, H. Cerecetto, M. Gonzalez, M. Paulino, C. O. Salas, *RSC Adv.* **2015**, *5*, 65153.
- [23] F. Prati; C. Bergamini; M. T. Molina; F. Falchi; A. Cavalli; M. Kaiser; R. Brun; R. Fato; M. L. Bolognesi *J. Med. Chem.* **2015**, *58*, 6422.
- [24] S. Bruno, E. Uliassi, M. Zaffagnini, F. Prati, C. Bergamini, R. Amorati, G. Paredi, M. Margiotta, P. Conti, M. P. Costi, M. Kaiser, A. Cavalli, R. Fato, M. L. Bolognesi, *Chem. Biol. Drug Des.* **2017**, *90*, 225.
- [25] R. P. Verma, *Bioorg. Med. Chem.* **2005**, *13*, 1059.
- [26] J. M. Miguel del Corral, M. A. Castro, M. Gordaliza, M. L. Martin, A. M. Gamito, C. Cuevas, A. San Feliciano, *Bioorg. Med. Chem.* **2006**, *14*, 2816.
- [27] N. Kotoku, K. Higashimoto, M. Kurioka, M. Arai, A. Fukuda, Y. Sumii, Y. Sowa, T. Sakai, M. Kobayashi, *Bioorg. Med. Chem. Lett.* **2014**, *24*, 3389.
- [28] P. Zizkova, D. Blaskovic, M. Majekova, L. u. Svorc, L. Rackova, L. u. Ratkowska, M. Veverka, L. u. Horakova, *Mol. Cell. Biochem.* **2014**, *386*, 1.

- [29] S. Enayat, M. Seyma Ceyhan, B. Taskoparan, M. Stefek, S. Banerjee, *Arch. Biochem. Biophys.* **2016**, *596*, 84.
- [30] A. Voskiene, B. Sapijanskaite, V. Mickevicius, K. Kantminiene, M. Stasevyich, O. Komarovska-Porokhnyavets, R. Musyanovych, V. Novikov, *Monatsh. Chem.* **2011**, *142*, 529.
- [31] A. Voskiene, B. Sapijanskaite, V. Mickevicius, I. Jonuskiene, M. Stasevyich, O. Komarovska-Porokhnyavets, R. Musyanovych, V. Novikov, *Molecules* **2012**, *17*, 14434.
- [32] E. Leyva, L. I. Lopez, R. F. G. de la Cruz, C. G. Espinosa-Gonzalez, *Res. Chem. Intermed.* **2017**, *43*, 1813.
- [33] N. C. de Lucas, R. J. Correa, S. J. Garden, G. Santos, R. Rodrigues, C. E. M. Carvalho, S. B. Ferreira, J. C. Netto-Ferreira, V. F. Ferreira, P. Miro, M. L. Marin, M. A. Miranda, *Photochem. Photobiol. Sci.* **2012**, *11*, 1201.
- [34] N. C. de Lucas, C. P. Ruis, R. I. Teixeira, L. L. Marcal, S. J. Garden, R. J. Correa, S. Ferreira, J. C. Netto-Ferreira, V. F. Ferreira, *J. Photochem. Photobiol., A* **2013**, *276*, 16.
- [35] C. de S. Lisboa, N. C. de Lucas, S. J. Garden, *Dyes Pigm.* **2016**, *134*, 618.
- [36] R. C. de S. Oliveira, R. J. Correa, R. S. P. Teixeira, D. D. Queiroz, R. de S. Souza, S. J. Garden, N. C. de Lucas, M. D. Pereira, J. S. Bello Forero, E. C. Romani, E. S. Ribeiro, *J. Photochem. Photobiol., B* **2016**, *165*, 1.
- [37] M. D. L. Tonin, S. J. Garden, M. M. Jotani, S. M. S. V. Wardell, J. L. Wardell, E. R. T. Tiekink, *Acta Crystallogr. E* **2017**, *73*, 738.
- [38] R. I. Teixeira, I. C. dos Santos, S. J. Garden, P. F. Carneiro, V. F. Ferreira, N. C. de Lucas, *ChemistrySelect* **2017**, *2*, 11732.
- [39] E. R. T. Tiekink, *Chem. Commun.* **2014**, *50*, 11079.
- [40] M. Paul, S. Chakraborty, G.R. Desiraju, *J. Am. Chem. Soc.* **2018**, *140*, 2309.
- [41] C. R. Kaiser, K. C. Pais, M. V. N. De Souza, J. L. Wardell, S. M. S. V. Wardell and E. R. T. Tiekink, *CrystEngComm* **2009**, *11*, 1133.
- [42] E. Gognon, S. D. Halperin, V. Metivaud, K. E. Maly, J. D. Wuest, *J. Org. Chem.* **2010**, *75*, 399.
- [43] R. Montis, M. B. Hursthouse, *CrystEngComm* **2012**, *14*, 5242.
- [44] A. K. Jordão, V. F. Ferreira, A. C. Cunha, J. L. Wardell, S. M. S. V. Wardell and E. R. T. Tiekink, *CrystEngComm*, **2012**, *14*, 6534-6539.
- [45] A. C. Cunha, V. F. Ferreira, A. K. Jordão, M. C. B. V. de Souza, S. M. S. V. Wardell, J. L. Wardell, P. A. Tan, R. P. A. Bettens, S. K. Seth and E. R. T. Tiekink, *CrystEngComm* **2013**, *15*, 4917.
