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Design of and Mechanistic Studies on a Biomimetic Iron–Imidazole Catalyst System for Epoxidation of Olefins with Hydrogen Peroxide

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Abstract: Novel iron catalysts, both defined and in situ generated, for the epoxidation of aromatic and aliphatic olefins with hydrogen peroxide as terminal oxidant are described. Our catalyst approach is based on bio-inspired 1-aryl-substituted imidazoles in combination with cheap and abundant iron trichloride hexahydrate. We show that the free 2-position of the imidazole ligand motif plays a key role for catalytic activity, as substitution leads to a dramatic depletion of yield and conversion. X-ray studies, UV/Vis titrations, and NMR studies were carried out to clarify the mechanism.

Keywords: epoxidation · homogeneous catalysis · iron · N ligands · reaction mechanisms

Introduction

Catalytic epoxidation of olefins provide oxiranes, which are of central importance in various fields of chemistry ranging from pharmaceutical intermediates to monomers for bulk polymers. From an industrial point of view aliphatic epoxides are of special interest, namely, 1,2-propylene oxide and ethylene oxide, which are annually produced on a million-ton scale.[1] These large scale productions are based on heterogeneous catalysts, for example, with Ti-substituted molecular sieve silicalite (TS-1) for the epoxidation of propylene[2] or silver catalysts supported on Al_2O_3 for the production of ethylene oxide.[3] State-of-the-art heterogeneous catalysts make use of benign oxidants such as hydrogen peroxide or molecular oxygen, but require relatively harsh reaction conditions. Hence, there is a continuing interest in more active and selective catalysts. In this respect molecularly defined transition-metal complexes provide beneficial models for new types of oxidation catalysts. Known homogeneous metal complexes that make use of hydrogen peroxide are mainly based on ruthenium,[4] rhenium,[5] manganese,[6] and more recently iron.[7] Notably, until today the development of a generally applicable, active and selective catalyst system which can epoxidize both aromatic and aliphatic olefins is still a challenging goal.

Using iron as metal center of the catalyst implies many advantages compared to precious metals. It is the second most abundant metal in the earth crust (4.7 wt%) and relatively non-toxic. A variety of iron salts and iron complexes are currently commercially available on a large scale. It is noteworthy that iron is involved in manifold biological systems as fundamental key element, for instance, in metalloproteins like methane monooxygenases for the metabolic aerobic pathway of methane to methanol.[8] Figure 1 shows an example of a non-heme Fe^{II}/α-ketoglutarate (αKG) dependent halogenase,[9a] in which two histidine ligands and one chloride ion are coordinated to iron in the central core. The remaining iron coordination sites are occupied by the co-factor αKG and a water molecule.

Based on these structurally well-characterized enzymes, many model complexes have been prepared to explore mechanistic issues and their use in oxidation catalysis (Scheme 1).[10] Unfortunately, each of these systems has limitations such as tedious complex preparation, limited substrate scope, low selectivity and the use of "non-green" or expensive oxidants such as iodoso compounds and peracids.[12]

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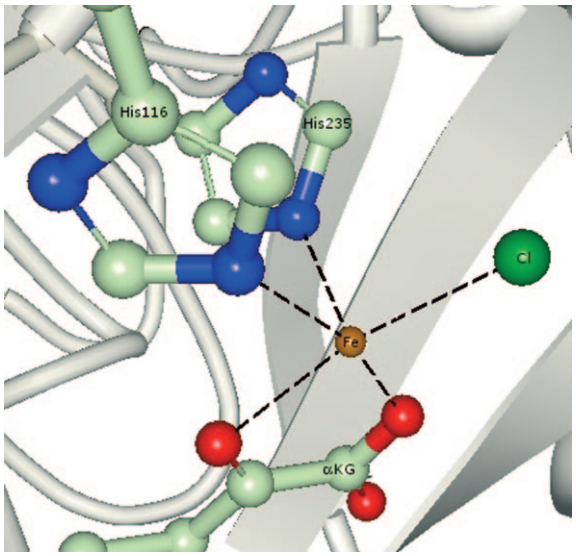
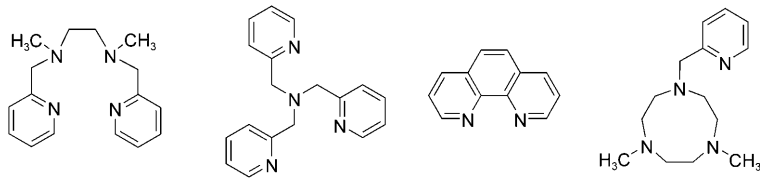


Figure 1. Non-heme iron halogenase SyrB2.[9b] C gray, N blue, O red, Cl green, Fe brown.



Scheme 1. Bio-inspired ligands of iron complexes for epoxidation of olefins.[11]

On the basis of our background in epoxidation chemistry of aromatic olefins using hydrogen peroxide as an oxygen source in the presence of a catalyst generated in situ from $FeCl_3 \cdot 6H_2O$, pyridine-2,6-dicarboxylic acid (H_2pydic) and an organic base like pyrrolidine,[13] we recently developed a simplified two-component catalyst system consisting of 5-chloro-1-methylimidazole (5-Cl-1-MeIm) and $FeCl_3 \cdot 6H_2O$, which is able to catalyze the epoxidation of various substrates, such as substituted styrenes and stilbenes.[14] Furthermore, we demonstrated epoxidation of several aliphatic olefins with an improved three-component system consisting of $FeCl_3 \cdot 6H_2O$, H_2pydic and different *N*-benzylamines.[15]

Here we report a detailed study on improving our biomimetic protocol involving a two-component catalyst and demonstrate that iron-based catalysts can epoxidize both aliphatic and aromatic olefins with hydrogen peroxide in good yield and with high selectivity.

