

# Iron-catalysed oxidation and halogenation of organic matter in nature

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**Environmental context.** Natural organohalogenes produced in and released from soils are of utmost importance for ozone depletion in the stratosphere. Formation mechanisms of natural organohalogenes are reviewed with particular attention to recent advances in biomimetic chemistry as well as in radical-based Fenton chemistry. Iron-catalysed oxidation in biotic and abiotic systems converts organic matter in nature to organohalogenes.

**Abstract.** Natural and anthropogenic organic matter is continuously transformed by abiotic and biotic processes in the biosphere. These reactions include partial and complete oxidation (mineralisation) or reduction of organic matter, depending on the redox milieu. Products of these transformations are, among others, volatile substances with atmospheric relevance, e.g. CO<sub>2</sub>, alkanes and organohalogenes. Natural organohalogenes, produced in and released from soils and salt surfaces, are of utmost importance for stratospheric (e.g. CH<sub>3</sub>Cl, CH<sub>3</sub>Br for ozone depletion) and tropospheric (e.g. Br<sub>2</sub>, BrCl, Cl<sub>2</sub>, HOCl, HOBr, ClNO<sub>2</sub>, BrNO<sub>2</sub> and BrONO<sub>2</sub> for the bromine explosion in polar, marine and continental boundary layers, and I<sub>2</sub>, CH<sub>3</sub>I, CH<sub>2</sub>I<sub>2</sub> for reactive iodine chemistry, leading to new particle formation) chemistry, and pose a hazard to terrestrial ecosystems (e.g. halogenated carbonic acids such as trichloroacetic acid). Mechanisms for the formation of volatile hydrocarbons and oxygenated as well as halogenated derivatives are reviewed with particular attention paid to recent advances in the field of mechanistic studies of relevant enzymes and biomimetic chemistry as well as radical-based processes.

Received 8 November 2014, accepted 2 March 2015, published online 22 June 2015

## Introduction

The oxidation and halogenation of organic substrates, induced or catalysed by iron complexes and oxygen-based oxidants (e.g. O<sub>2</sub>, peroxides) is of importance in biology, chemical research and industrial processes as well as in the environment. Extensive knowledge has been assembled in recent years in the area of detailed reaction mechanisms, substrate and product selectivity and the optimisation of active iron species and reaction conditions. It is of importance to note that although many of the reactions and mechanisms in the field of biological processes, chemical reactions and environmentally relevant transformations are similar in terms of reaction conditions, structures of the active iron complexes, product distribution and yields, there are also large and important differences: in biological processes, substrate and product selectivity generally are close to 100% and turnover frequencies need to be enormous, i.e. close to absolute selectivity, close to quantitative yield, and very fast reactions are the rule. In industrial processes, high yields and product selectivities are of importance, but a broad

scope with respect to substrates is also desirable, and high catalyst stability, i.e. large turnover numbers are of importance for commercial reasons. In environmental transformations, very low yields of environmentally relevant products need to be considered. Owing to the large surface of the earth, yields in the parts per billion range, which in biological and industrial processes are completely insignificant, may lead to enormous amounts of products, accumulated in the atmosphere where they influence the terrestrial ecosystem. Although there are many differences in the various fields in terms of relevance and reaction conditions and, therefore, also in terms of reaction mechanisms, it appears that, to a large extent, general concepts that have emerged in recent years, in particular from biomimetic coordination chemistry, are generally relevant. However, it seems that the different communities are not sufficiently aware of important results assembled in the different research fields. Therefore, we review important recent results of iron-induced oxidation processes of organic substrates, obtained specifically in the fields of bioinorganic, biomimetic and mechanistic

inorganic chemistry, as well as in the area of environmental organic chemistry. Thorough mechanistic work has been the focus of biomimetic coordination chemistry and trace analysis is of specific importance in environmental chemistry. It appears that mechanistic ideas emerging from biomimetic studies may be adapted with much profit to novel products and reactions detected in environmental sciences, and this could lead to a shift of some of the paradigms but care needs to be taken in terms of generalisation and overinterpretation. Also, there is some hope that various of the novel environmentally relevant reactions found in recent years may lead to interesting new discoveries in the area of coordination and biochemistry. Therefore, although the present review is primarily addressed at environmental scientists, bio- and inorganic chemists may also find it useful.

