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**Electronic Supplementary Information (ESI)** 

# Hydrogen-Atom and Oxygen-Atom Transfer Reactivities of Iron(IV)-Oxo Complexes of Quinoline-Substituted Pentadentate Ligands

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Compound	1·BF <sub>4</sub>	2•ClO <sub>4</sub> •(C <sub>6</sub> H <sub>6</sub> ) <sub>3.5</sub>	3•(ClO <sub>4</sub> ) <sub>2</sub>	4•(OTf) <sub>2</sub>	6•(BF <sub>4</sub> ) <sub>2</sub>	8•H <sub>2</sub> O	5
Empirical formula	FeC <sub>31</sub> H <sub>25</sub> F <sub>5</sub> BN <sub>5</sub>	C <sub>52</sub> H <sub>46</sub> Cl <sub>2</sub> FeN <sub>5</sub> O <sub>4</sub>	C <sub>33</sub> H <sub>28</sub> Cl <sub>2</sub> FeN <sub>6</sub> O <sub>8</sub>	$C_{33}H_{31}F_6FeN_5O_9S_2$	C <sub>31.4</sub> H <sub>29.2</sub> B <sub>2</sub> F <sub>8</sub> FeN <sub>7</sub>	C <sub>27</sub> H <sub>23</sub> FeCl <sub>2</sub> N <sub>5</sub> O <sub>9</sub> . (H <sub>2</sub> O)	$C_{138}H_{135}N_{21}Fe_4Cl_8O_{44}$
Temperature	293 K	100 K	100.5 K	120 K	100(2) K	130 K	120(2) K
Formula weight	542.41	931.69	763.36	875.60	734.09	706.27	3298.66
Crystal system	Monoclinic	Triclinic	Triclinic	Monoclinic	Monoclinic	Monoclinic	Monoclinic
Space group	C2/c	P-1	P-1	$P2_{I}/c$	$P2_l/n$	$P2_{I}/n$	P2/c
a, Å	23.299(3)	10.045(2)	11.758(2)	13.0414(10)	10.6861(2)	12.4606(13)	27.7862(19)
b, Å	13.0291(12)	15.048(4)	11.780(3)	13.1870(9)	15.5556(3)	17.2148(19)	10.3486(4)
<i>c</i> , Å	23.720(3)	15.943(4)	13.236(3)	21.1873(19)	21.2745(4)	13.1304(13)	28.723(2)
α, deg	90.00	74.903(7)	78.686(7)	90	90.00	90	90.00
$\beta$ , deg	115.782(16)	85.254(7)	74.909(7)	94.150(8)	96.524(2)	99.235(4)	117.928(10)
γ, deg	90.00	74.212(7)	66.246(7)	90	90.00	90	90.00
Volume, Å <sup>3</sup>	6483.79	2238.8(9)	1611.4(6)	3634.2(5)	3513.53(12)	2780.1(5)	7297.3(10)
Z	8	2	2	4	4	1	2
$D_{\text{calcd.}}, \text{Mg/m}^3$	1.111	1.382	1.573	1.60	1.388	1.687	1.501
$\mu$ Mo-K $\alpha$ , mm <sup>-1</sup>	0.495	0.509	0.698	5.230	0.505	0.805	0.628
F(000)	2248	970	785.7	1792	1498	1448	3404
$\theta$ range, deg	2.94-28.90	2.384-25.027	2.247-24.738	3.398-77.031	1.927- 30.871	2.459 - 25.065	2.974 - 25.349
Reflections collected	21164	16557	13670	23307	19807	20724	28565
Reflections unique	7365	7561	5405	7632	9919	4905	13328
R(int)	0.1039	0.1171	0.0736	0.0956	0.0287	0.1051	0.0534
Data $(I \ge 2\sigma(I))$	2838	7561	5405	7632	9919	4905	13328
Parameters refined	343	577	452	512	470	415	1018
Goodness-of-fit on $F^2$	0.883	1.024	1.031	1.020	1.028	1.291	1.020
$R_{I}[I > 2\sigma(I)]$	0.0721	0.0859	0.0913	0.0685	0.0580	0.0928	0.0845
wR <sub>2</sub>	0.1524	0.2007	0.2433	0.1652	0.1592	0.2150	0.2081
CCDC number	2113914	2113532	2113531	2113533	2113534	2045257	2113535

## $\label{eq:table_state} Table \ S1. \ Crystallographic \ data \ for \ complexes \ 1, \ 2, \ 3, \ 4, \ 6, \ 8 \ \text{and} \ [\{Fe^{III}(L2-Qn)(OH_2)\}_2(\mu-O)](ClO_4)_4 \ (5).$