Results and Discussion

Catalysis experiments: Starting with our previously described in situ 5-Cl-1-MeIm/iron system, the aim was to increase conversion and yield by introducing additives. The original in situ two-component system consisted of 10 mol% of ligand (5-Cl-1-MeIm) with a catalyst loading of 5 mol% $FeCl_3 \cdot 6H_2O$ in *tert*-amyl alcohol.[14] As model substrate for catalytic testing *trans*-stilbene was chosen owing to its stability and ease of handling. From the results of an optimization process, 2–3 equivalents of 30% hydrogen peroxide are used as oxygen source under ambient conditions (air and RT). Initially, various acidic and basic co-ligands were applied in the model reaction. Other Fe-dependant reactions (e.g., oxidation of benzyl alcohol to benzaldehyde) are significantly influenced by such additives.[16] Earlier, we also discovered the strong dependence of selectivity on pH in osmium-catalyzed dihydroxylation of olefins with oxygen as terminal oxidant.[17] Selected results of our investigation are shown in Table 1. Apparently, the acidity of the reaction system plays an important role in selectivity and conversion. Small amounts (<5 mol%) of weak acids like acetic acid, benzoic acid or iminodiacetic acid slightly increased or at least maintained conversion and selectivity (Table 1, entries 2, 8–12). Addition of a higher concentration of benzoic acid (10 mol%) led to a decrease of nearly 50% in yield and 35% in selectivity. Similarly "strong" acids such as *p*-toluenesulfonic acid, phosphoric acid and nitric acid as additives (Table 1, entries 13–15) gave only poor conversion and low selectivity.

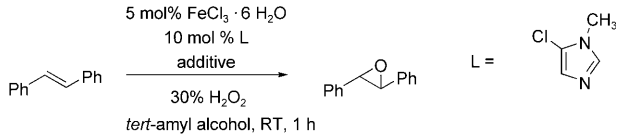
Amines such as bipyridine and pyrrolidine diminished significantly yield and conversion (Table 1, entries 3 and 4). Probably, the higher concentration of N-donor ligands reduces the epoxide yield by occupying the coordination sites of the iron center or reduces the Lewis acidity of the active catalyst species. Surprisingly, inorganic bases like NaOH and $NaHCO_3$ decreased the yield and selectivity only slightly (around 10%; Table 1, entries 5 and 6). Salt additives did not show any clear trend and often slightly increased yield and conversion (Table 1, entries 17–21). In conclusion, the results indicate a correlation between acidity and catalyst activity.

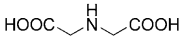
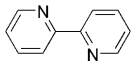
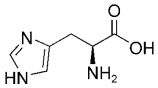
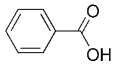
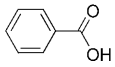
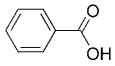
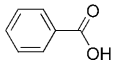
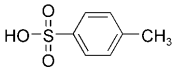
Because combinations of peracetic acid and various iron complexes are known to be efficient epoxidation catalysts,[18,19] we performed several experiments to exclude formation of the corresponding peracids by an iron-catalyzed process (Scheme 2). However, experiments with peracetic acid instead of hydrogen peroxide as oxidant[20] do not support in situ generation of peracid. Here, conversion and yield diminished significantly to only about 5%.

Next, we examined the influence of the structure of the imidazole ligand more closely. Unfortunately, our prior two-component system consisting of $FeCl_3 \cdot 6H_2O$ and 5-Cl-1-MeIm was able to epoxidize only aromatic olefins (e.g. styrenes, stilbenes) to the corresponding oxiranes in moderate to excellent yields.[14]

To get a first impression of the reactivity of the shown ligands and to ensure comparability to the former work *trans*-

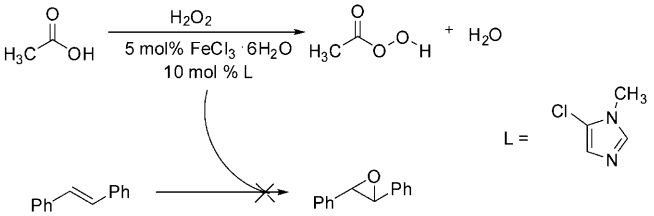
Table 1. Influence of additives on the epoxidation of *trans*-stilbene.[a]



Entry	Additive	[Additive] [mol %]	Conversion [%][b]	Yield [%][b]	Selectivity [%][c]
1	–	–	83	80	97
2		5	89	87	98
3		5	51	44	86
4		5	9	7	73
5	NaOH	5	79	71	90
6	$NaHO_3$	5	86	73	84
7[d]		5	84	83	>99
8		5	86	84	98
9		5	85	84	99
10		10	58	37	63
11		2.5	76	75	99
12		1	84	81	97
13		5	29	23	79
14	H_3PO_4	5	0	0	0
15	HNO_3	5	69	55	81
16		5	81	76	95
17	LiCl	5	89	87	98
18	LiCl	10	87	85	98
19	LiCl; HCl	5; 0.5	86	83	98
20	KCl	5	80	73	91
21	NH_4Cl	5	87	85	97
22	NBS	5	88	85	97
23		5	89	86	97

[a] Reaction conditions: 0.5 mmol *trans*-stilbene, 5 mol% $FeCl_3 \cdot 6H_2O$ and 10 mol% 5-Cl-1-MeIm, *tert*-amyl alcohol (9 mL), 0.44 mmol dodecane as internal standard were added in sequence at room temperature in air. To this mixture, a solution of 30% H_2O_2 (115 μL, 1 mmol) in *tert*-amyl alcohol (885 μL) was added over 1 h at room temperature in air by syringe pump. [b] Conversion and yield were determined by GC analysis. [c] Selectivity refers to the chemoselectivity of epoxide from olefin. [d] No *ee* detectable.

stilbene was retained as model substrate. The results are presented in Table 2. A broad range of imidazoles lead to moderate to good yields (Table 2, entries 3–6, 8–12). In general, *N*-aryl imidazoles gave better results than *N*-benzyl derivatives (Table 2, entries 1–3). Besides, the substitution pattern on the aryl ring seems to be important. Thus, methyl and isopropyl groups or fused benzene rings enhanced the yield significantly. Moreover, yield and conversion rose with halogen substitution, but decreased when electron-donating methoxy groups (in *para* and *ortho* positions) were introduced. While none of these ligands gave improved results for *trans*-stilbene compared to the 5-Cl-1-MeIm ligand (Table 1, entry 1), these ligands display better performance in the epoxidation of aliphatic olefins (see below).



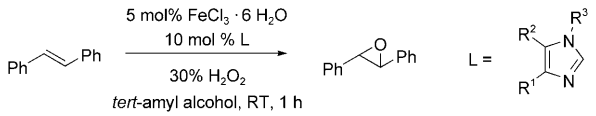
Scheme 2. Possible formation of peracetic acid in the reaction system.

