Pure Appl. Chem., Vol. 84, No. 8, pp. 1685–1704, 2012.
http://dx.doi.org/10.1351/PAC-CON-11-11-08

Practical iron-catalyzed atom/group transfer and insertion reactions*

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Abstract: Iron-catalyzed reactions are receiving a surge of interest owing to the natural abundance and biocompatibility of Fe and the urge to develop practically useful sustainable catalysis for fine chemical industries. This article is a brief account of our studies on the C–O and C–N bond formation reactions catalyzed by Fe complexes supported by oligopyridine, macrocyclic tetraaza, and fluorinated porphyrin ligands. The working principle is the in situ generation of reactive Fe=O and Fe=NR intermediates supported by these oxidatively robust N-donor ligands for oxygen atom/nitrogen group transfer and insertion reactions. The catalytic reactions include C–H bond oxidation of saturated hydrocarbons (up to 87 % yield), epoxidation of alkenes (up to 96 % yield), *cis*-dihydroxylation of alkenes (up to 99 % yield), epoxidation–isomerization (E–I) reaction of aryl alkenes (up to 94 % yield), amination of C–H bonds (up to 95 % yield), aziridination of alkenes (up to 95 % yield), sulfimidation of sulfides (up to 96 % yield), and amide formation from aldehydes (up to 89 % yield). Many of these catalytic reactions feature high regio- and diastereoselectivity and/or high product yields and substrate conversions, and recyclability of the catalyst, demonstrating the applicability of Fe-catalyzed oxidative organic transformation reactions in practical organic synthesis.

Keywords: amidation; catalysis; atom/group transfer; iron; oxidation.

INTRODUCTION

Being the most abundant transition metal on Earth and a key metal in a number of metalloproteins, Fe offers significant advantages, including being *cheap*, *biocompatible*, *sustainable*, and *green*, compared with Pt group transition metals such as ruthenium and palladium. Fe has a wide range of oxidation states, thus allowing formation of reactive Fe-ligand multiple-bonded (e.g., Fe=O and Fe=N) species in high oxidation states. Such species have been postulated as active reaction intermediates in many heme- and nonheme-mediated biological processes. Examples include Fe^{IV}=O and/or Fe^{V}=O species in biological oxidations mediated by cytochrome P450 [1], methane monooxygenase (MMO) [2] and Rieske dioxygenase [3], and the putative Fe=NH or Fe≡N species in nitrogen fixation mediated by nitrogenase [4].

Pure Appl. Chem.* **84, 1673–1784 (2012). A collection of invited papers based on presentations at the 16th International Symposium on Organometallic Chemistry Directed Towards Organic Synthesis (OMCOS-16), Shanghai, China, 24–28 July 2011.
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In recent years, there has been a surge of interest in seeking first-row transition-metal alternatives for Pt group metal catalysts as a result of the rising concern for sustainable future and environmental protection. In spite of several successful examples of Fe catalysis in industries such as Fischer–Tropsch synthesis in oil refinery process and Haber–Bosch nitrogen-fixation process, examples of Fe catalysis that are operationally simple and can be used in practical fine chemical industry are scarce.

One approach to develop Fe catalysis is to ride on the advantages of the extensive works on biomimetic Fe complexes to produce a panel of Fe catalysts that could match the catalytic activity of heme or nonheme enzymes. A vital hitch is that simple ligand architecture cannot offer the same protective surrounding as the active site in Fe-containing enzymes, causing the synthetic analogues to suffer from demetalation, ligand decomposition, or activity deterioration in the course of catalysis, particularly in an oxidative environment.

Our development of Fe catalysis followed our previous studies on C=C and C–H bond oxidation by oxygen atom transfer of ruthenium-oxo complexes including *trans*- [5,25] and *cis*-dioxoruthenium(VI) [6] and alkene aziridination and C–H bond amination by nitrogen group transfer of bisimidoruthenium(VI) complexes [7]. We endeavored to explore the possibility of extending the chemistry of high-valent metal-oxo and metal-imido complexes from Ru to Fe (Fig. 1), and to use strongly chelating and oxidatively robust ligands to develop practical Fe catalysis for organic synthesis. The types of Fe-catalyzed atom or group transfer reactions described herein are depicted in Fig. 1.

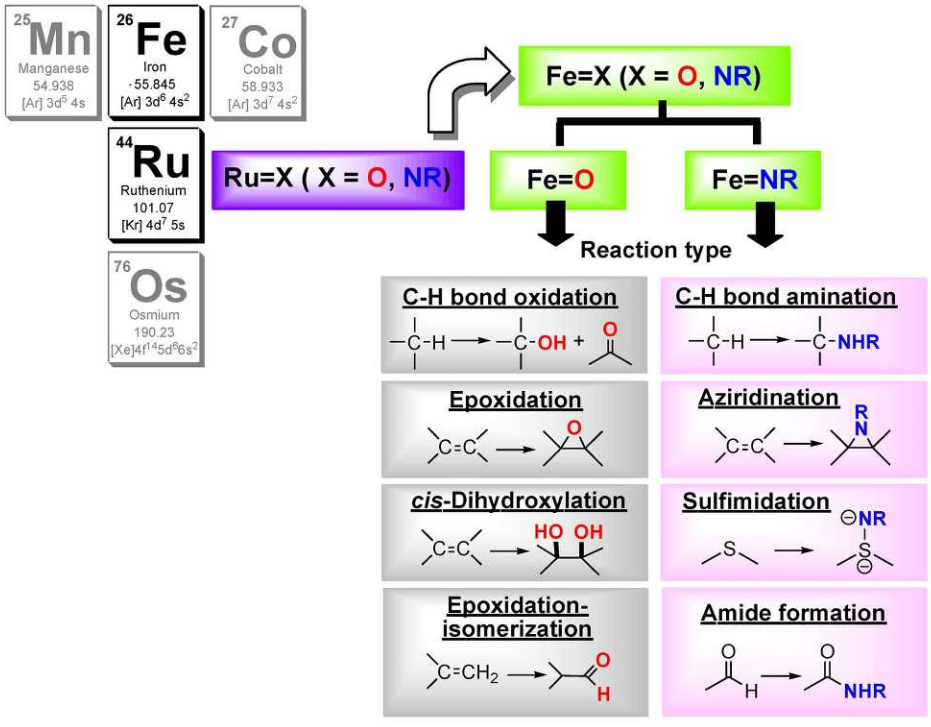


Fig. 1 Fe-catalyzed oxygen atom transfer and nitrogen group transfer reactions involved in this article.

IRON-CATALYZED OXYGEN ATOM TRANSFER REACTIONS

In 1983, Barton and co-workers reported preferential oxidation at secondary (2°) C–H bonds of adamantane catalyzed by Fe^{II}/Fe^{III} compounds in the presence of pyridyl ligands under aerobic conditions, later known as Gif chemistry. The reactive nonheme high-valent Fe-oxo species supported by

N-donor ligands [Fe^{V}-oxo and/or Fe^{IV}-oxo species] were postulated to be directly responsible for C–H bond hydroxylation [8]. Shortly thereafter, extensive studies on reaction conditions, as well as debates on the mechanism of Gif chemistry against Fenton chemistry [9], appeared in the literature.

Since the discovery of Gif chemistry, tremendous studies on nonheme catalyzed C–H bond oxidation have been reported [10]. In 2003, Que and co-worker reported the first X-ray crystal structure of mononuclear nonheme Fe^{IV}-oxo complex $[Fe^{IV}(O)(tmc)(MeCN)](OTf)_2$ [11]. Similar examples of structurally characterized Fe^{IV}-oxo complexes were subsequently reported [12]. Recently, the Fe^{V}-oxo complex $[Fe^{V}(O)(TMAL)]^{-}$ with its structure characterized by X-ray analysis and spectroscopic means was reported by Collins and co-workers [13].

Despite the fact that many ligand systems have been designed for Fe-catalyzed oxidation of C–H and C=C bonds, the reported Fe catalysts display one or several of the following limitations: incomplete substrate conversion, formation of significant amount of side product(s), used in largely excess substrate(s), relatively narrow scope of substrates, demetalation of Fe catalyst, and oxidative decomposition of the organic ligand.

In our endeavor to develop Fe-catalyzed organic reactions, we found that pyridyl ligands are oxidatively robust, thereby improving the stability of the as-formed Fe catalysts. Because of their robustness, recycling of pyridyl ligands becomes feasible. Another benefit of using pyridyl ligands is that they are strong chelator to Fe^{II} center [14], thus allowing rapid in situ regeneration of the Fe catalyst by simple addition of new batch of Fe salt to the reaction mixture. We have employed a series of Fe catalysts with N-donor ligands including oligopyridines, trichloroterpyridine, and N_4-macrocyclic tetraaza ligand, for practical organic transformations. The structures of these catalysts are depicted in Fig. 2.