# Synthesis and structural characterization of the ferric oxo-bridged dinuclear complex [{Fe<sup>III</sup>(L2-Qn)(OH<sub>2</sub>)}<sub>2</sub>( $\mu$ -O)](ClO<sub>4</sub>)<sub>4</sub>(5)

A solution of L2-Qn (100 mg, 0.214 mmol) was combined with a solution of  $Fe(ClO_4)_2 \cdot xH_2O$  (55 mg, 0.214 mmol) in 5 mL of acetonitrile. The resultant mixture was allowed to stir for 3 h at room temperature and the dark-red reaction mixture was concentrated to ~2 mL upon slow evaporation under ambient air. The resulting concentrated acetonitrile solution was placed into an ethyl acetate bath for slow diffusion and stored for seven days to obtain single crystals suitable for X-ray crystallographic analysis. The isolated dark-red crystals were found to correspond to the Fe(III) oxo-bridged dinuclear complex **5**. Yield: 80 mg (25%).

### Crystal and molecular structure of $[{Fe^{III}(L2-Qn)(OH_2)}_2(\mu-O)](ClO_4)_4(5)$

Single crystals of 5 were obtained through vapour diffusion of ethyl acetate into an acetonitrile solution yielded dark red crystals suitable for X-ray diffraction. Relevant crystallographic data for this ferric oxobridged dinuclear complex is summarized in Table S1 and selected bond lengths and angles are listed in Table S2. The ferric oxo-bridged dinuclear complex 5 crystallizes in the monoclinic space group P2/c. Two independent cations [{Fe(L2-Qn)(OH<sub>2</sub>)}<sub>2</sub>( $\mu$ -O)]<sup>4+</sup> are present in the asymmetric unit, one of them is shown Figure S1. The dinuclear molecular structure (Figure S1) shows that the iron(II) ion adopts a distorted octahedral coordination sphere with four positions occupied by the heterocyclic nitrogen donors of the pentadentate ligand (N1, N2, N3 and N4) and one bridging oxygen atom as well as one terminal labile water molecule in the axial position. The fifth heterocyclic nitrogen donor of quinoline was not coordinated to the iron centre due to the long distance (Fe1-N2 3.656(5) Å). Bond distances in the equatorial and axial planes are differ from those observed for the mononuclear iron(II) complexes of L2-**On** (Table S2) The central amine nitrogen (N2) of the ligand backbone is coordinated *trans* to the bridging oxygen atom (O1) while Fe1-N2 bond lengths 2.287(5) Å is considerable longer due to strong trans influence of the bridging oxo moiety (O1) and similarly longer Fe1-N3 bond lengths 2.200(4) Å due to trans influence of the axial water ligand. The other distances are quite similar, ranging from 2.140(4) (Fe1-N4) to 2.156(4) Å (Fe1-N1).



**Figure S1**. A Mercury plot of the X-ray structure of ferric oxo-bridged dinuclear complex (5) shown with 50% probability ellipsoids, all hydrogen atoms and counter ions are omitted for clarity.

#### *X-ray structure determination*

The crystals of **5** was immersed in cryo-oil, mounted in a MiTeGen loop, and measured at a temperature of 120 K on a Bruker Kappa Apex II or on a Rigaku Oxford Diffraction Supernova diffractometer using Mo K $\alpha$  ( $\lambda = 0.71073$ ) radiation. The *CrysAlisPro*<sup>1</sup> program package was used for cell refinements and data reduction. Multi-scan absorption correction (*CrysAlisPro*<sup>1</sup>) was applied to the intensities before structure solutions. The structure was solved by charge flipping method using the *SUPERFLIP*<sup>2</sup> software or by using direct methods and the *SHELXT*<sup>3</sup> program. Structural refinements were carried out using *SHELXL*.<sup>3</sup>

Fe(1)-O(1)	1.7893(8)
Fe(1)-O(2)	2.013(3)
Fe(1)-N(4)	2.140(4)
Fe(1)-N(1)	2.156(4)
Fe(1)-N(3)	2.200(4)
Fe(1)-N(2)	2.287(5)
O(1)-Fe(1)#1	1.7894(8)
Fe(1B)-O(1B)	1.7845(10)
Fe(1B)-O(2B)	2.016(4)
Fe(1B)-N(4B)	2.155(4)
Fe(1B)-N(3B)	2.168(5)
Fe(1B)-N(1B)	2.209(5)
Fe(1B)-N(2B)	2.265(6)
O(1B)-Fe(1B)#2	1.7844(10)

**Table S2**. Selected bond lengths [Å] and angles [°] for  $[{(2PyN2Q)Fe}_2(\mu-O)](ClO_4)_4$ 

Symmetry transformations used to generate equivalent atoms: #1 -x+1,y,-z+1/2 #2 -x,y,-z+1/2



Figure S2. Variable Temperature <sup>1</sup>H NMR spectra (500 MHz, 295 K) of complex 3 in CD<sub>3</sub>CN.