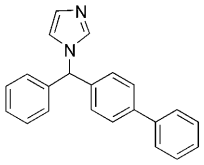
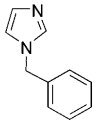
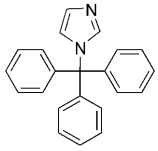
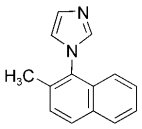
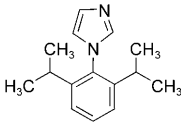
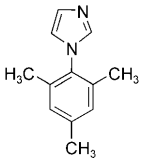
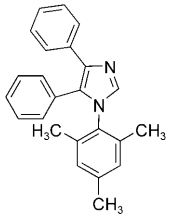
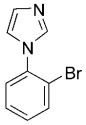
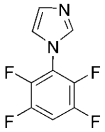
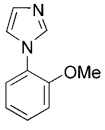
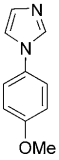
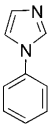
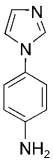
Scope and limitations: To explore the scope and limitations of the ligands, four 1-substituted imidazoles (**3**, **5**, **9**, **11**) were applied on more challenging aromatic and aliphatic substrates (Figure 2). In all experiments with yields greater than 20%, good to excellent chemoselectivity (66 to >99%) for epoxide formation was observed. In the case of aromatic olefins the best performance was observed for substrates containing mono- or di-substituted double bonds, with yields of up to 94% (Figure 2a). Surprisingly, the only exception was *cis*-stilbene, for which all catalysts showed lower yields. On the other hand aliphatic substrates (Figure 2b) are oxidized with somewhat lower yields compared to aromatic counterparts. However, compared to other known iron catalysts excellent results are obtained for both types of olefins with the imidazole-based systems.

For both aliphatic and aromatic substrates imidazole ligand **5** gave the best results. Tables 3 and 4 detail the scope and limitations of this novel iron catalyst system.

The aromatic substrates *trans*-stilbene and styrene (Table 3, entries 1 and 3) gave good to excellent yields and high selectivity similar to or improved with respect to the parent 5-Cl-1-MeIm system.[14] *p*-Chlorostyrene showed a slight enhancement in yield and selectivity (Table 3, entry 5) compared to 5-Cl-1-MeIm, whereas the epoxidation yield of styrene is improved by about 15%. Also, the more difficult trisubstituted olefin α-methyl-*trans*-stilbene gave an improved yield relative to the former system. Most notably, the activity of the catalyst system strongly rises for aliphatic olefins (Table 4) in comparison to the 5-Cl-1-MeIm system. Internal olefins such as *trans*-2-octene and *trans*-5-decene (Table 4, entries 3 and 6), show 44–49% conversion and greater than 80% selectivity. More specifically, the yield of *trans*-5-decene increases from 13 to 37% compared with 5-Cl-1-MeIm. Moreover, the cyclic olefin cyclooctene is oxidized in good yield and selectivity. Here, the yield increases from 28% with 5-Cl-1-MeIm to 65% with imidazole **5** (Table 4, entry 1).

Table 2. Variation of the imidazole ligand.[a]



Entry	Imidazole		Conversion [%][b]	Yield [%][b]	Selectivity [%][c]
1		**1**	38	32	85
2		**2**	37	31	85
3		**3**	56	48	85
4		**4**	83	78	95
5		**5**	72	66	92
6		**6**	75	74	98
7		**7**	18	13	74
8		**8**	70	65	93
9		**9**	76	70	92
10		**10**	46	41	90
11		**11**	54	50	94
12		**12**	74	66	89
13		**13**	4	2	56

[a] Reaction conditions: 0.5 mmol *trans*-stilbene, 5 mol% $FeCl_3 \cdot 6H_2O$ and 10 mol% imidazole derivative, *tert*-amyl alcohol (9 mL), 0.44 mmol dodecane as internal standard were added in sequence at room temperature in air. To this mixture a solution of 30% H_2O_2 (170 μL, 1.5 mmol) in *tert*-amyl alcohol (830 μL) was added over 1 h at room temperature by syringe pump. [b] Conversion and yield were determined by GC analysis. [c] Selectivity refers to the chemoselectivity of epoxide from olefin.

For the poorly reactive and therefore challenging terminal aliphatic olefins, catalytic methods for epoxidation are limited.[21] The **5**/iron system gave 53% yield for 2-methyl-1-heptene (Table 4, entry 2) and 18% yield for 1-octene. Interestingly, *N*-trityl-imidazole gave 25% conversion, 20% yield and 80% selectivity. In addition, the catalyst demonstrates good chemoselectivity for the olefin over the hydroxyl group (Table 4, entry 4), while the 5-Cl-1-MeIm system gave no yield at all with 1-hydroxy-3-hexene.

Mechanistic considerations: The substitution pattern of the imidazole ligand is of crucial importance for obtaining significant catalyst activity. As shown in Scheme 3 substitution in the 2-position of the imidazole moiety leads to a significant depletion of yield compared to unsubstituted counterparts. For instance, a catalyst containing imidazole as ligand afforded stilbene oxide in 38% yield, while a catalyst based on 2-methylimidazole gave stilbene oxide in less than 5% yield. This indicates that the 2-position is of main importance.

One reason for the decreased reactivity of the 2-substituted imidazoles might be participation of a carbene-type ligand in the reaction due to their σ-donor strength.[22] However, formation of iron carbene complexes (in situ formation of the carbene, see Supporting Information) with different carbene ligands showed neither conversion nor yield (Scheme 4). Hence, it is unlikely that carbene-type ligands take part in this reaction.