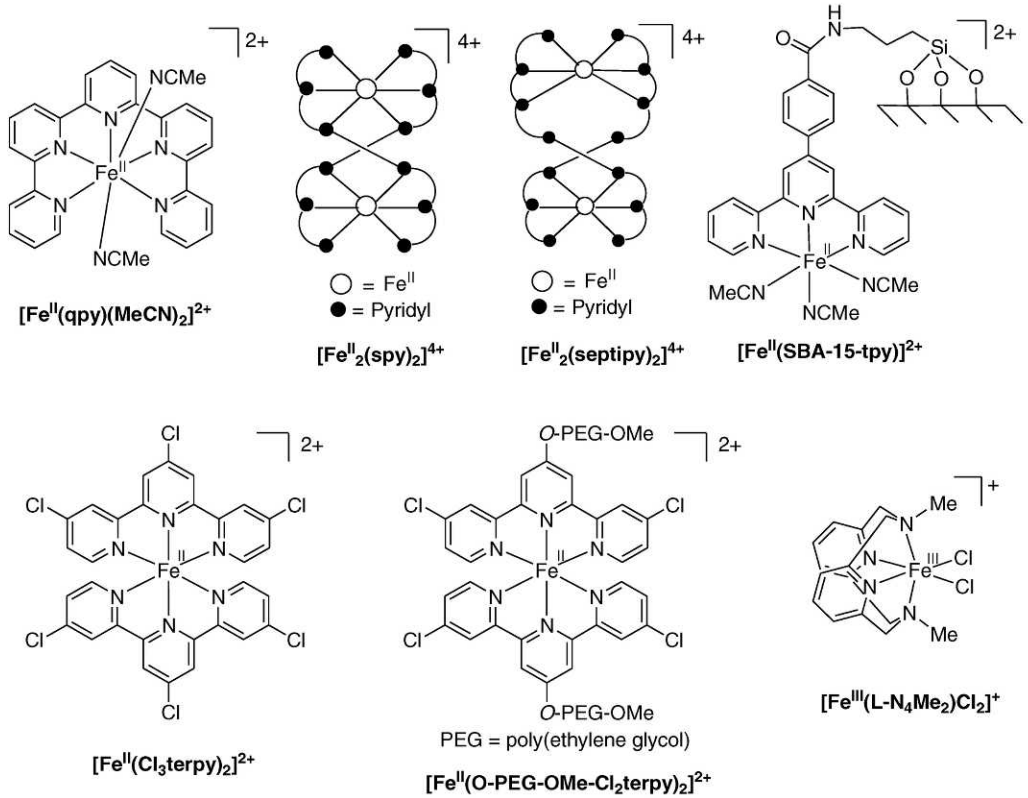


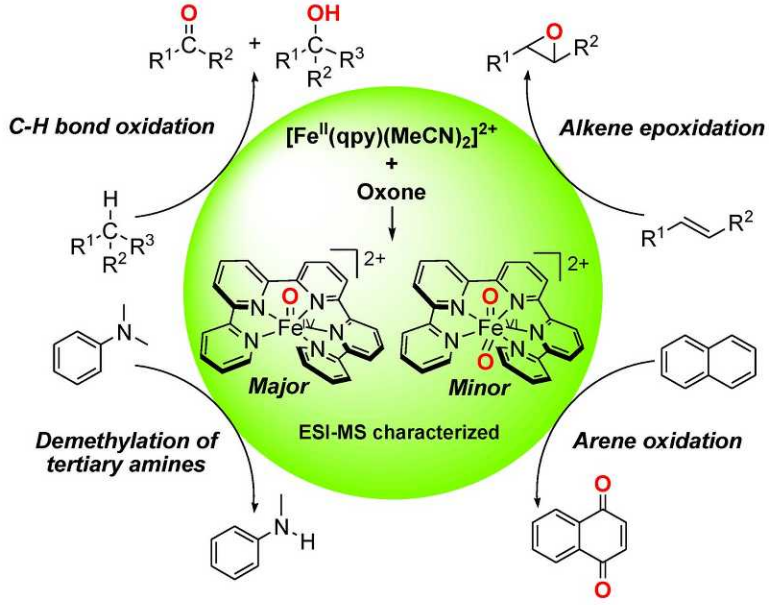
Fig. 2 Structures of Fe complexes involved in this article.

Oxygen atom transfer toward C–H bonds

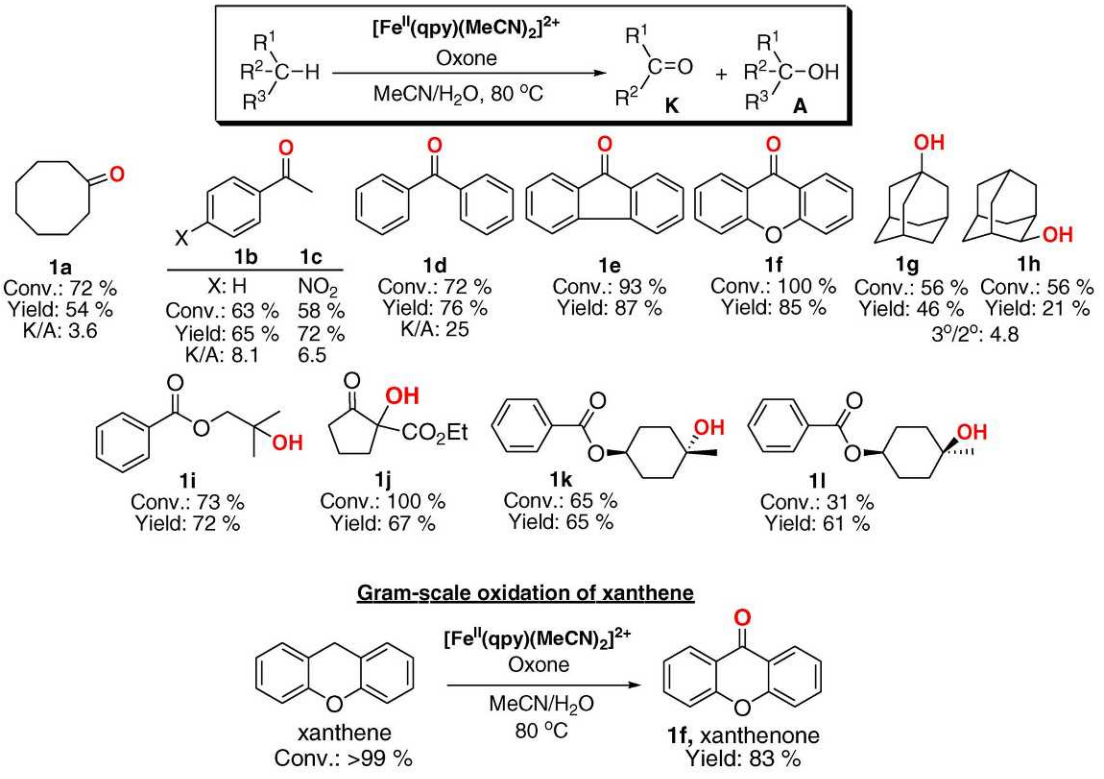
A notable Fe system for alkane C–H bond oxidation was reported by White and Chen in 2007 using $[Fe^{II}(S,S\text{-PDP})(MeCN)_2]^{2+}$ as catalyst and H_2O_2 as terminal oxidant in the presence of acetic acid, exhibiting selectivity toward tertiary (3°) C–H bonds in the oxidation of unactivated aliphatic alkanes [15]. The system could be applied to selective oxidation of complex natural compounds such as (+)-artemisinin [15], (–)-ambroxide [16], and (–)-dihydropleuromutilone [16].

We previously studied the oxidation of C–H bonds catalyzed by Ru complexes such as $[Ru^{II}(F_{20}TPP)(CO)]$-PEG [$F_{20}TPP$ = 5,10,15,20-tetrakis(pentafluorophenyl)porphyrinato dianion] [17] and $[Ru^{II}(D_4\text{-Por*})(CO)]$ [18] using 2,6-dichloropyridine *N*-oxide (2,6-Cl_2pyNO) as terminal oxidant. The $[Ru^{II}(F_{20}TPP)(CO)]$-PEG-catalyzed oxidation of adamantane led to 65 % substrate conversion and afforded 1-adamantanol in 80 % yield (based on conversion) [17]. Enantioselective oxidation of the benzylic C–H bonds of ethylbenzenes catalyzed by $[Ru^{II}(D_4\text{-Por*})(CO)]$ gave (*S*)-1-phenylethanols with up to 76 % ee [18].

Very recently, we found that Fe oligopyridine complexes $[Fe^{II}(qpy)(MeCN)_2]^{2+}$, $[Fe^{II}_2(spy)_2]^{4+}$, $[Fe^{II}_2(septipy)_2]^{4+}$, and SBA-supported $[Fe^{II}(SBA\text{-}15\text{-}tpy)]^{2+}$ (Fig. 2) are active catalysts for oxidation of various organic compounds including alkanes, alkenes, arenes, tertiary amines, and *N*-acryl cyclic amines using Oxone as terminal oxidant (Scheme 1) [19]. The "$[Fe^{II}(qpy)(MeCN)_2]^{2+}$ + Oxone" system can effectively oxidize saturated C–H bonds to ketones and/or alcohols (**1a–l**) with product yields of up to 87 % (**1e**) and ketone to alcohol (K/A) ratios of up to 25 (**1d**) as depicted in Scheme 2. Notably, this system can be scaled up to 10 mmol scale in the oxidation of xanthene, affording xanthenone (**1f**) in 83 % yield with >99 % substrate conversion (Scheme 2).