Figure S3. UV-vis spectrum of complex 6 (0.3 mM) in acetonitrile at 298 K.



**Figure S4. (a, above)** The variable temperature <sup>1</sup>H NMR spectrum of diastereotopic protons of  $[Fe^{II}(L1-Qn)(CH_3CN)](ClO_4)_2$  (6·ClO<sub>4</sub>) from 298 K (bottom) to 238 K (top) (b, below) Temperaturedependent evolution of the <sup>1</sup>H NMR spectrum of diastereotopic protons of 6 at 298 K (A), 283 K (B), 273 K (C), 263 °C (D), 253 °C (E), 243 °C (F), 233 K (G).



Fig. S4(b)



Figure S5. Zero-field Mössbauer spectrum of the solid sample of complex 6 at 293 K.

## Preparation and characterization of [Fe<sup>IV</sup>(O)(L2-Qn)]<sup>2+</sup> (7)

Complex **3** was reacted with excess (5 equiv) solid IBX ester (isopropyl 2-iodoxybenzoate ester) in acetonitrile at room temperature to form  $[Fe^{IV}(O)(L2-Qn)]^{2+}$  (7). Formation of 7 occurred instantaneously at room temperature and was indicated by the appearance of an absorption band at  $\lambda_{max} = 770$  nm (Figure 5), which is characteristic for ligand field (d-d) transitions of the iron(IV) ion in Fe<sup>IV</sup>=O species<sup>4</sup>,<sup>5</sup> and constitutes a measure of the strength of the equatorial ligand field. By that measure, the ligand field is considerably weakened in comparison with the parent  $[Fe^{IV}(O)(N4Py)]^{2+}$  complex, for which this transition occurs at 696 nm.<sup>6</sup> The room temperature decay profile of 7 shows that its half-life is 29 min (Figure S6), which may be compared to that of  $[Fe^{IV}(O)(N4Py)]^{2+}$ , which is 60 h.



**Figure S6.** Formation of **7** upon treatment of **3** (0.5 mM) with IBX-ester (2.5 mM) in acetonitrile at 298 K; Inset: time trace of the decay of 770 nm band.



Figure S7. <sup>1</sup>H-NMR (500 MHz) spectrum of complex  $[Fe^{IV}(O)(L1-Qn)]^{2+}$  8 in CD<sub>3</sub>CN at 298 K.

#### Reactivity studies of [Fe<sup>IV</sup>(O)(L2-Qn)]<sup>2+</sup>(7)

#### Oxygen atom transfer (OAT) reactions – oxidation of thioethers and alkenes

The initial investigation of the OAT capacity of 7 involved oxidation of thioanisole. This confirmed the results previously obtained for the same substrate.<sup>7,8</sup> Involvement of the Fe<sup>IV</sup>=O species was established by carrying out the catalytic oxidation reactions in the presence of <sup>18</sup>O-labeled water (H<sub>2</sub><sup>18</sup>O). Upon completion of the reaction, GC-MS analysis of the reaction mixture revealed the presence of signals corresponding to PhS(=O)CH<sub>3</sub> (*m/z* 140) and PhS(=<sup>18</sup>O)CH<sub>3</sub> (*m/z* 142) (Figure S8a). An incorporation of 47% <sup>18</sup>O into PhS(O)CH<sub>3</sub> clearly demonstrates the presence of an Fe<sup>IV</sup>=O species in the OAT reaction, as it is established that high-valent iron-oxo complexes easily undergo exchange of their oxygen with <sup>18</sup>O-labeled water even before oxo transfer to organic substrates.<sup>9,10</sup> Using a variation of *para*-substituted thioanisoles as substrates (*cf.* Figure S8b), a Hammett plot was created by plotting the logarithm of relative observed pseudo first-order rate constants for the p-substituted thioanisole against corresponding substituent constant ( $\sigma$ ) values. A linear correlation was found with  $\rho = -1.07$ , indicating the electrophilic nature of 7 (Figure S8b). Maiti and computational means; the thorough computational study indicates the initial formation of an Fe(III)-OR intermediate that can undergo isomerization so that both *cis*- and *trans*-substituted epoxides are formed.