- [46] I. U. Khan, H. Mubashar-u-Rehman, Ejaz, W. T. A. Harrison, *Z. Kristallogr. – Cryst. Mat.* **2014**, *229*, 53.
- [47] K. B. Ghiassi, X. B. Powers, J. Wescott, A. L. Balch, M. M. Olmstead, *Cryst. Growth Des.* **2016**, *16*, 447.
- [48] K. B. Ghiassi, A. J. Guenther, N. D. Redeker, J. A. Boatz, B. G. Harvey, M. C. Davis, A. P. Chafin, T. J. Groshens, *Cryst. Growth Des.* **2018**, *18*, 1030.
- [49] S. T. Nguyen, T. L. Ellington, K. E. Allen, J. D. Gorden, A. L. Rheingold, G. S. Tschumper, N. I. Hammer, D. L. Watkin, *Cryst. Growth Des.* **2018**, *18*, 3244.
- [50] P. Venkatesan, M. Cerón, S. Thamocharan, F. Robles, M. J. Percino, *CrystEngComm* **2018**, *20*, 2681.
- [51] L. Checińska, A. Józwiak, M. Ciechańska, C. Paulmann, J. J. Holstein, B. Dittrich, M. Małecka, *Z. Kristallogr. – Cryst. Mat.* **2018**, *233*, 675.
- [52] M. A. Spackman, *Z. Kristallogr. – Cryst. Mat.* **2018**, *233*, 641.
- [53] L. R. Gomes, J. N. Low, A. B. Turner, G. J. R. Watson, T. C. Baddeley, J. L. Wardell, *Z. Kristallogr. – Cryst. Mat.* **2018**, *233*, DOI: <https://doi.org/10.1515/zkri-2017-2144>.
- [54] M. L. Bolognesi, F. Lizzi, R. Perozzo, R. Brun, A. Cavalli, *Bioorg. Med. Chem. Lett.* **2008**, *18*, 2272.
- [55] CrysAlis PRO. Rigaku Oxford Diffraction, Yarnton, Oxfordshire, England, **2015**.
- [56] G. M. Sheldrick, *Acta Crystallogr. A* **2008**, *64*, 112
- [57] G. M. Sheldrick, *Acta Crystallogr. C* **2015**, *71*, 3.
- [58] L. J. Farrugia, *J. Appl. Crystallogr.* **2012**, *45*, 849.
- [59] A. L. Spek, *J. Appl. Crystallogr.* **2003**, *36*, 7.
- [60] DIAMOND, Visual Crystal Structure Information System, Version 3.1, CRYSTAL IMPACT, Postfach 1251, D-53002, **2006**.
- [61] J. Gans, D. Shalloway, *J. Mol. Graph. Model.* **2001**, *19*, 557.

- [62] C. R. Groom, I. J. Bruno, M. P. Lightfoot, S. C. Ward, *Acta Crystallogr. B* **2016**, *72*, 171.
- [63] Yu. A. Simonov, A. A. Dvorkin, T. I. Malinovskii, L. N. Markovskii, V. I. Kal'chenko, A. P. Kartoflitskaya, V. T. Kolesnikov, *Crystallogr. Rep.* **1986**, *31*, 1120.
- [64] S. R. Choudhury, P. Gamez, A. Robertazzi, C.-Y. Chen, H. M. Lee, S. Mukhopadhyay, *Cryst. Growth Des.* **2008**, *8*, 3773.
- [65] J. Zukerman-Schpector, I. Haiduc, E. R. T. Tiekink, *Chem. Commun.* **2011**, *47*, 12682.
- [66] J. Zukerman-Schpector, I. Haiduc, E. R. T. Tiekink, *Adv. Organomet. Chem.* **2012**, *60*, 49.
- [67] J. Zukerman-Schpector, E. R. T. Tiekink, *CrystEngComm* **2014**, *16*, 6398.
- [68] C. Murcia-Garcia, A. Bauzá, G. Schnakenburg, A. Frontera, R. Streubel, *CrystEngComm* **2015**, *17*, 1769.
- [69] S. K. Singh and A. Das, *Phys. Chem. Chem. Phys.* **2015**, *17*, 9596.
- [70] M. J. Turner, J. J. McKinnon, S. K. Wolff, D. J. Grimwood, P. R. Spackman, D. Jayatilaka and M. A. Spackman, CrystalExplorer17, University of Western Australia, **2017**.
- [71] M. A. Spackman, J. J. McKinnon, D. Jayatilaka, *CrystEngComm* **2008**, *10*, 377.
- [72] D. Jayatilaka, D. J. Grimwood, A. Lee, A. Lemay, A. J. Russel, C. Taylo, S. K. Wolff, C. Chenai, A. Whitton, TONTO – A System for Computational Chemistry, **2005**.
- [73] A. L. Rohl, M. Moret, W. Kaminsky, K. Claborn, J. J. Mackinnon, B. Kahr, *Cryst. Growth Des.* **2008**, *8*, 4517.
- [74] F. P. A. Fabbiani, D. R. Allan, S. Parsons and C. R. Pulham, *CrystEngComm* **2005**, *7*, 179.
- [75] J. J. McKinnon, D. Jayatilaka, M. A. Spackman, *Chem. Commun.* **2007**, 3814.
- [76] M. M. Jotani, J. L. Wardell, E. R. T. Tiekink, *Z. Kristallogr. – Cryst. Mat.* <https://doi.org/10.1515/zkri-2018-2101>