Scheme 1 $[Fe^{II}(qpy)(MeCN)_2]^{2+}$-catalyzed oxidation of various organic compounds with Oxone.



Scheme 2 $[Fe^{II}(qpy)(MeCN)_2]^{2+}$-catalyzed C–H bond oxidation with Oxone.

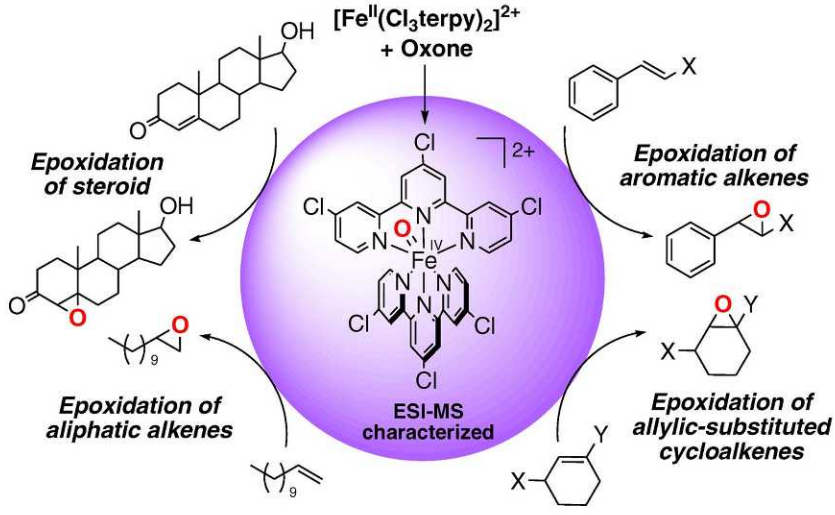
The oxidation reactions catalyzed by Fe oligopyridine complexes with Oxone as terminal oxidant are likely to involve reactive Fe=O intermediates. Formation of a mixture of Fe=O species, predominantly Fe^{IV}-oxo species (such as $[Fe^{IV}(qpy)O]^{2+}$, Scheme 1) with minor amount of dioxoiron(VI) species (such as $[Fe^{VI}(qpy)O_2]^{2+}$, Scheme 1), was suggested by high-resolution electrospray ionization-mass spectrometry (ESI-MS) analysis of both reactions of $[Fe^{II}(qpy)(MeCN)_2]^{2+}$ and $[Fe^{II}_2(septipy)_2]^{4+}$ with Oxone [19]. In a previous work [20], we performed density functional theory (DFT) calculations on *trans*-dioxoiron(VI) complex $[Fe(NH_3)_2(NMeH_2)_2O_2]^{2+}$, together with detection of $[Fe^{VI}(qpy)O_2]^{2+}$ by ESI-MS analysis.

Oxygen atom transfer to C=C bonds

Epoxidation of alkenes

Despite numerous studies on Fe porphyrin-catalyzed epoxidation of alkenes with various oxidants [21], practical nonheme Fe catalysts for alkene epoxidation remain sparse in the literature. A pioneering work in this area is by Valentine and co-workers using $[Fe^{II}(cyclam)(OTf)_2]$ as catalyst and H_2O_2 as terminal oxidant; this system is capable of oxidizing *cis*-stilbene to corresponding *cis*-epoxide with high stereoretention (*cis*/*trans* = 94:6) [22]. Another notable example was reported by Beller and co-workers using simple Fe^{III} salt in combination with pyridine-2,6-dicarboxylic acid and pyrrolidine and with H_2O_2 as terminal oxidant, showing high reactivity and excellent selectivity for the epoxidation of electron-rich aromatic alkenes such as styrenes [23].

In our earlier work, we studied the aerobic epoxidation of styrenes catalyzed by ruthenium porphyrins, such as $[Ru^{VI}(\beta\text{-}Ph_8\text{-}tpp)O_2]$ [24] and $[Ru^{II}(D_4\text{-}Por^*)(CO)]$ [25]. Subsequent efforts were



Scheme 3 $[Fe^{II}(Cl_3terpy)_2]^{2+}$-catalyzed epoxidation of alkenes with Oxone.

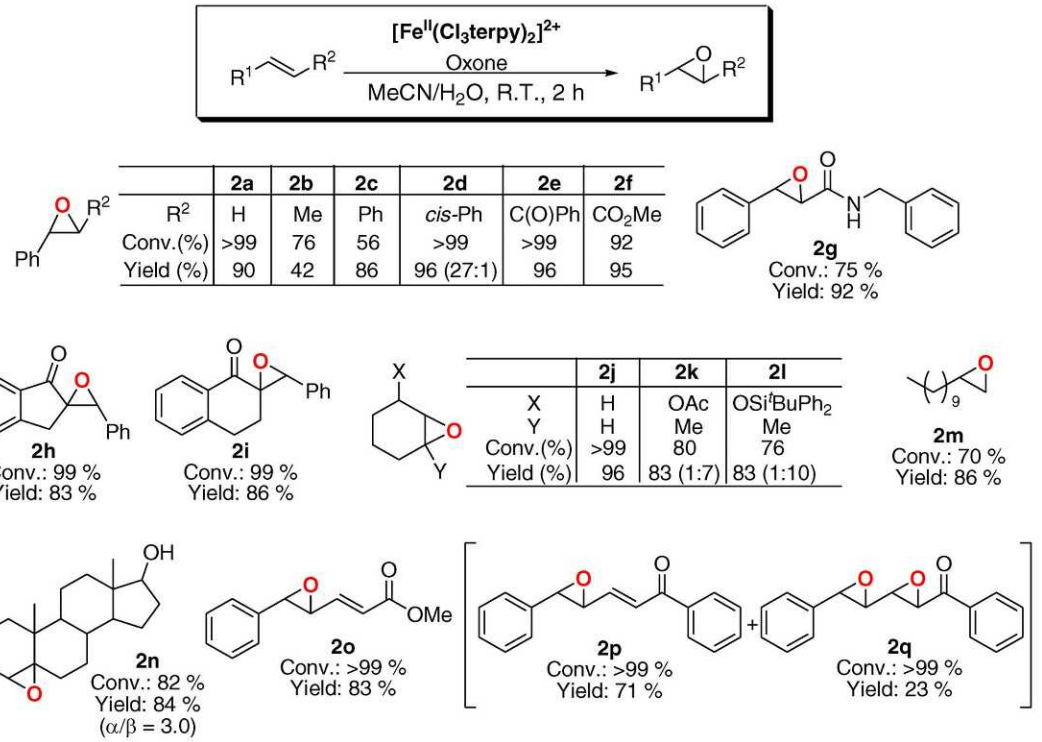
devoted to the development of a practical catalyst for alkene epoxidation, and $[Ru^{II}(2,6\text{-}Cl_2tpp)(CO)]$-MCM-41 was found to be a good catalyst which gave a product turnover number (TON) of up to 4.6×10^3 [26]. Recently, we reported an oxidatively robust Fe^{II} catalyst, $[Fe^{II}(Cl_3terpy)_2]^{2+}$, and its polymer-supported derivative, $[Fe^{II}(O\text{-PEG-OMe-}Cl_2terpy)_2]^{2+}$ (Fig. 2), for epoxidation of various alkenes with Oxone as terminal oxidant under mild conditions (Scheme 3) [27].

The "$[Fe^{II}(Cl_3terpy)_2]^{2+}$ + Oxone" system, like the system employing catalyst $[Fe^{II}(qpy)(MeCN)_2]^{2+}$ [19], could effectively oxidize both electron-rich and -deficient alkenes to their corresponding epoxides (**2a–p**) in good-to-excellent yields (up to 96 %) at room temperature after 2 h, demonstrating good tolerance of various functional groups including ester and unprotected hydroxyl groups (Scheme 4). The epoxides of allylic-substituted cycloalkenes (**2j–l**) could be obtained in up to 96 % yield with diastereomeric ratio of 1:7 or 1:10. Steroid was selectively oxidized to corresponding epoxide (**2n**) with α/β ratio of 3.0 (Scheme 4).

In the epoxidation of α,β,γ,δ conjugated alkenes such as 2,4-pentadienophenone and 5-phenyl-2,4-pentadienoic acid methyl ester, γ,δ-monoepoxide (**2p**, 71 % yield) and α,β,γ,δ-diepoxide (**2q**, 23 % yield) were obtained for the former substrate, and only γ,δ-monoepoxide (**2o**, 83 % yield) was obtained for the latter substrate (Scheme 4). In contrast, the epoxidation of these substrates with $2,6\text{-}Cl_2$pyNO catalyzed by a Ru porphyrin afforded α,β-monoepoxide as the major product [28].

Compared with simple terpyridine, the Cl_3terpy ligand is more oxidatively robust and could be recovered from the reaction mixture. The ligand was reused simply by adding a new batch of Fe^{II} salt to the reaction mixture to regenerate the $[Fe^{II}(Cl_3terpy)_2]^{2+}$ complex in situ. A PEG-supported ligand, *O*-PEG-OMe-Cl_2terpy, could be easily separated from the reaction products and was recycled for up to five runs for the epoxidation of chalcone, with chalcone α,β epoxide (**2e**) obtained in 93 % yield (89 % substrate conversion) on completion of five runs [27].