Another possibility for the different reactivity could be interaction between the proton in 2-position of the coordinated imidazole ligand and the intramolecular iron species (e.g., ferric hydroperoxo species FeOOH) due to hydrogen

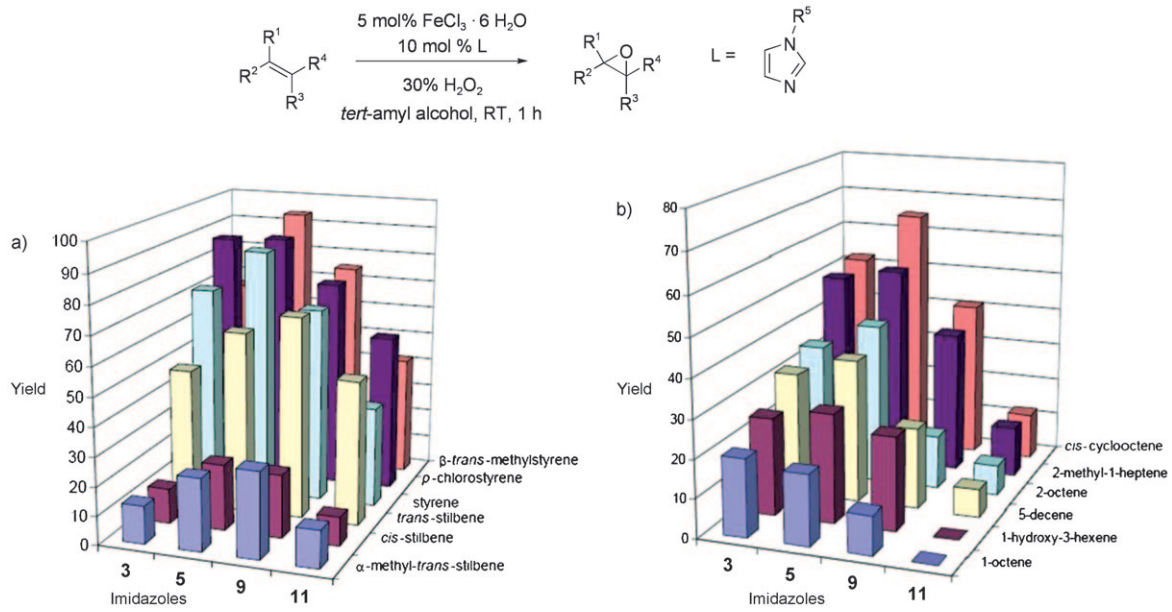
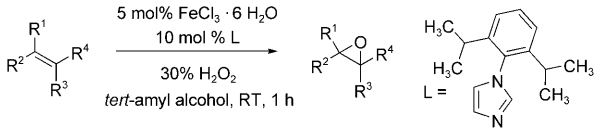
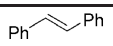
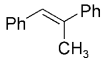
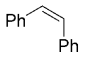
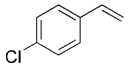
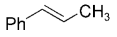


Figure 2. Epoxidation of aliphatic (a) and (b) aromatic olefins in the presence of imidazoles **3**, **5**, **9** and **11**.

Table 3. Scope and limitations of aromatic olefins.[a]



R^1, R^2, R^3, R^4 = H, Alkyl, Aryl

Entry	Substrate	Conversion [%][b]	Yield [%][b]	Selectivity [%][c]
1		72	66	92
2		32	25	77
3		100	87	87
4		34	23	67
5		92	88	96
6		94	94	>99

[a] Reaction conditions: 0.5 mmol *trans*-stilbene, 5 mol% $FeCl_3{\cdot}6H_2O$ and 10 mol% imidazole **5**, *tert*-amyl alcohol (9 mL), 0.44 mmol dodecane were added in sequence at room temperature in air. To this mixture, a solution of 30% H_2O_2 (170 μL, 1.5 mmol) in *tert*-amyl alcohol (830 μL) was added over 1 h at room temperature by syringe pump. [b] Conversion and yield were determined by GC analysis. [c] Selectivity refers to the chemoselectivity of epoxide from olefin.

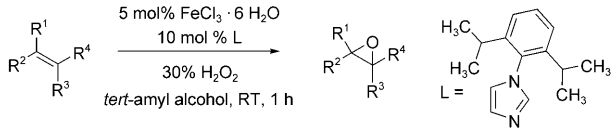
bonding, or an intermolecular interaction between free imidazole and the iron species mentioned above (Scheme 5). Similar effects of intramolecular or intermolecular interactions are proposed in other oxidation reactions.[11e,23,24]

An intermolecular interaction is excluded, since catalysts containing a mixture of *N*-benzylimidazole and *N*-benzyl-2-methylimidazole in a ratio of 9:1 (13.5:1.5) gave comparable yields (7% and 5%, respectively) of stilbene oxide to those obtained with pure *N*-benzyl-2-methylimidazole (5%, see Scheme 3). Similar results were achieved with imidazole and 2-methylimidazole.[25]

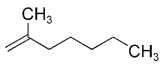
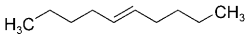
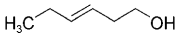
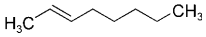
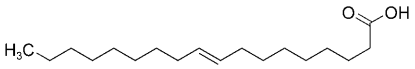
Next, we correlated the results of Table 2 with the ^{1}H NMR chemical shift of the free ligands. It is known that metal–ligand interactions facilitate hydrogen bonding.[26] Figure 3 shows the correlation of yield and selectivity with the chemical shift for the N=C(H)–N proton. Unfortunately, no clear dependency of yield and chemical shift is observable. For further understanding of the active catalysts, UV/Vis spectroscopic investigations with $FeCl_3{\cdot}6H_2O$ in the presence of the best imidazole ligand, namely, 2,6-diisopropyl-*N*-phenylimidazole (IPrPIm), and simple imidazole were undertaken. The experiments were performed in analogy to the reaction conditions of the epoxidation (vide supra). Due to the characteristic iron–imidazole bands in the UV/Vis spectra, it is possible to determine the ligand-to-metal ratio in solution.[27] Owing to the strong absorbance of the solvent *tert*-amyl alcohol, the measurements were analyzed above 225 nm.[28] In the range of 250–400 nm typical high-energy transitions for iron complexes are observed (Figure 4).[29] On addition of imidazole **5** a broad shoulder appeared which is assigned to a metal-to ligand charge-transfer band of the emerging iron complex.[31]

In the UV/Vis titration experiments, various amounts of **5** were added to a solution of $FeCl_3{\cdot}6H_2O$ in *tert*-amyl alcohol. Addition of the ligand led to a linear increase in absorbance at all four chosen wavelengths; the highest absorption is observed at 430 nm. A plateau indicating quantitative complex formation is reached at a ligand-to-metal ratio of 3:1 (Figure 4). Moreover, a large excess of the imidazole ligands (10 and 40 equiv ligand to 1 equiv iron) did not show any considerable change, and the position of the plateau was constant. Both full concentration (Figure 5a) and half-concentration (Figure 5b) of the imidazole/iron system resulted