**Figure S8.** (a) GC-MS spectrum showing the presence of both PhS(=O)CH<sub>3</sub> (m/z 140) and PhS(=<sup>18</sup>O)CH<sub>3</sub> (m/z 142) upon oxidation of thioanisole by complex 7. (b) A Hammett plot of the logarithms of relative observed *pseudo* first-order rate constants ( $k_{rel}$ ) for various *para*-substituted thioanisoles against corresponding substituent constant ( $\sigma$ ) values.

Having established the OAT capability of 7, the ability of the iron(II) complex [Fe<sup>II</sup>(L2-Qn)(CH<sub>3</sub>CN)]<sup>2+</sup> (3), to effect catalytic oxidation of various olefins was investigated. The catalytic OAT reactions were performed under standard reaction condition in a mole ratio of 1:5:100 for catalyst:IBX-ester:substrate in acetonitrile at room temperature. The results are presented in Table S3. Oxidation of styrene afforded styrene oxide in 36% yield (entry 1, Table 4); in addition, a small amount ( $\sim 2\%$ ) of 2-phenylacetaldehyde was formed. The formation of 2-phenylacetaldehyde from the styrene oxide, formed via Meinwald rearrangement, may be facilitated by the Lewis acidic Fe<sup>IV</sup>=O intermediate.<sup>12</sup> Various Lewis acid catalysts,<sup>13</sup> including high valent vanadium oxo complexes<sup>14</sup> are well known to catalyze such rearrangement reactions. A dual behavior was observed for cyclohexene (entry 2), which under the catalytic conditions undergoes both OAT and combined HAT/OAT reactions (presumably via an oxygen rebound mechanism), resulting in the formation of the corresponding OAT product cyclohexene oxide in 3% yield and the hydroxylated product 2-cyclohexen-1-ol in 6% yield (relative to the limiting reactant, i.e. IBX-ester). Partial oxidation of cyclohexen-1-ol effected the formation of 2-cyclohexenone in 4% yield. The other substrates (Entries 3 to 8) afforded corresponding epoxides as major products while maintaining stereoselectivities (as evaluated based on a GC-MS library), strongly supporting a metalbased oxidant. The markedly low yield of epoxide for trans-stilbene (entry 8) as compared to cis-stilbene (entry 7) is presumably due to the involvement of a more hindered transition state for the oxygen atom transfer to the *trans* isomer, and are in keeping with the observations by Maiti and coworkers.<sup>11</sup>

	$\begin{array}{c} R_1 \\ R_2 \\ R_2 \end{array} \xrightarrow{R_4} \\ R_4 \\ Acetonitrile, 3 h, r.t. \end{array} \xrightarrow{R_1} \\ R_2 \\ R_2 \\ R_4 \end{array}$										
Entry	Substrate	Product	TON*	Yield**	Product						
				(%)	<b>Distribution (%)</b>						
1			1.80	36	95						
			0.10	2	5						
2	$\bigcirc$		0.16	3	23						
			0.18	4	30						

Table S3. Olefin substrate scope for oxygen atom transfer reactions catalyzed by  $[Fe^{II}(L2-Qn)(CH_3CN)]^{2+}(3)$ .



Reaction conditions: Catalyst: IBX-ester: Substrate = 1:5:100. \*TON is calculated with respect to the catalyst (**3**), and is here defined as the number of turnovers within a period of 3h. \*\*Yield is calculated with respect to the IBX-ester (limiting reagent). \*\*\*Analyzed by GC-MS only. The experimental details have been described in the Experimental Section.

#### Hydrogen-atom transfer (HAT) reactions – alkene and alkane oxidation

Rasheed *et al.*<sup>7</sup> have demonstrated the HAT reactivity of **7** with a number of alkane substrates having C-H bond dissociation energies (BDE's) ranging from 81-99.3 kcal/mol, viz. triphenylmethane, cumene, ethylbenzene, toluene, cyclooctane, 2,3-dimethylbutane, and cyclohexane. Investigation of this reactivity under similar conditions gave normalized reaction rates in complete agreement with the above-mentioned study. Complex **7** reacts much faster with substrates having Weaker C–H bonds, while its reactivity becomes slower in the presence of substrates with strong C–H bonds. The primary kinetic isotope effect (KIE) was determined by measuring the rate constants for reaction of **7** with cyclohexane and toluene and their corresponding deuteroisotopomers (C<sub>6</sub>D<sub>12</sub> and C<sub>6</sub>D<sub>5</sub>CD<sub>3</sub>, respectively). The KIE values were found to be 5.6 for cyclohexane and 14.1 for toluene (Figure S8). These relatively large KIE values indicate that the reaction of **7** with alkanes proceeds via a rate-limiting HAT step.