On the basis of the high stereoselectivity observed in the $[Fe^{II}(Cl_3terpy)_2]^{2+}$-catalyzed epoxidation of *cis*-stilbene and the detection of Fe^{IV}-oxo species $[Fe^{IV}(Cl_3terpy)_2O]^{2+}$ (Scheme 3) from the reaction mixture by ESI-MS, the involvement of high-valent Fe=O intermediate responsible for the oxygen atom transfer reaction was proposed.



	2a	2b	2c	2d	2e	2f
R^2	H	Me	Ph	*cis*-Ph	C(O)Ph	CO_2Me
Conv.(%)	>99	76	56	>99	>99	92
Yield (%)	90	42	86	96 (27:1)	96	95

	2j	2k	2l
X	H	OAc	OSi^tBuPh_2
Y	H	Me	Me
Conv.(%)	>99	80	76
Yield (%)	96	83 (1:7)	83 (1:10)

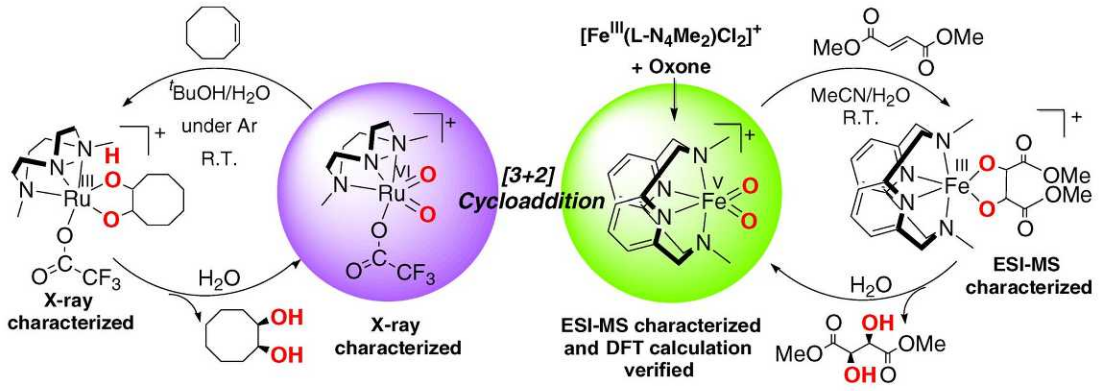
Scheme 4 $[Fe^{II}(Cl_3terpy)_2]^{2+}$-catalyzed epoxidation of alkenes with Oxone.

cis-Dihydroxylation of alkenes

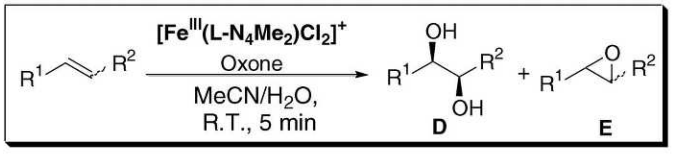
Fe-catalyzed *cis*-dihydroxylation of alkenes was pioneered by Que and co-workers [29], and a high product yield (73–87 %) was achieved for several electron-rich alkenes with moderate diol selectivity (1.5–4.3 diol to epoxide ratio) by using $[Fe^{II}(5\text{-}Me_3tpa)(MeCN)_2]^{2+}$ as catalyst and with H_2O_2 as terminal oxidant [30]. To date, the development of a practical non-osmium-based alkene *cis*-dihydroxylation system that can offer comparable effectiveness as Sharpless "AD-mix" protocol [31] remains a formidable challenge.

Our interest in Fe-catalyzed *cis*-dihydroxylation of alkenes was initiated by our previous work on successful isolation of a reactive *cis*-dioxoruthenium(VI) complex, $[Ru^{VI}(Me_3tacn)O_2(O_2CCF_3)]^+$, which is capable of oxidizing alkenes to *cis*-diols through a [3 + 2] cycloaddition mechanism (Scheme 5) [32a]. A "$[Ru^{III}(Me_3tacn)Cl_3] + H_2O_2$" protocol was subsequently developed and optimized to give impressive catalytic reactivities toward *cis*-dihydroxylation of electron-rich alkenes to *cis*-diols in up to 96 % yield. This protocol could be performed in a ~100 g scale in the oxidation of cyclic alkenes providing *cis*-diols in up to 92 % yield [32b].

Recently, we employed the Fe catalyst $[Fe^{III}(L\text{-}N_4Me_2)Cl_2]^+$ (Fig. 2) for *cis*-dihydroxylation of various alkenes with Oxone at room temperature using limiting amount of substrates [33]. For the oxidation of electron-rich alkenes, nearly complete substrate conversion was achieved and *cis*-diol (**3a–c,i,k**) was formed in up to 67 % yield with *cis*-diol to epoxide ratio (D/E) of up to 16.8 (**3a**) (Scheme 6). Striking performance was found in the oxidation of electron-deficient alkenes, affording corresponding *cis*-diols as major product (**3d–h,j,l,m**) in up to 99 % yield with up to 99 % substrate conversion within 5 min at room temperature (Scheme 6). Particularly, the $[Fe^{III}(L\text{-}N_4Me_2)Cl_2]^+$-catalyzed alkene *cis*-dihydroxylation could be scaled up to a 10 g scale by using methyl cinnamate as substrate, affording the *cis*-diol product (**3d**) in 84 % yield with 85 % substrate conversion (Scheme 6). The



Scheme 5 Non-osmium *cis*-dihydroxylation of alkenes developed by our group.



	3a	3b	3c
X	H	OMe	Cl
Conv.(%)	>99	>99	>99
Yield (%)	67	46	65
D/E	16.8	---	7.2

	3d	3e	3f	3g	3h
X	OMe	Me	NHMe	NMe_2	Ph
Conv.(%)	94	92	90	90	>99
Yield (%)	81	65	73	72	75
D/E	20.3	10.8	14.6	12	8.5

3i Conv.: 96 % Yield: 60 % D/E: 12

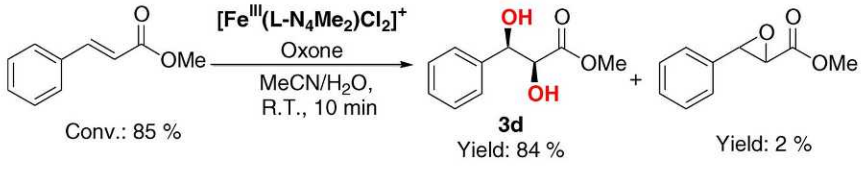
3j Conv.: 94 % Yield: 67 %

3k Conv.: 71 % Yield: 64 %

3l Conv.: >99 % Yield: 99 %

3m Conv.: 94 % Yield: 77 %

10 Gram-scale *cis*-dihydroxylation of methyl cinnamate



Scheme 6 $[Fe^{III}(L\text{-}N_4Me_2)Cl_2]^+$-catalyzed *cis*-dihydroxylation of alkenes with Oxone.

"$[Fe^{III}(L\text{-}N_4Me_2)Cl_2]^+$ + Oxone" system was relatively green and simple and could serve as an alternative method for *cis*-diol production.

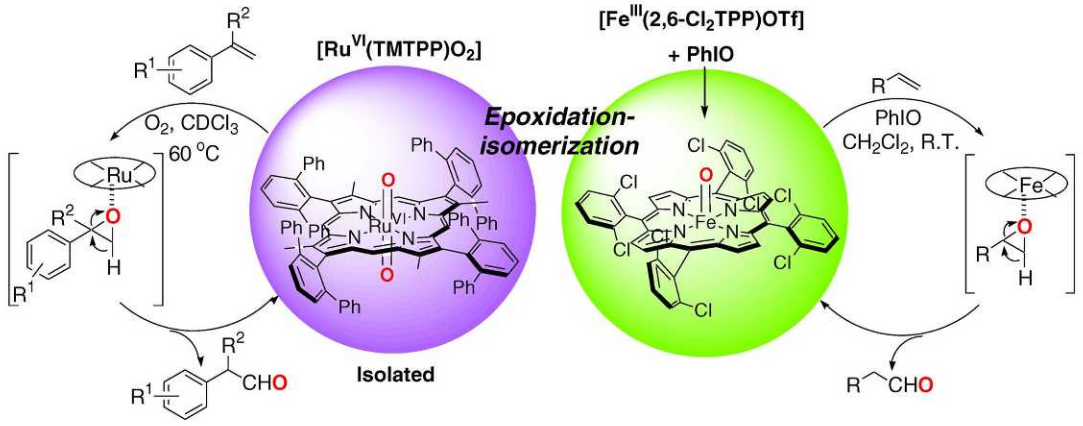
Mechanistic studies of the $[Fe^{III}(L\text{-}N_4Me_2)Cl_2]^+$-catalyzed alkene *cis*-dihydroxylation by high-resolution ESI-MS revealed the possible participation of reactive *cis*-dioxoiron(V) intermediate, $[Fe^{V}(L\text{-}N_4Me_2)O_2]^+$. Considering also the isotope labeling studies and DFT calculation results on the

$[Fe^{III}(L\text{-}N_4Me_2)Cl_2]^+$-catalyzed *cis*-dihydroxylation of dimethyl fumarate with Oxone, a concerted but highly asynchronous [3 + 2] cycloaddition pathway involving *cis*-dioxoiron(V), which is in line with our previous works on *cis*-dioxoruthenium(VI) complexes, was proposed.