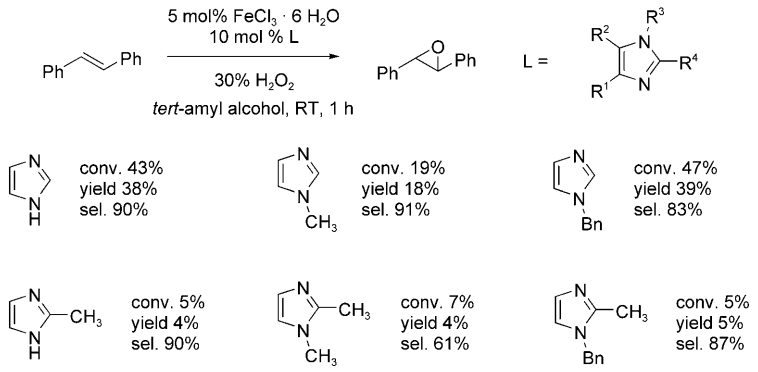
Table 4. Scope and limitations of aliphatic olefins.[a]



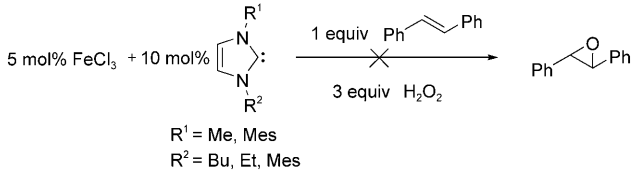
R^1, R^2, R^3, R^4 = H, Alkyl, Aryl

Entry	Substrate	Conversion [%][b]	Yield [%][b]	Selectivity [%][c]
1		77	65	84
2		67	53	82
3		44	37	82
4		38	28	74
5		24	18	75
6		49	42	86
7		26	8	31

[a] Reaction conditions: 0.5 mmol *trans*-stilbene, 5 mol% $FeCl_3$·6H_2O and 10 mol% imidazole derivative, *tert*-amyl alcohol (9 mL), 0.44 mmol dodecane, were added in sequence at room temperature in air. To this mixture, a solution of 30% H_2O_2 (170 μL, 1.5 mmol) in *tert*-amyl alcohol (830 μL) was added over 1 h at room temperature by syringe pump. [b] Conversion and yield were determined by GC analysis. [c] Selectivity refers to the chemoselectivity of epoxide from olefin.



Scheme 3. Some selected results of imidazole ligands in the epoxidation of *trans*-stilbene (reaction conditions are similar to those reported in Table 2).



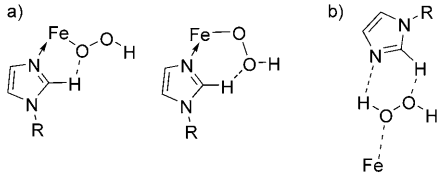
Scheme 4. Use of iron carbene complexes in the epoxidation of stilbene.

in the same ligand-to-metal ratio and did not show any significant difference.[32] Hence, it is likely that the major iron complex in solution contains three imidazole ligands.

Next, the crystallization of defined molecular iron imidazole complexes was tried, and led to the synthesis of two new binuclear iron(III) complexes **A** and **B** with imidazole ligands **5** and **12** (Figure 6). In case of imidazole **5** it was even possible to crystallize the corresponding iron complex directly from the *tert*-amyl alcohol solvent of the epoxidation reaction.

The observed μ-oxo dinuclear N_4(Cl)FeOFeCl_3 pattern is known for both porphyrin and non-heme iron-containing enzymes.[33] Additionally, this type of complex was postulated as intermediate in oxygen transfer from Fe^{IV} to Fe^{II}.[34] Recently, it was also confirmed that the formation of tetradentate μ-oxo diiron(III) species is based on the reaction between iron(II) complexes and dioxygen.[35] Here, the formation of the μ-oxo complex should take place via incorporation of water, because no change of oxidation state is observed.

In general, for the unsymmetrical diiron(III) complexes **A** and **B** the coordination geometry at Fe1 can be described as an octahedron, whereas that at Fe2 is tetrahedral (Figure 6). One chlorine atom, the μ-oxo bridge and four nitrogen atoms of the imidazole ligands coordinate to Fe1, and three further chlorine atoms and the oxygen atom which bridges the metal centers to Fe2. Complexes **A** and **B** can be formally classified into one "cationic" part with the Fe1 center and one "anionic" part consisting of Fe2 and four anionic ligands. In contrast to known tetradentate polyimidazole[36] or tris(6-pyridylmethyl)amine ligands,[35] the chlorido ligand (Figure 6, Cl1) is situated *trans* to the oxo bridge. Compared to known complexes, the Fe1–Cl1 bond length in **A** and **B** are also significantly longer.



Scheme 5. Possible interactions with H-2 in iron imidazole complexes. a) Intramolecular interaction; b) intermolecular interaction.

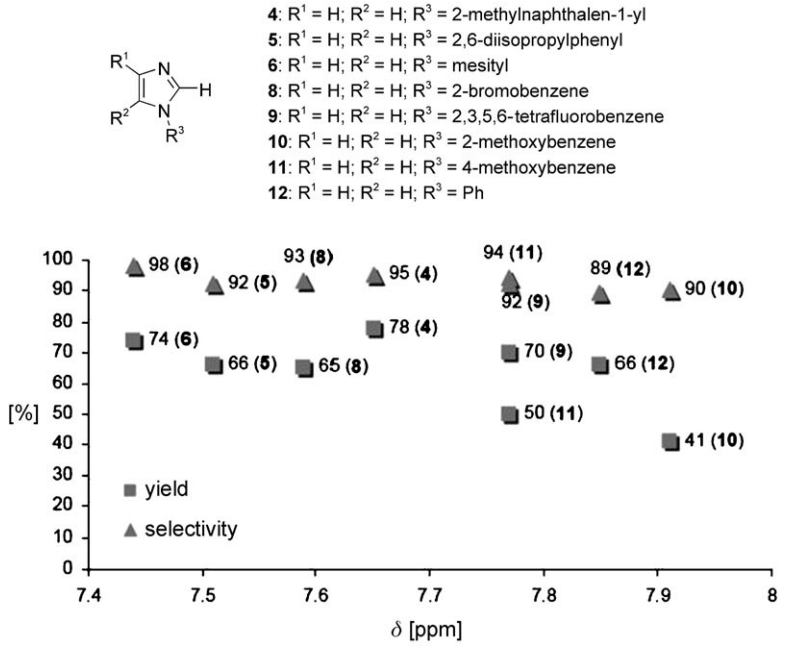


Figure 3. Yield and selectivity of *trans*-stilbene oxide formation versus chemical shift of N=C(H)–N proton of aromatic *N*-substituted imidazoles.[30]