**Figure S8.** Plot of KIE using the  $k_2$  values for the oxidation of (a) toluene and toluene- $d_8$  and (b) cyclohexane and cyclohexane- $d_{12}$  by 7.

Based on this observed HAT activity, we investigated the capability of **3** to act as an alkane oxidation catalyst in the presence of IBX ester as the terminal oxidant. We anticipated that the catalytic oxidations would proceed via the formation of the ferryl complex **7** as an intermediate, as has been implicated in several previous studies.<sup>7,8,15,16,17,18,19,20</sup> The catalytic reactions were carried out using a 1:5:10 ratio of catalyst:oxidant:substrate, and the products were analyzed by GC-MS. The initial catalytic reactions involved alkene oxidation via HAT; the substrates used were 1,4-cyclohexadiene and 9,10-dihydroanthracene (Table S4, entries 1 and 2). As expected, 1,4-cyclohexadiene underwent dehydrogenation to give benzene as the exclusive product, in 70% yield. With 9,10-dihydroanthracene,

both pure HAT (dehydrogenation) was observed to give anthracene in 18% yield but also the formation of the corresponding *para*-quinone via a combination of hydrogen atom transfer and oxygen atom transfer. Triphenylmethane underwent a rapid conversion to triphenyl methanol in 92% yield (entry 3), while reaction with cyclohexane, with a higher C-H bond dissociation energy of 99.3 kcal/mol, occurred slowly to form cyclohexanol and cyclohexanone in 5% and 2% yields, respectively, giving an alcohol/ketone (A/K) ratio 2.9. The A/K ratio is an important parameter often used to characterize oxidative catalytic systems in terms of viability of the reaction through an iron-centered species or through a radical mechanism. High A/K ratios (greater than 1) are indicative of involvement of iron-centered species in the reaction.<sup>21</sup> In the present case, the value 2.9 clearly indicates an iron-centered mechanism and the value obtained is in the range of the highest values reported for similar reaction systems involving iron complexes of tetra- or pentadentate nitrogen donor ligands.<sup>6,202223</sup> The A/K ratio tends to decrease with time due to further oxidation of the alcohol to the corresponding ketone. Therefore, substrates with lower C-H bond energies are more likely to form ketone over a given reaction time. This is clearly supported by the low alcohol yield when ethyl benzene (C-H BDE 87 kcal/mole) and toluene (C-H BDE 91 kcal/mole) were used as substrates. For ethyl benzene, only 36% alcohol was produced while in the case of toluene no benzyl alcohol was observed - only benzaldehyde was isolated (entries 4 and 5, respectively in Table S4). To verify the possibility of over-oxidation, the oxidation of benzyl alcohol and 1phenylethanol by 3 was performed. Under standard reaction conditions, the alcohols were rapidly oxidized to benzaldehyde and acetophenone in high yields (cf. Experimental Section). Rana et al.<sup>7</sup> reported A/K ratios of 1 or <1 for reactions of ethylbenzene, toluene and cyclohexane with 7 in air (rather than 3 and oxidant as in the present study).

Involvement of iron-centered species in the oxidation reaction was further supported by selectivity experiments. In the oxygen-rebound mechanism (a combination of HAT and OAT steps) that has been established for the cytochrome P450 class of enzymes and many heme and non-heme model complexes, selective oxidation of C–H bond is indicative of little to no formation of long-living radicals.<sup>24</sup> Substrates containing both secondary (2°) and tertiary (3°) carbon atoms can potentially be oxidized in the two available positions. It is well established that iron centered oxidation tends to give higher selectivity for the tertiary position.<sup>17,19</sup> Oxidation of adamantane offers a 3°/2° selectivity of 13. A moderate 3°/2° selectivity of 4 was observed for the oxidation of methylcyclohexane. In both cases a certain amount of ketone corresponding to the secondary alcohol was also formed (entries 8 and 9).

Oxidation of 1,2-dimethylcyclohexane (both *cis*- and *trans*-isomers) is a useful model reaction to test both regio- and stereoselectivity studies. Poor  $3^{\circ}/2^{\circ}$  selectivity and loss of stereo-configuration of the methyl groups in *cis*-1,2-dimethylcyclohexane point towards the radical pathway. In the oxidation reaction of *cis*-1,2-dimethylcyclohexane, the tertiary isomers were formed in higher yield  $(3^{\circ}/2^{\circ})$  selectivity of 2.9), while the stereospecificity was maintained towards the formation of the corresponding *cis*-alcohol(1S,2S)-1,2-dimethylcyclohexanol. The by-products were the tertiary *trans*-alcohol and ketones formed through the activation of secondary C–H bonds of *cis*-1,2-dimethylcyclohexane (entry 8). In contrast, *trans*-1,2-dimethylcyclohexane was found to be less regioselective forming the ketone products in higher yield and exhibiting similar stereospecificity for the formation of *trans*-alcohol ( $3^{\circ}/2^{\circ}$  selectivity of 2.2, entry 11).