Epoxidation–isomerization of alkenes

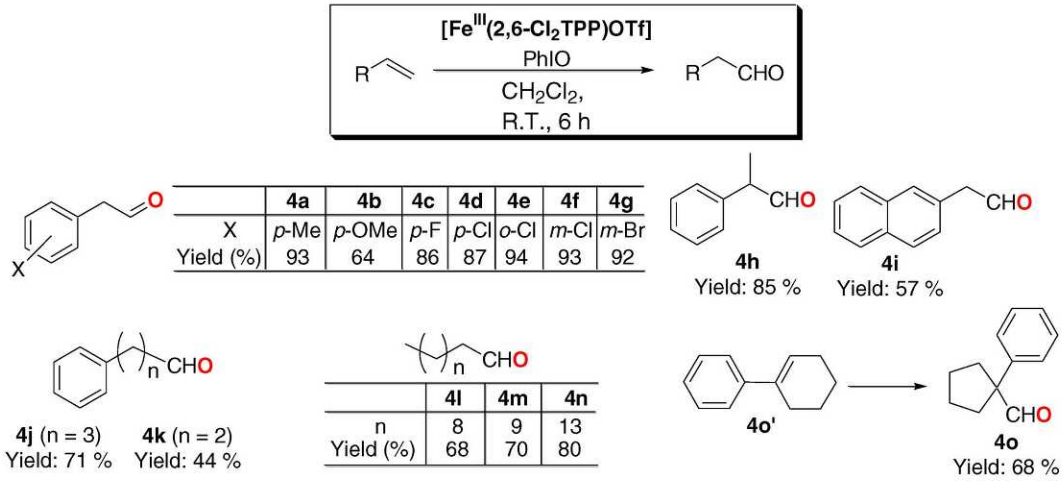
Other than the oxidation of alcohol and reduction of ester, direct oxidation of alkene to aldehyde or methyl ketone is an alternative route to aldehyde or ketone synthesis, as elegantly demonstrated by Wacker oxidation [34], a reaction that converts ethylene to acetaldehyde by dioxygen or air in the presence of $PdCl_2/CuCl_2$ as catalyst [34a].

Our early success in selective "Wacker-type" oxidation of alkenes was achieved by using ruthenium porphyrin $[Ru^{IV}(2,6\text{-}Cl_2TPP)Cl_2]$ or $[Ru^{IV}(TMP)Cl_2]$ as catalyst and with 2,6-Cl_2pyNO as oxidant; the aldehydes were obtained in up to 99 % yield with complete substrate conversion [35]. The reaction was found to proceed by a tandem epoxidation–isomerization (E–I) pathway. In 2008, we reported aerobic E-I reaction of terminal alkenes catalyzed by $[Ru^{IV}(TMP)Cl_2]$, $[Ru^{IV}(TMP)O_2]$, or $[Ru^{VI}(TMTPP)O_2]$ (Scheme 7) with a high efficiency and selectivity toward aldehyde formation (up to 94 % yield) [36]. The $[Ru^{VI}(TMTPP)O_2]$ catalyst was recycled up to five times without significant loss in catalytic performance, giving a total product TON of 1144. The substrate scope in the ruthenium porphyrin-catalyzed E–I reaction was confined to aryl alkenes such as styrenes; aliphatic alkenes remained unreactive.



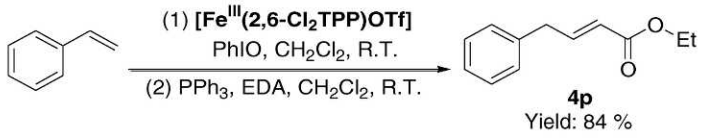
Scheme 7 Iron- and ruthenium-catalyzed E–I of alkenes developed by our group.

We recently extended the E–I reaction to Fe^{III} porphyrin catalyst $[Fe^{III}(2,6\text{-}Cl_2TPP)OTf]$ using iodosobenzene (PhIO) as terminal oxidant (Scheme 7) [37]. In the $[Fe^{III}(2,6\text{-}Cl_2TPP)OTf]$-catalyzed E–I reaction, both aryl and aliphatic alkenes could be oxidized to their corresponding aldehydes (**4a–o**) in good-to-high yields with no C=C bond cleavage observed (Scheme 8). Styrenes and closely related aryl alkenes were converted to aldehydes **4a–i** in yields (up to 94 %) comparable to those obtained for the Ru-catalyzed analogues. For the trisubstituted alkene **4o'** (Scheme 8), quaternary aldehyde **4o** was obtained in 68 % yield, probably resulting from alkyl migration in the isomerization step. Unlike Wacker oxidations of unfunctionalized aliphatic alkenes (except ethylene), which usually afford methyl ketone as the main product, the "$[Fe^{III}(2,6\text{-}Cl_2TPP)OTf]$ + PhIO" system selectively oxidizes aliphatic alkenes to aldehydes **4l–n** in up to 80 % yield (Scheme 8), providing a complementary method to the conventional Wacker oxidations.



Scheme 8 [Fe^{III}(2,6-Cl_2TPP)OTf]-catalyzed E–I of alkenes with PhIO.

Iron porphyrin has previously been reported to be an effective catalyst for olefination of aldehyde with ethyl diazoacetate (EDA) and Ph_3P [38]. By combining the Fe-catalyzed E–I reaction of alkene and Fe-catalyzed olefination of aldehyde, a one-pot synthesis of α,β-unsaturated ester (**4p**) from styrene was developed using [Fe^{III}(2,6-Cl_2TPP)OTf] as catalyst, with **4p** isolated in 84 % yield (Scheme 9) [37]. The system gives a good example of an "all-in-one" approach in versatile compound synthesis and fine chemicals process chemistry.



Scheme 9 [Fe^{III}(2,6-Cl_2TPP)OTf]-catalyzed one-pot synthesis of an α,β-unsaturated ester from styrene.

IRON-CATALYZED NITROGEN GROUP TRANSFER REACTIONS

Transition-metal-mediated nitrogen group transfer reactions constitute a powerful strategy for C–N bond formation. Since the pioneering works by Breslow [39] and Mansuy [40] and their co-workers in the 1980s, these types of reaction catalyzed by the compounds of a number of transition metals, such as Mn, Ru, Co, Rh, Cu, Ag, and Au, have been developed. An important development in this endeavor is the introduction of dirhodium(II,II) complexes as catalysts. Owing to the low natural abundance of Rh on Earth, there is a surge of interest to develop inexpensive and biocompatible metal complexes as alternatives to dirhodium(II,II) catalysts, particularly the interest in Fe catalysts for the construction of C–N bonds.

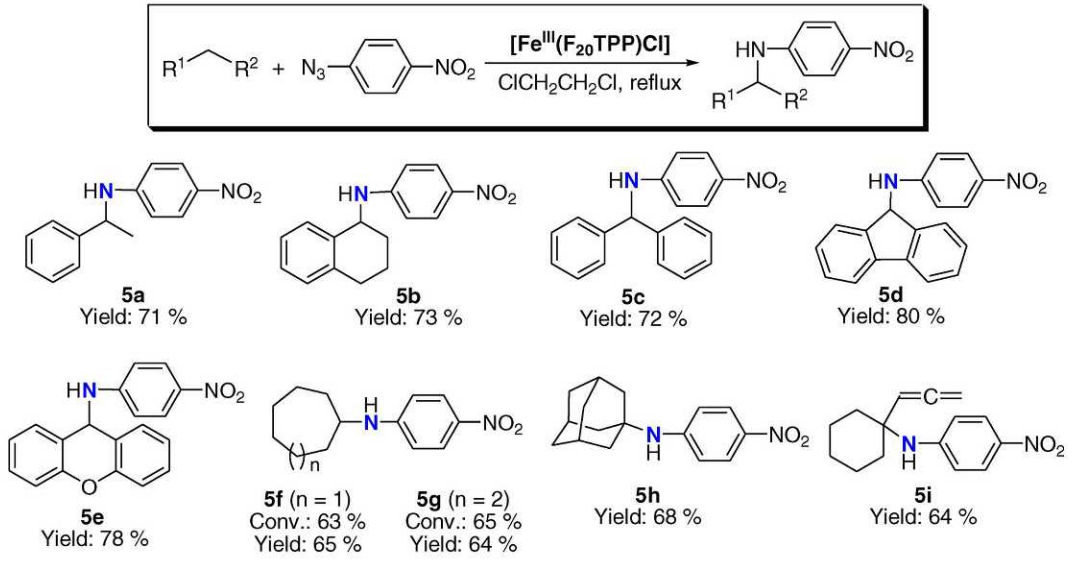
Nitrogen group transfer toward C–H bonds

Intermolecular amination of C–H bonds

The first examples of Fe-catalyzed inter- and intramolecular nitrogen group transfer to C–H bonds were reported in 1982 [39] and 1983 [41], respectively, by Breslow and Gellman. These reactions using [Fe^{III}(TPP)Cl] as catalyst resulted in the intermolecular amination of cyclohexane with iminoiodane