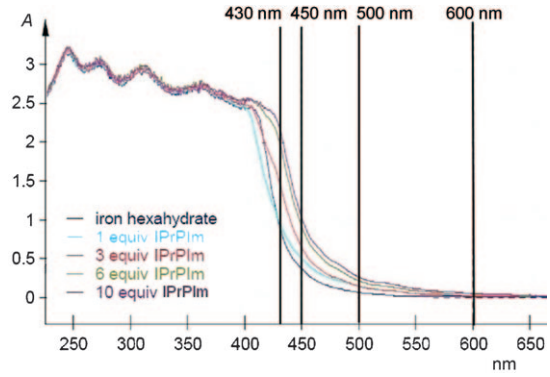


Figure 4. Selected UV/Vis spectra during the titration.

The catalytic reactions of the defined complexes are shown in Schemes 6 and 7. Both complexes exhibit approximately half of the activity of the in situ system. Surprisingly, further addition of imidazole or tetra-*n*-butylammonium chloride led to considerably lower yields of the epoxide. However, addition of imidazole hydrochloride dramatically increased the yield and led to activity close to that of the in situ system. When we added 5 mol% of HCl to the reaction mixture we obtained 49% conversion and 45% yield for complex **A**, and 60% conversion and 54% yield for complex **B**. Thus, the μ-oxo diiron complexes can be converted to the active species again. Apparently, this type of complex is a less active species which is in equilibrium with the active catalyst.

Finally, we were able to synthesize a new mononuclear Fe^{III} complex **C** with the best in situ ligand for epoxidation of aromatic olefins (Figure 7). Here, four imidazole ligands surround the iron center in the solid state. As expected for d^5 Fe^{III}, the geometry at the metal center is octahedral with the chlorine atoms in a *transoid* arrangement. Bond lengths and angles are similar to those of known iron complexes with four simple imidazole ligands, reported by Obrey et al.[37] and later Cotton et al.[38] For comparison we synthesized the known complex according to the protocol by Cotton et al. The catalytic reactivity towards the model substrate *trans*-stilbene is presented in Table 5.

Remarkably, both mononuclear complexes gave higher conversion and yield than the in situ systems (Table 5). Clearly, the novel mononuclear 5-Cl-1-MeIm iron complex is a powerful and highly selective defined epoxidation catalyst.

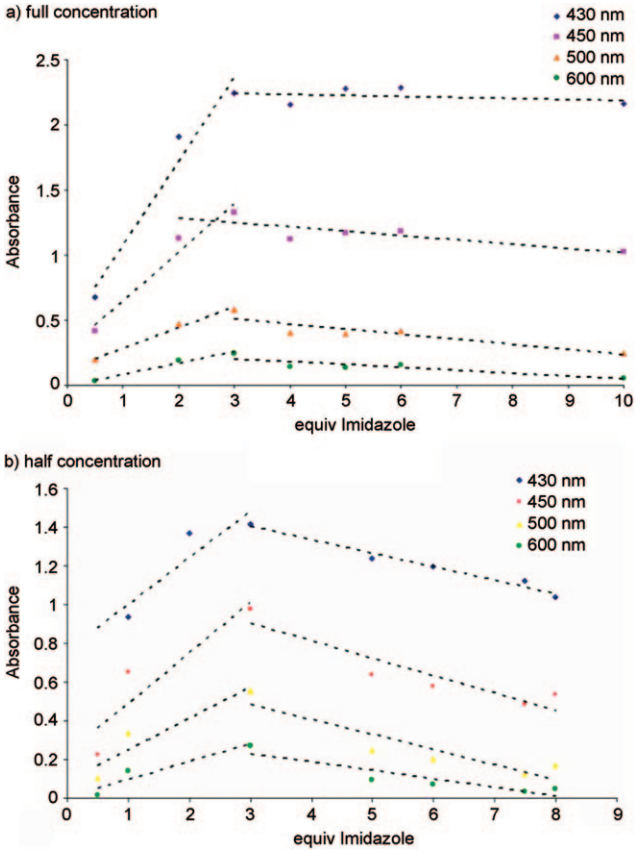


Figure 5. UV/Vis titration of $FeCl_3 \cdot 6H_2O$ with imidazole at full (a) and half concentration (b).

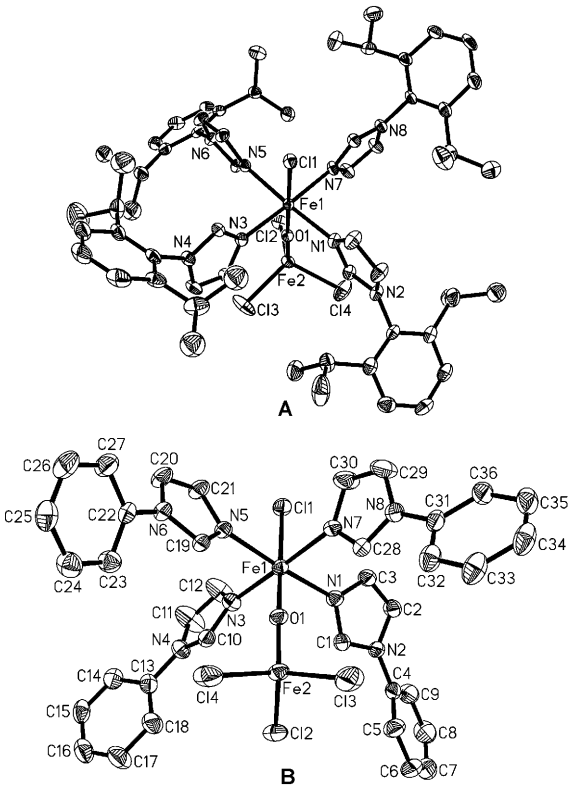


Figure 6. Molecular structure of [{*N*-(2,6-diisopropylphenyl)imidazole}$_4$ClFeOFeCl$_3$] (**A**) and [(*N*-phenylimidazole)$_4$ClFeOFeCl$_3$] (**B**). Thermal ellipsoids correspond to 30% probability. Hydrogen atoms are omitted for clarity.