 
 Complex 3
 OH

 IBX-ester (5 equiv)
 R1

 Acetonitrile, 3 h, r.t.
 R2
 Ĥ. R₁ Product TON\* Yield\*\* (%) Entry Substrate Product **Distribution (%)** 100 1 14 0.70 90 2 0.90 18 C 0.09 2 10 Ö 100 3 Ph, Ph OH 4.60 92 Ph. ∠Ph Ρh Ρ'n 4 <mark>О</mark>Н 1.80 36 100 5 10 100 0.51  $\mathbf{i}$ 100 0.05 10 6 ĊН 5 72 7 OH 0.23 28 0.08 2 0.63 13 62 8 ЮН 19 0.17 4 0.22 19 4 9 OH 81 1.10 22 11 3 0.16 ОН 2 7 0.10

Table S4	Substrate	scope	for hyd	lrogen	atom	transfer	reactions	catalyzed	by [Fe <sup>II</sup>	(L2-Qn)	$(CH_{3}CN)]^{2+}$
(3).											

		<i>↓</i> <b>↓</b> <sup>●</sup>			
10	$\sim$	СССОН	0.52	10	63
		С	0.18	4	25
			0.07	1	6
			0.05	1	6

Reaction condition (for entries 2, 3 and 9): Catalyst: IBX-ester: Substrate = 1:5:10. Reaction condition (for other entries): Catalyst: IBX-ester: Substrate = 1:5:100. \*TON is calculated with respect to the catalyst (3). \*\*Yield is calculated with respect to the IBX-ester (limiting reagent). The experimental details have been described in the Experimental Section.

#### Multivariate analysis of oxidation reactions

#### Results

A Box-Behnken experimental design was performed to evaluate the relative amounts of catalyst and peroxide and the reaction time for oxidation of cyclohexane (CyH). Table S3 shows the combination of each variable, the % conversion to cyclohexanol (CyOH) and cyclohexanone (CyO) and the selectivity toward the formation of cyclohexanol (CyOH).

**Table S5**. Combination of variables and the response obtained by the analysis of the products formed by the catalytic oxidation of cyclohexane (CyH).

Entry	Catalyst	Peroxide	Time (h)	0∕ CuOU	9/ CuO	%СуОН
Entry	(mol%)	$(\log[n/n])$	Time (n)	%СуОП	70CyU	Selectivity <sup>a</sup>
1	0.10	0.0	2	1.89	0.31	86
2	3.00	0.0	2	4.07	4.22	49
3	1.55	-0.7	2	4.36 <sup>b</sup>	5.03 <sup>b</sup>	46
4	1.55	0.7	2	12.06	5.06	70
5	3.00	0.0	6	4.36	4.93	47
6	1.55	-0.7	6	4.45 <sup>b</sup>	4.82 <sup>b</sup>	48
7	0.10	0.0	6	2.21	0.32	87
8	1.55	0.7	6	14.04	7.21	66
9	0.10	-0.7	4	4.43 <sup>b</sup>	0.70 <sup>b</sup>	86
10	3.00	-0.7	4	4.63 <sup>b</sup>	5.09 <sup>b</sup>	48
11	0.10	0.7	4	3.10	0.21	94
12	3.00	0.7	4	9.62	12.24	44
13	1.55	0.0	4	3.49	3.88	47
14	1.55	0.0	4	3.89	3.93	50

<sup>a</sup>The selectivity towards CyOH was calculated by 100x%CyOH/(%CyOH+%CyO).

<sup>b</sup>Yield calculated using peroxide as the limiting reagent.

#### Cyclohexanol (CyOH) Formation

The response surface for the conversion to CyOH had  $R^2 = 0.865$  and the residual dispersions both presented low values and random dispersion (Figure S9), thus it can be considered a valid model.



Figure S9. Raw residuals obtained for modeling the % conversion of CyOH.

Figure S10 shows the response surfaces for the interaction between the three variables studied for the conversion of CyH into CyOH. The optimum region for the catalyst is between the center point (1.55 mol %) and the maximum (3 mo l%). The optimum response for hydrogen peroxide is 0.7 (corresponding to an excess of peroxide of 5:1 in relation to the CyH). The optimal region for the reaction time is 2 to 6 hours. Values shorter than 2 h were not tested, as there would be a greater probability of not having conversions significantly higher than zero in the very mild conditions of catalyst and peroxide used, deteriorating the prediction power of the mathematical model applied.