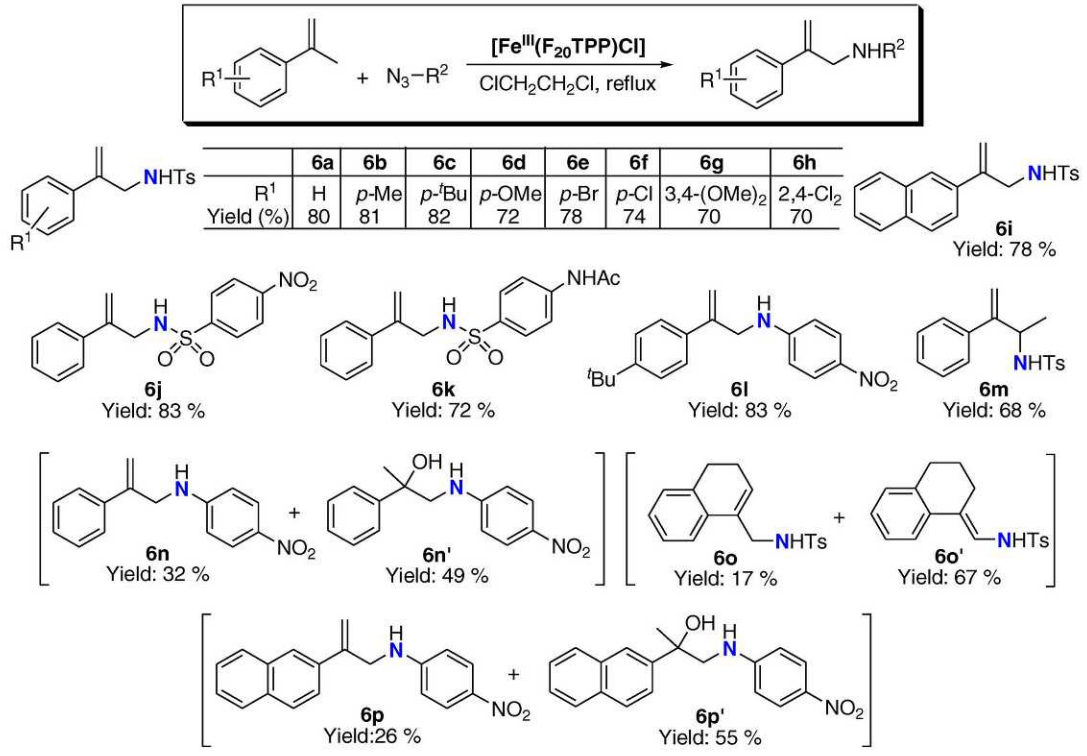
PhI=NTs (Ts = *p*-tosyl) to give about 10 % product yield [39] and the intramolecular amination of a PhI=NSO_2Ar derivative in 77 % product yield [41]. Afterwards, iminoiodanes such as PhI=NTs have been extensively used as the nitrogen source in metal-catalyzed nitrogen group transfer reactions. An alternative type of nitrogen source that has attracted much attention in recent years is organic azides, as the nitrogen group transfer using organic azides is more environmentally benign and has a higher atom economy (the byproduct is nitrogen gas, unlike the byproduct PhI formed from PhI=NSO_2Ar).

In 2010, we reported that [$Fe^{III}(F_{20}TPP)Cl$] is an effective catalyst for intermolecular nitrogen group transfer reactions with organic azides such as arylazides and arysulfonylazides as nitrogen sources [42]. Using this "[$Fe^{III}(F_{20}TPP)Cl$] + organic azide" protocol, the amination of saturated C–H bonds, including benzylic ones (**5a–e**) and that of cycloalkanes (**5f–i**), with 4-nitrophenyl azide gave product yields of up to 80 % (Scheme 10). For adamantane (**5h**), the amination reaction occurred at tertiary (3°) C–H bond; no products derived from secondary (2°) C–H bonds were detected. Similarly, 1-cyclohexylallene (**5i**) was also aminated at its 3° C–H bond, with the allene moiety and 2° C–H bonds remaining intact (Scheme 10).



Scheme 10 [$Fe^{III}(F_{20}TPP)Cl$]-catalyzed amination of saturated C–H bonds with 4-nitrophenyl azide.

Under similar reaction conditions, allylic amination took place when α-methylstyrenes were used as substrates. The reaction of 4-*tert*-butyl-α-methylstyrene with 4-nitrophenyl azide gave product **6l** in 83 % yield (Scheme 11). A panel of α-methylstyrenes reacted with arylsulfonylazides to afford allylic amination products in 68–83 % yields (**6a–k,m,o**, Scheme 11). However, for the reactions of α-methylstyrene and 2-isopropenyl-naphthalene with 4-nitrophenyl azide, both allylic amination (**6n,p**) and hydroxyamination products (**6n',p'**) were obtained. The allylic amination products might result from ring opening of aziridine intermediates, and the reaction should be viewed as a formal direct allylic C–H bond insertion. Ring opening and hydrolysis of the aziridine intermediates may give the hydroxyamination products.



Scheme 11 [$Fe^{III}(F_{20}TPP)Cl$]-catalyzed allylic amination of alkenes with organic azides.

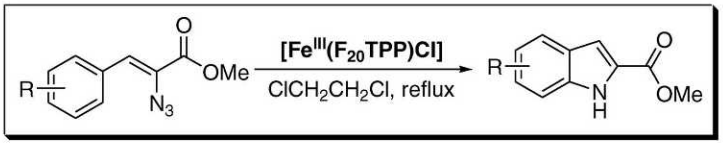
Intramolecular amination of C–H bonds

We have extended the application of "[$Fe^{III}(F_{20}TPP)Cl$] + organic azide" protocol to the intramolecular amination of C–H bonds, leading to the synthesis of alkaloids including indoles, indolines, tetrahydroquinolines, and dihydroquinazolinones (DQs) in high yields (Schemes 12–14) [43].

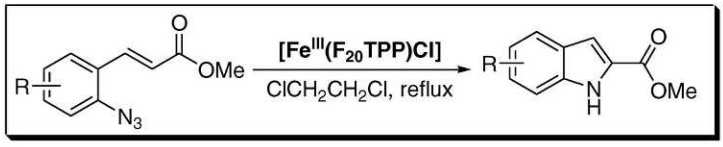
Methyl α-azido-cinnamates readily underwent intramolecular amination of aryl C–H bonds to give indoles (**7a–i**) in 85–95 % yields (Scheme 12). These results are comparable to those of the [$Rh^{II}_2(O_2CR)_4$]-catalyzed analogues reported by Driver and co-workers [44].

Indoles can also be formed by the intramolecular amination of vinyl C–H bonds from the *ortho*-azido-cinnamates; the corresponding indoles (**7a,8b–f)** were obtained in 86–91 % yields (Scheme 12). The electronic effect of substituent on the substrates in this reaction was found to be negligible.

Intramolecular amination of saturated C–H bonds was achieved using *ortho*-azido-alkylbenzenes and *ortho*-azido-benzamides as substrates. From the reaction of *ortho*-azido-alkylbenzenes, indolines (**9a,b**), indoles (**9e,f**), and tetrahydroquinolines (**9c,d** and **9g–j**) were obtained in 72–81 % yields with moderate diastereoselectivity (dr = 2–4:1) (Scheme 13). The amination of *ortho*-azidobenzamide derivatives gave DQs (**10a–h**) as major product in up to 83 % yield (Scheme 14). Quinazolinones (Q) were observed along with the DQs **10c–g** (DQ/Q = 3.7–8.1). Notably, the primary (1°) C–H bond of dimethylamine group was aminated to afford DQ **10f** in 63 % yield.



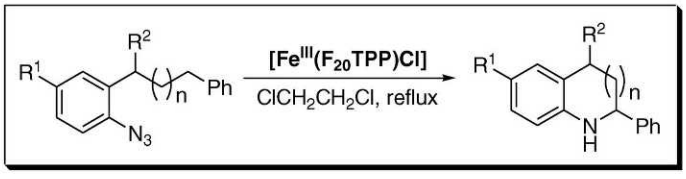
	7a	7b	7c	7d	7e	7f	7g	7h	7i
R	H	*p*-Me	*p*-^{t}Bu	*p*-OMe	*p*-Br	*p*-Cl	*o*-Cl	*p*-F	2,4-Cl_2
Yield (%)	91	93	93	95	89	89	88	90	85



	7a	8a	8b	8c	8d	8e
R	H	*p*-OMe	*p*-Br	*p*-Cl	*p*-F	2,4-$(OMe)_2$
Yield (%)	89	88	89	90	91	86

8f
Yield: 89 %

Scheme 12 [$Fe^{III}(F_{20}TPP)Cl$]-catalyzed intramolecular C–H bond amination of methyl α-azido-cinnamates and *ortho*-azido-cinnamates.