In view of all these observations we propose the mechanism shown in Scheme 8. In agreement with UV/Vis investigations we assume equilibrium of dinuclear and mononuclear iron complexes, which undergo fast ligand/solvent exchange in the reaction mixture.[39] Free coordination sites on the metal center may react with hydrogen peroxide to form a highly reactive iron hydroperoxo complex. The imidazole ligand stabilizes intramolecularly the corresponding hydroperoxo species by hydrogen bonding at the 2-position.

Conclusions

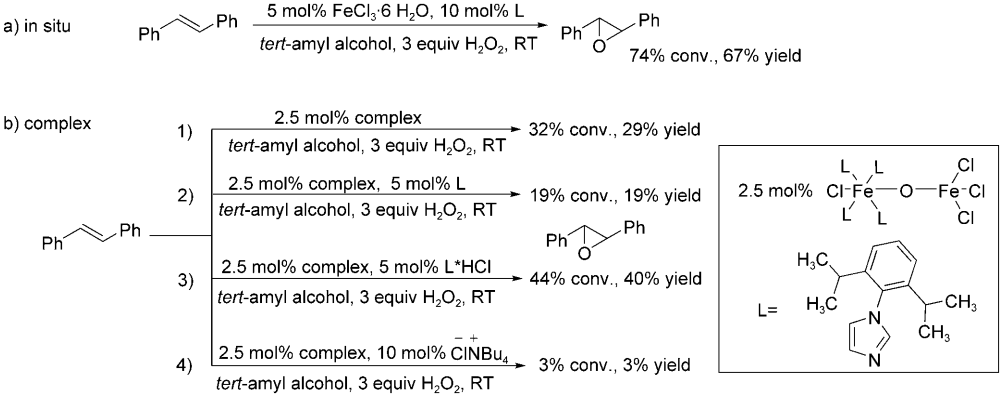
In conclusion, we have developed and examined novel bioinspired iron catalysts for hydrogen peroxide based epoxidation of both aromatic and aliphatic olefins. For the first time we have shown that defined iron imidazole complexes are capable of epoxidizing challenging aliphatic olefins. In general, high chemoselectivity is achieved, whereas cyclooctene and 2-methyl-1-heptene showed the best yields. Besides, mechanistic investigations demonstrate that mononuclear iron(III) species are in equilibrium with an μ-oxo diiron(III) complex by reaction with water. Three new defined molecular iron complexes were isolated and characterized by X-ray diffraction. Notably, these complexes show significant catalytic activity. Further work concerning transient oxygenated species and detailed information about the catalytic cycle is ongoing.

Experimental Section

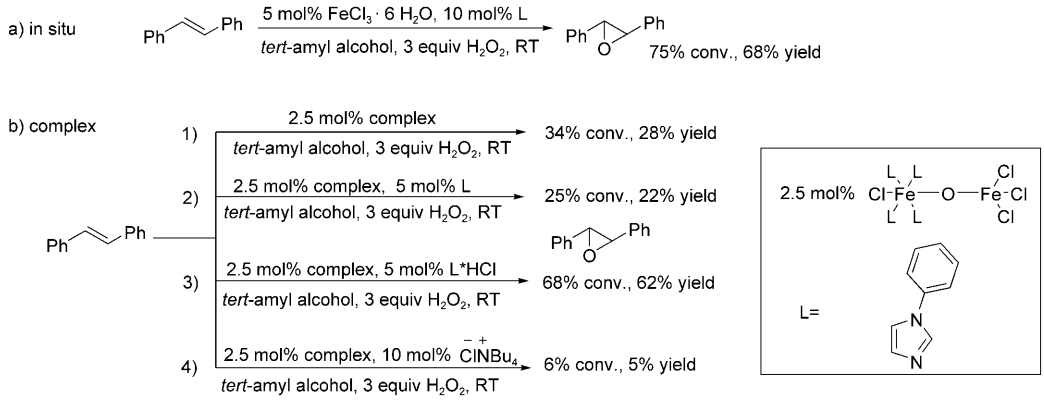
General remarks: The imidazole ligands (Table 2, entries 1, 4–10) were synthesized according to literature protocols.[40] All other reagents were used as purchased from commercial suppliers (Aldrich, Fluka, Merck, etc.) without further purification. "30%" aqueous H_2O_2 from Merck was used as received. The peroxide content varied from 30 to 40%, as determined by titration. GC analyses were performed with a Hewlett Packard HP 6890 model spectrometer. GC calibrations for alkenes and epoxides were carried out with authentic samples and dodecane as internal standard. NMR spectra were measured on a Bruker ARX 300 or ARX 400 spectrometer. For more analytical details, see Supporting Information.

Epoxidation of olefins (general procedure): In a test tube, $FeCl_3 \cdot 6H_2O$ (0.025 mmol), *tert*-amyl alcohol (9 mL), imidazole ligand (0.050 mmol), olefin (0.50 mmol) and dodecane (GC internal standard, 100 μL) were added in sequence at room temperature in air. A solution of 30% aqueous hydrogen peroxide (170 μL, 1.5 mmol) in *tert*-amyl alcohol (830 μL) was added to this mixture over 1 h at room temperature by a syringe pump. Conversion and yield were determined by GC analysis without further manipulations.

UV/Vis analysis: UV/Vis measurements were performed at 20°C with a Specord S600 spectral photometer. 1 cm quartz cuvettes were used with solutions prepared as follows: In analogy to the reaction, $FeCl_3 \cdot 6H_2O$ (6.76 mg, 0.05 mmol) was stirred together with *x* equiv imidazole in 9 mL of *tert*-amyl alcohol. From the clear solution 3 mL was transferred into



Scheme 6. Activity of the synthesized iron(III)complex with *N*-(2,6-diisopropyl)phenylimidazole (**5**).



Scheme 7. Activity of the synthesized iron(III) complex with *N*-phenylimidazole.

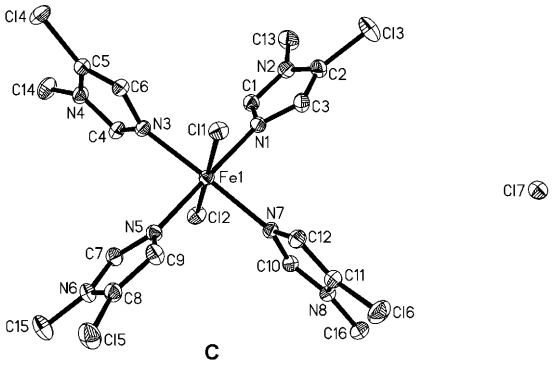


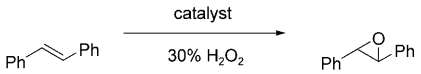
Figure 7. Molecular structure of *trans*-[$FeCl_2$(5-chloro-*N*-methylimidazole)$_4$]Cl (**C**). Thermal ellipsoids correspond to 30% probability. Hydrogen atoms are omitted for clarity.

quartz cuvettes. Temperature-controlled measurements were recorded at four different wavelengths and at least three times for every data point.