By applying the best conditions for the conversion of CyH into CyOH in the range evaluated in this work, a % conversion of about 14 % was obtained for CyOH, and about 7 % conversion into CyO, with a degree of selectivity towards CyOH of about 66 %.



Figure S10. Response surfaces for cyclohexane (CyO) conversion.

#### Cyclohexanone (CyO) Formation

The response surface obtained for conversion of CyH into CyO had  $R^2=0.924$ . The raw residues presented satisfactory results, with absolute experimental errors (Figure S11) lower than  $\pm 1.5\%$  in relation to the predicted by the model, along with a random dispersion. Therefore, interpretation of the response surfaces obtained can be done adequately.



Figure S11. Raw residuals obtained for modeling the % conversion of cyclohexanone (CyO).

On analyzing Figure S12, it can be observed that reaction time was not significant in the range of 2 to 6 hours; the optimal amount of peroxide points to the maximum value studied (5 times excess in relation to CyH) as does also the catalyst loading towards 3 mol %. The amount of catalyst is the most significant difference between the conversion of CyH into CyOH or CyO. This fact suggests that the catalyst effects the first step of oxidation of CyH into CyOH and thereafter is used again to oxidize CyOH into CyO; thus it may be added in higher concentration. Another significant difference can be observed in the strong interaction between the amount of catalyst and peroxide (Figure S12, middle and bottom). At lower peroxide quantities, the increase in catalyst concentration does not lead to a significant increase in the amount of CyO formed. On the other hand, at the highest level of peroxide tested, there is a significant increase in CyO formation as the amount of catalyst is increased. This corroborates that the species formed by the interaction between catalyst and peroxide is crucial for the formation of the

products, especially CyO. Under these conditions, the % conversion into CyO was about 12 % and into CyOH about 10 %, with selectivity towards CyOH of about 45%.



Figure S12. Response surfaces for the cyclohexanone (CyO) conversion.

#### Selectivity for cyclohexanol (CyOH)

The response surface for modeling in relation to the CyOH selectivity had  $R^2 = 0.989$  and presented very low difference between predicted and observed values and a random dispersion of model residuals, as can be seen in Figure S13, validating the model for further analysis.



Figure S13. Raw residuals obtained for modeling the cyclohexanol (CyOH) selectivity.

On analyzing Figure S14, it can be inferred that the best conditions to maximize the formation of CyOH rather than CyO were: catalyst concentration in the lowest level evaluated of 0.1 mol %, the lowest level of peroxide corresponding to 5 times excess of CyH in relation to peroxide, and a reaction time in the range of 2-6 hours. In this optimal condition, a selectivity of about 90% was obtained towards formation of CyOH, with conversions of about 3 and 0.2 % for CyOH and CyO, respectively.



Figure S14. Response surfaces for cyclohexanol (CyOH) selectivity.

#### Experimental details for the Multivariate analysis of oxidation reactions

The oxidation reactions were carried out in 4.5 mL amber glass vials capped with screw cap with silicone septa coated with PTFE, in which the catalyst, oxidant ( $H_2O_2$ ), substrate (cyclohexane) and analytical grade acetonitrile (as reaction solvent) were mixed until a volume of 4.5 mL was reached. Each assay was performed under magnetic stirring at 20 °C. The amount of substrate added in each reaction was 278 µmol (equivalent to a mass of 23.4 mg) and the amounts of catalyst (mol %) and hydrogen peroxide (log n/n<sub>Cv</sub>) were calculated from this value.

The limits chosen for the experimental design were based on preliminary tests and in the literature. For the proportion of the catalyst, the lowest level chosen was 0.1 mol %, which corresponds to a ratio of 1:1000 with respect to the substrate. As the highest level, 3 mol % was chosen, with the center point at 1.55 mol%. The proportion of peroxide used was 0.2, 1 and 5 times in relation to the number of moles of the substrate. To fit the model in the multivariate treatment, this scale was logarithmized, obtaining values between -0.7 and +0.7, corresponding respectively to five times excess of cyclohexane and five times of peroxide (the central point corresponds to equimolar amounts of substrate/oxidant). The reaction time was evaluated in the interval between 2 to 6 hours, with center point at 4 hours. Table S3 (vide supra) shows the combination of variables for each assay and the responses obtained as % conversion of CyOH and CyO. Statistica 7 (StatSoft Inc., Tulsa, USA) was used for data treatment. The mathematical model used had 10 coefficients, including: one for the intercept, three linear terms (one for each factor), three quadratic terms and three linear terms accounting for the interaction between time and catalyst, time and peroxide and peroxide and catalyst. Five degrees of freedom remained in each model, which were used to estimate the significance of each coefficient. Model validation was performed by both inspecting the values of the determination coefficient  $(R^2)$  and the visual inspection of randomness of the model residuals.