9a
Yield: 80 %

9b
Yield: 75 %

9c (R^1 = H)
Yield: 79 %

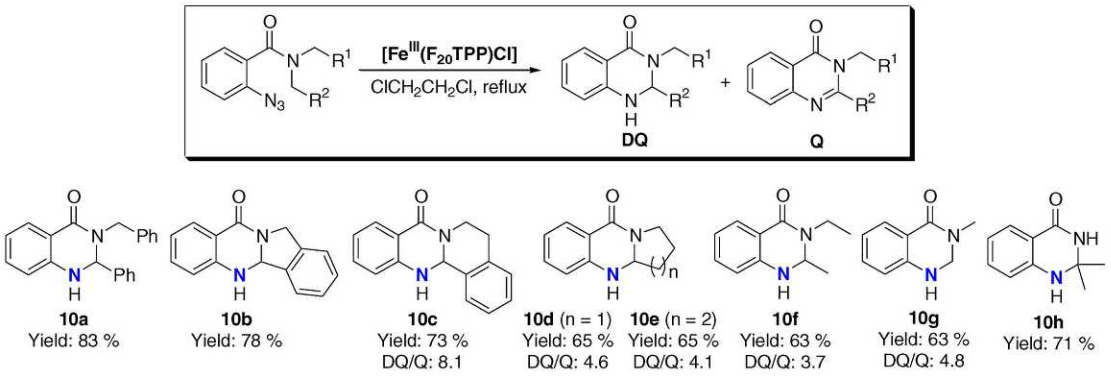
9d (R^1 = F)
Yield: 81 %

9e (R^1 = H)
Yield: 76 %

9f (R^1 = F)
Yield: 78 %

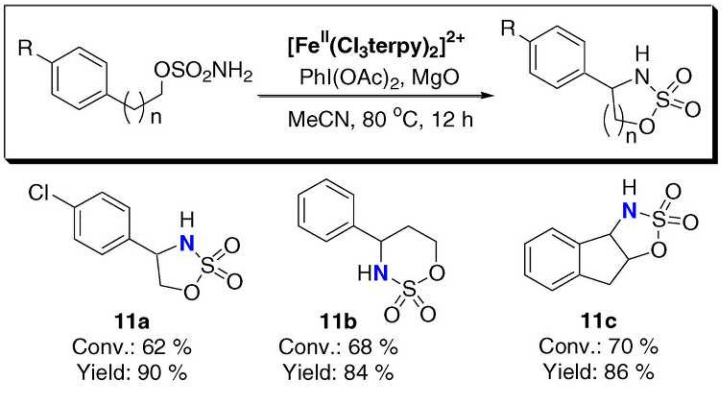
	9g	9h	9i	9j
R^1	H	F	Cl	Br
Yield (%)	72	79	75	73

Scheme 13 [$Fe^{III}(F_{20}TPP)Cl$]-catalyzed intramolecular C–H bond amination from *ortho*-azido-alkylbenzenes.



Scheme 14 [$Fe^{III}(F_{20}TPP)Cl$]-catalyzed intramolecular amination of *ortho*-azido-benzamides.

Besides [$Fe^{III}(F_{20}TPP)Cl$], nonheme Fe complex [$Fe^{II}(Cl_3terpy)_2$]$(ClO_4)_2$ is also an effective catalyst for intramolecular amination of saturated C–H bonds. In the presence of the latter catalyst, sulfamate esters underwent amination at 80 °C to give products **11a–c** in 84–90 % yields (Scheme 15) [27].



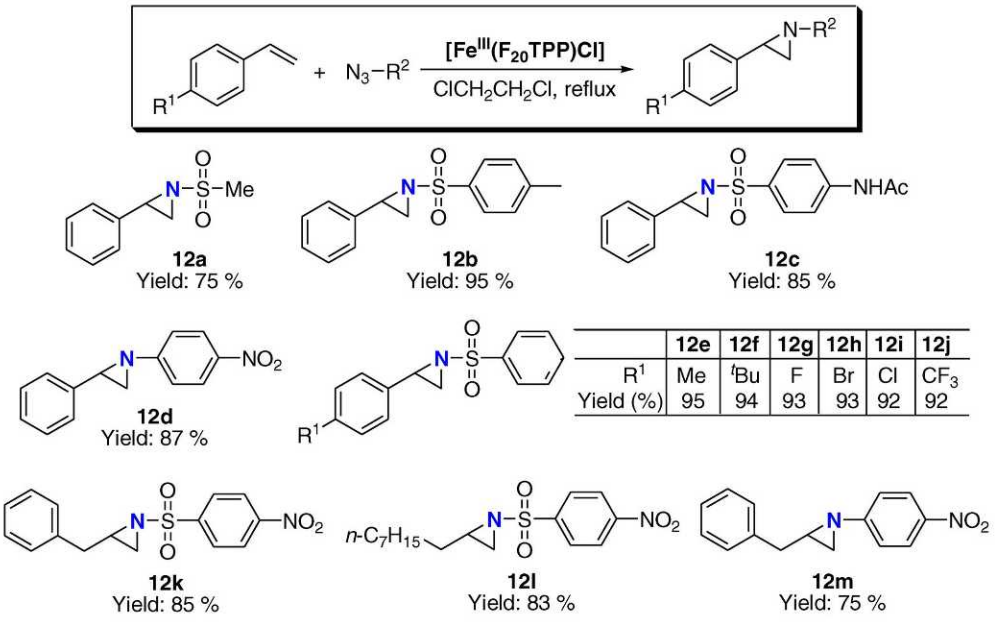
Scheme 15 [$Fe^{II}(Cl_3terpy)_2$]$^{2+}$-catalyzed intramolecular amination of sulfamate esters.

Nitrogen group transfer toward C=C bonds

Intermolecular aziridination of alkenes

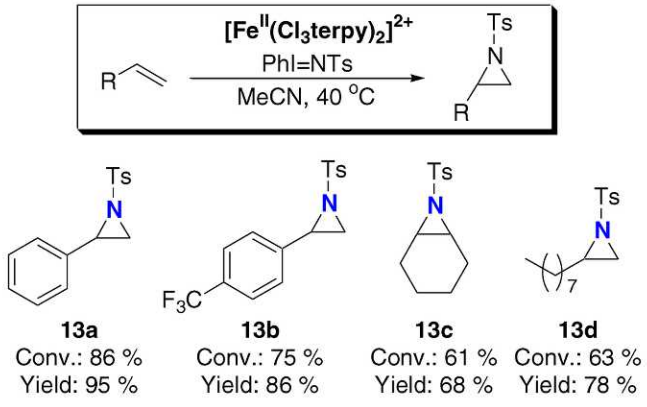
Transition-metal-catalyzed nitrogen group transfer to alkenes is a powerful method for the synthesis of aziridines, which are useful building blocks in organic synthesis and commonly found in bioactive molecules. Mansuy and co-workers reported, in 1984, the first example of an Fe-catalyzed alkene aziridination [40], using [Fe^{III}(TTP)Cl] as catalyst and PhI=NTs as nitrogen source with the aziridine product formed in moderate yield. Up to 90 % yield of aziridination product was obtained in a subsequent work [45] upon employing the more efficient catalyst [$Fe^{III}(2,6\text{-}Cl_2TPP)(ClO_4)$]. In our studies on Ru-catalyzed aziridination [7,46], Ru porphyrins were found to be capable of catalyzing inter- and intramolecular aziridination in up to 87 % yield with iminoiodanes or "$PhI(OAc)_2$ + NH_2R" as nitrogen source.

The "[$Fe^{III}(F_{20}TPP)Cl$] + organic azide" protocol described above is also effective for intermolecular aziridination of alkenes [42]. By using sulfonyl azide or 4-nitrophenyl azide as nitrogen source, a panel of styrene derivatives was converted to the corresponding aziridines (**12a–j,m**) in 75–95 % yields (Scheme 16). Aziridination of an aliphatic alkene gave **12l** in 83 % yield.



Scheme 16 $[Fe^{III}(F_{20}TPP)Cl]$-catalyzed aziridination of alkenes with sulfonyl azides and 4-nitrophenyl azide.

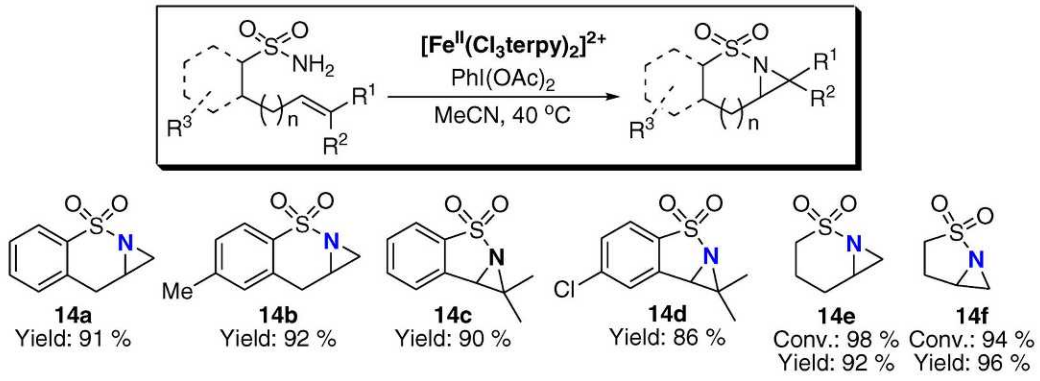
$[Fe^{II}(Cl_3terpy)_2](ClO_4)_2$ can catalyze the intermolecular aziridination of aryl alkenes and aliphatic alkenes with PhI=NTs, affording the corresponding aziridines (**13a–d**) in up to 95 % yield with up to 86 % substrate conversion (Scheme 17) [27]. ESI-MS analysis of the reaction mixture of $[Fe^{II}(Cl_3terpy)_2](ClO_4)_2$ with PhI=NTs revealed a cluster peak that can be assigned to $[Fe^{IV}(Cl_3terpy)_2(NTs)]^{2+}$, providing support for the intermediacy of Fe^{IV}=NTs species in the $[Fe^{II}(Cl_3terpy)_2]^{2+}$-catalyzed aziridination of alkenes.