X-ray crystal structure analysis: Data were collected on a STOE IPDS II diffractometer using graphite-monochromated $Mo_{K\alpha}$ radiation. The structures were solved by direct methods (SHELXS-97)[41] and refined by full-matrix least-squares techniques on F^2 (SHELXL-97)[40] XP (Bruker AXS) was used for graphical representations.

Compound **A**: $C_{60}H_{80}Cl_4Fe_2N_8O$, $M_r = 1182.82$, triclinic, space group $P\bar{1}$, $a = 11.8817(5)$, $b = 13.3486(5)$, $c = 22.0564(9)$ Å, $\alpha = 103.311(3)$, $\beta = 105.083(3)$, $\gamma = 94.950(3)°$, $V = 3246.9(2)$ Å^3, $Z = 2$, $\rho_{calcd} = 1.210\ g\,cm^{-3}$, $\mu = 0.654\ mm^{-1}$, $T = 200$ K, 52163 reflections measured, 14921 independent reflections ($R_{int} = 0.0817$), of which 6593 were observed ($I > 2\sigma(I)$), $R_1 = 0.0407$ ($I > 2\sigma(I)$), $wR_2 = 0.0697$ (all data), 668 refined parameters.

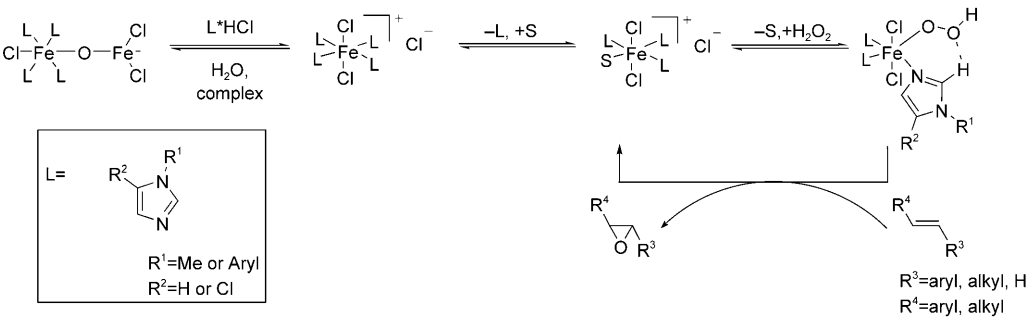
Table 5. Comparison of the in situ catalyst system and defined iron complexes.[a]



Entry	Catalyst system	Conversion [%][c]	Yield [%][c]	Selectivity [%][d]
1[a]	*trans*-[$FeCl_2$(5-Cl-1-MeIm)$_4$]Cl	99	91	92
2[a]	in situ system (5-Cl-1-MeIm)	91	84	93
3[b]	*trans*-[$FeCl_2$(imidazole)$_4$]Cl	33	26	77
4[b]	in situ system (imidazole)	21	18	85

[a] Reaction conditions: 0.25 mmol *trans*-stilbene, 5 mol% iron complex (e.g., 5 mol% $FeCl_3 \cdot 6H_2O$ and 20 mol% 5-chloro-1-methylimidazole), *tert*-amyl alcohol (5 mL), 0.44 mmol dodecane as internal standard were added in sequence at room temperature in air. To this mixture, a solution of 30% H_2O_2 (85 μL, 0.75 mmol) in *tert*-amyl alcohol (915 μL) was added over 1 h at room temperature by syringe pump. [b] Reaction conditions: 0.5 mmol *trans*-stilbene, 5 mol% iron complex (e.g., 5 mol% $FeCl_3 \cdot 6H_2O$ and 20 mol% imidazole), *tert*-amyl alcohol (9 mL), 0.44 mmol dodecane as internal standard were added in sequence at room temperature in air. To this mixture, a solution of 30% H_2O_2 (115 μL, 1.0 mmol) in *tert*-amyl alcohol (885 μL) was added over 1 h at room temperature by syringe pump. [c] Conversion and yield were determined by GC analysis. [d] Selectivity refers to the chemoselectivity of epoxide from olefin.

Compound **B**: $C_{36}H_{32}Cl_4Fe_2N_8O$, $M_r = 846.20$, monoclinic, space group $P2_1/n$, $a = 13.8321(5)$, $b = 15.7173(4)$, $c = 23.4636(10)$ Å, $\beta = 104.677(3)°$, $V = 4934.6(3)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.139\ g\,cm^{-3}$, $\mu = 0.836\ mm^{-1}$, $T = 200$ K, 53587 reflections measured, 9186 independent reflections ($R_{int} = 0.0594$), of which 4872 were observed ($I > 2\sigma(I)$), $R_1 = 0.0356$ ($I > 2\sigma(I)$), $wR_2 =$



Scheme 8. Proposed mechanism of the epoxidation reaction with the iron/imidazole system.

0.0727 (all data), 412 refined parameters. PLATON/SQUEEZE[42] was used to remove disordered solvent.

Compound **C**: $C_{16}H_{25}Cl_7FeN_8O_{2.5}$, $M_r = 673.44$, monoclinic, space group $C2/c$, $a = 13.6304(3)$, $b = 13.2331(3)$, $c = 30.5846(6)$ Å, $\beta = 92.843(2)°$, $V = 5509.8(2)$ Å^3, $Z = 8$, $\rho_{calcd} = 1.624$ g cm^{-3}, $\mu = 1.259$ mm^{-1}, $T = 200$ K, 40596 reflections measured, 5829 independent reflections ($R_{int} = 0.0349$), of which 4264 were observed ($I > 2\sigma(I)$), $R_1 = 0.0335$ ($I > 2\sigma(I)$), $wR_2 = 0.0864$ (all data), 317 refined parameters.

CCDC-714375, CCDC-714376, and CCDC-714377 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif

Acknowledgements

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