After the completion of each experiment carried out according to Table S2, the reaction vessel was sonicated for 10s to remove bubbles formed by the decomposition of hydrogen peroxide, and then 80  $\mu$ L were diluted in 2 mL of acetone containing excess of triphenylphosphine (PPh<sub>3</sub>). A volume of 1  $\mu$ L was then injected into the gas chromatograph for the quantification of the products using the areas obtained in the calibration curves previously prepared. Reaction with triphenylphosphine transformed the unstable cyclohexyl hydroperoxide (also formed during oxidation) into cyclohexanol, according to Scheme S9.



Scheme S1. Oxidation reactions of the substrate used.

Quantification of CyOH and CyO was performed with authentic standards of both compounds, by building calibration curves using toluene as internal standard. Toluene was added after reaction completion. Peak areas of the main fragment of each compound (57 m/z for CyOH, 55 m/z for CyO and 91 m/z for toluene) were used as the analytical response to build the calibration curves. Each calibration showed excellent determination coefficient ( $R^2$ >0.998). Precision assays were also performed, resulting in relative standard deviations lower than 6% (n=3). Quantification limits by using 80 µL of reaction mixture in a final volume of 2 mL allowed detecting 0.5% conversions of both CyOH and CyO. Higher volumes of the reaction mixture were used when CyOH and/or CyO were not detected, so as no experiment had null response.

Separation and detection of CyOH and CyO was performed using a gas chromatograph GCMS-QP2010 Ultra from Shimadzu (Kyoto, Japan), equipped with automatic sampler AOC-20i and split/splitless injector. Ultra-pure helium gas was used the mobile phase at 1.10 mL/min. An HP-5ms capillary column (Agilent Technologies, Santa Clara, USA), 30 m long, 0.25 mm internal diameter and 0.25 µm film thickness was used as the stationary phase, whose composition was 95% dimethyl/5% diphenyl polysiloxane. Sample ionization was performed by electron impact at 70eV and the fragments were separated by a quadrupole with unitary mass resolution.

Chromatographic separation was performed by the following temperature program: 40 °C for 3 min, 30 °C min<sup>-1</sup> up to 70 ° C, 50 °C min<sup>-1</sup> up to 300 ° C for 1.5 min, totaling 10.15 minutes of chromatographic run. Injection, interface and ion source temperatures were set at, respectively: 250 °C, 250 °C and 200 °C. The injection was performed in split mode at a ratio of 1:50 for 1 min, followed by a split ratio 1:5 for the rest of the run.



Figure S15. Second order rate constants for the oxidation of different aliphatic C-H bonds by  $[Fe^{IV}(O)(L1-Qn)]^{2+}$  (8) (at 298 K).



Figure S16. Plot of KIE using the  $k_2$  values for the oxidation of toluene and toluene- $d_8$  by  $[Fe^{IV}(O)(L1-Qn)]^{2+}(8)$ .



**Figure S17.** UV–vis spectral changes of complex  $[Fe^{IV}(O)(L1-Qn)]^{2+}$  (8) upon addition of 100 equiv. of thioanisole in acetonitrile at 233 K; Inset: Time trace of the decay of the 730 nm band.



Figure S18. Second order rate constant for thioanisole oxidation by  $[Fe^{IV}(O)(L1-Qn)]^{2+}(8)$ .

Entry	Substrate	Product	TON*	Yield** (%)	Product Distribution (%)
1	S_	₽ S S	2.70	90	100
2	$\sim$	0	0.03	1	5
			0.34	11	50
			0.31	10	45
3	C₅H <sub>11</sub>	C <sub>5</sub> H <sub>11</sub>	0.33	11	100
4	$\bigcirc$	0	1.10	37	93
			0.08	3	7

0	

Reaction conditions: Catalyst: IBX-ester: Substrate = 1:3:100. \*TON is calculated with respect to the catalyst (8), and is here defined as the number of turnovers within a period of 6 h. \*\*Yield is calculated with respect to the IBX-ester (limiting reagent). The experimental details have been described in the Experimental Section.



**Scheme S2.** OAT activity of **8** with different substrates. Reaction conditions: complex : IBX-ester : substrate = 1:3:100; Reaction time = 6 h in acetonitrile at 298 K. TON of the substrates is indicated in blue.

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