Scheme 17 $[Fe^{II}(Cl_3terpy)_2]^{2+}$-catalyzed aziridination of alkenes with PhI=NTs.

Intramolecular aziridination of alkenes

Following our previous work on $[Ru^{II}(F_{20}TPP)(CO)]$-catalyzed intramolecular amination of alkenyl sulfonamides with $PhI(OAc)_2$ [46c], we examined such reactions catalyzed by Fe complexes.



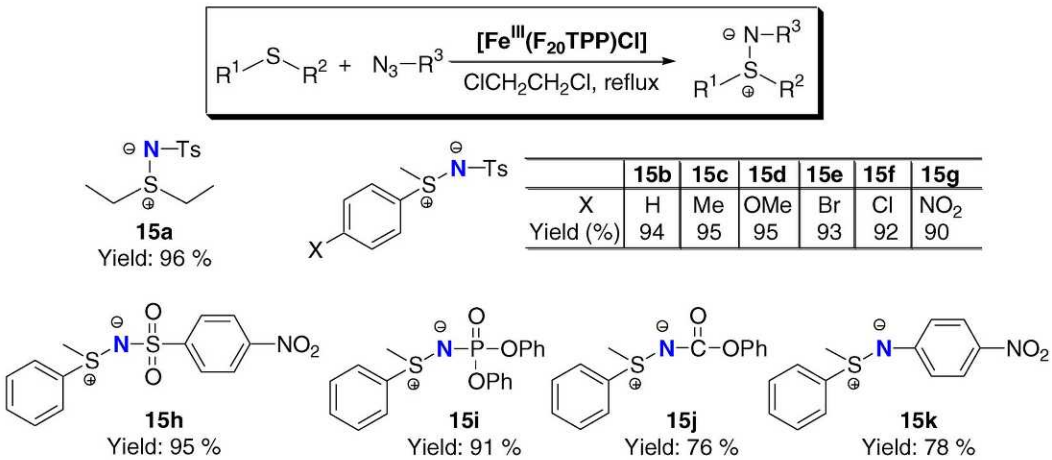
Scheme 18 $[Fe^{II}(Cl_3terpy)_2]^{2+}$-catalyzed intramolecular aziridination of alkenyl sulfonamides.

$[Fe^{II}(Cl_3terpy)_2](ClO_4)_2$ was found to be an efficient catalyst, catalyzing the intramolecular aziridination to afford aziridines **14a–f** in 86–96 % yields with up to 100 % substrate conversion (Scheme 18).

Sulfimidation of sulfides

Sulfimidation of sulfides via transition-metal-catalyzed nitrogen group transfer reaction is an efficient and straightforward method to synthesize sulfimides that are useful auxiliaries or building blocks in organic synthesis. The first examples of Fe-catalyzed sulfimidation of sulfides were reported by Bach and co-workers using $FeCl_2$ as catalyst and $BocN_3$ (Boc = *N-tert*-butyloxycarbonyl) as nitrogen source, with sulfimides obtained in up to 92 % yield [47].

In view of the success in $[Fe^{III}(F_{20}TPP)Cl]$-catalyzed aziridination of alkenes, we examined the catalytic ability of $[Fe^{III}(F_{20}TPP)Cl]$ toward sulfimidation of sulfides with TsN_3 [42]. Both diethyl sulfide (**15a**) and thioanisoles (**15b–g**) were readily converted to sulfimides with excellent product yields (90–96 %) (Scheme 19). Other organic azides such as *p*-nitrobenzenesulfonyl azide, diphenyl phosphoryl azide, phenyl carboxyl azide, and 4-nitrophenyl azide were also applicable, affording the corresponding sulfimidation products (**15h–k**) in 76–95 % yields (Scheme 19).

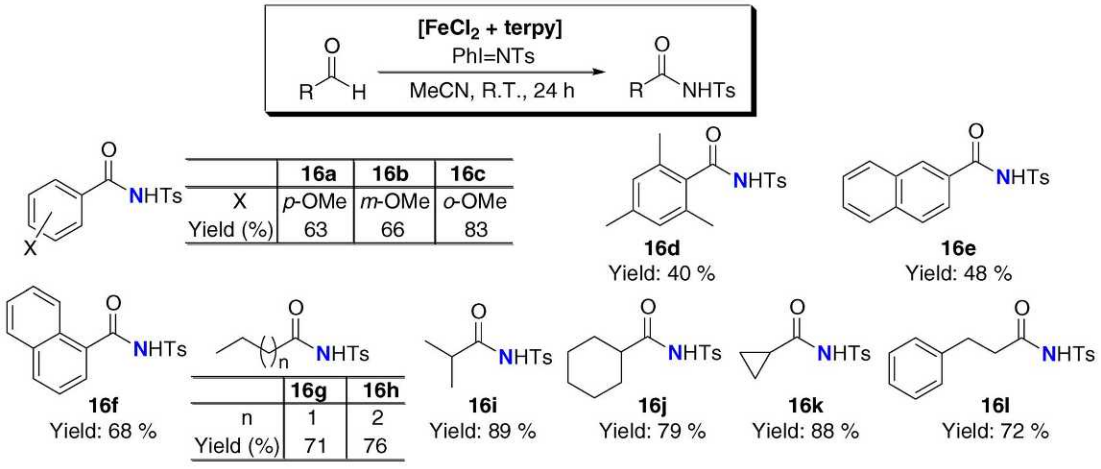


	15b	15c	15d	15e	15f	15g
X	H	Me	OMe	Br	Cl	NO_2
Yield (%)	94	95	95	93	92	90

Scheme 19 $[Fe^{III}(F_{20}TPP)Cl]$-catalyzed sulfimidation of sulfides with organic azides.

Direct formation of amides from aldehydes

A nonheme Fe^{II} complex generated in situ by the reaction of $FeCl_2$ with 2,2':6',2"-terpyridine (terpy) was found to be effective catalyst for amide formation from aldehydes with PhI=NTs as nitrogen source [48]. This "$FeCl_2$ + terpy + PhI=NTs" protocol can be applied to various aldehyde substrates, including aromatic and aliphatic ones, affording corresponding amides in 40–89 % yields (Scheme 20). Compared with aromatic aldehydes (except *o*-methoxybenzaldehyde), aliphatic aldehydes were more reactive, generally giving the amides (**16g–l**) in higher yields. Fe complexes with other ligands, including bipyridine, Cl_3terpy, $^tBu_3$terpy, and phosphine-based ligands such as Ph_3P, Cy_3P, $^nBu_3P$, and Me_3P, were found to be less effective toward the amide formation.



Scheme 20 Fe-catalyzed amide formation from aldehydes with PhI=NTs as nitrogen source.

Analysis of the reaction mixture of "$FeCl_2$ + terpy + PhI=NTs" by ESI-MS revealed a cluster peak assignable to $[Fe^{IV}(terpy)_2(NTs)]^{2+}$, suggesting the possible involvement of Fe^{IV}=NTs species in the catalytic amide formation. Very recently, similar catalytic system using "$FeCl_2$ + pyridine" for amide formation from aldehydes was reported by Chan and co-workers, in which case the participation of Fe-nitrene/imido group for insertion of formylic C–H bond of aldehyde via an H-atom abstraction/radical rebound pathway was proposed [49].

CONCLUSION

Fe-mediated atom/group transfer reactions not only hold a great significance in biomimetic studies, but also gain a lot of attraction as a useful tool for practical organic transformations owing to the sustainability, biocompatibility, and inexpensiveness of Fe.

Fe complexes, regardless of bearing heme ligand such as F_{20}TPP or nonheme ligands such as oligopyridines and macrocyclic tetraaza ligand, could efficiently catalyze oxygen atom transfer and nitrogen group transfer reactions of a wide range of organic compounds including alkanes, alkenes, arenes, tertiary amines, *N*-aryl cyclic amines, sulfides, and aldehydes under mild reaction conditions. The product turnover and efficiency of the Fe systems can be further improved by reusing oxidatively robust pyridyl ligands with in situ regeneration of Fe catalyst by addition of new batch of Fe salt, as well as by developing polymer-supported Fe catalysts for convenient recycling. Introducing pyridyl moiety and electron-withdrawing groups to the ligand strengthens the oxidative robustness of the lig-

and and thus enhances the stability of the Fe complexes, resulting in a better catalytic performance of the Fe catalysis toward the practical organic transformations.

Further insight into the mechanism was gained by means of high-resolution ESI-MS, providing evidences of the involvement of high-valent Fe=O and Fe=NTs intermediates in the Fe-catalyzed processes.

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