#### *Abiotic processes in natural environments*

Natural and anthropogenic organic matter is continuously transformed by abiotic and biotic processes in the biosphere. These reactions include oxidation, i.e. complete mineralisation, or reduction of organic matter, depending on the redox milieu, which is subdivided into oxic, suboxic and anoxic. Products of these transformation processes are, among others, volatile substances with atmospheric relevance, e.g. CO<sub>2</sub>, alkanes and halogenated alkanes. Also, organic acids play a key role in the mobilisation and bioavailability of minerals. Key reactions are metal ion-induced radical and non-heme iron-based processes.

#### *Iron in nature*

With a mean abundance of 4.2 %, iron is, after the redox-inactive aluminium, the second most abundant metal in the continental crust.<sup>[1]</sup> In primary minerals such as biotite, olivine and magnetite, iron is mostly present in its +2 oxidation state. Through

weathering processes, it is liberated in the presence of water, oxidised by oxygen and immobilised after hydrolysis as Fe<sup>III</sup> oxide-hydroxides (ferrihydrite, goethite and hematite), which are responsible for the brown or red colour of soils. The iron content of soils is in the range 0.5–5 %.<sup>[2]</sup> Fe<sup>III</sup> oxides are very stable weathering products and reside in soil under aerobic conditions. When microbial oxidation of organic material takes place, Fe<sup>III</sup> oxide serves as an electron acceptor and is reductively dissolved.<sup>[3]</sup> Diffusion into aerobic environments again leads to precipitation of Fe<sup>III</sup> oxide-hydroxides. Reductive dissolution and oxidative precipitation are parts of the Fe redox cycling under changing redox conditions.<sup>[4]</sup> Fe<sup>III</sup> is stable in aqueous soil solutions in oxic environments at pH < 3.5, whereas at pH > 4, Fe<sup>III</sup> concentrations are extremely low and limited to soluble Fe<sup>III</sup> complexes of organic ligands. In conclusion, iron availability in oxic soils is determined by the interaction of poorly crystalline iron minerals and soluble organic ligands such as humic acids,<sup>[5]</sup> microbially produced siderophores<sup>[6]</sup> and root exudates.<sup>[7]</sup>

Iron coordination compounds play an important role in proteins and enzymes.<sup>[8–10]</sup> These are involved in electron transfer, oxidation and oxygenation. Other redox-active metal ions such as copper, vanadium, nickel and manganese play similar roles in biotic systems but iron and copper are the most abundant.<sup>[11,12]</sup> Abiotic processes are believed to follow similar pathways and are responsible for the oxidation and oxygenation of organic matter. Copper- and iron-based oxygen activation and oxidation chemistry<sup>[8–10]</sup> are ubiquitous, high-valent manganese model chemistry is gaining more attention recently<sup>[13–18]</sup> and various studies on high-valent nickel chemistry also have recently been published.<sup>[19–21]</sup> Here, we concentrate on iron chemistry. Fig. 1 shows a general scheme for iron cycling in natural environments.<sup>[22]</sup>



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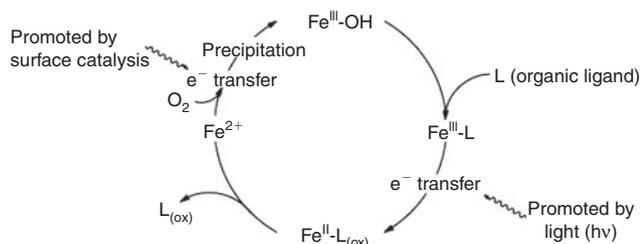
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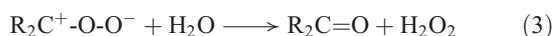
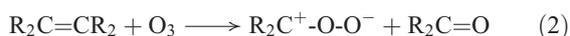
**Fig. 1.** Iron redox cycling in natural environments, adapted from Stumm and Sulzberger.<sup>[22]</sup>

### *H<sub>2</sub>O<sub>2</sub> in nature*

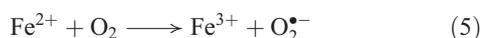
H<sub>2</sub>O<sub>2</sub> has multifarious sources in the biosphere. It is abundant in the atmospheric gas phase, clouds and water droplets<sup>[23]</sup> and is transported to soils and surface waters by rain.<sup>[24]</sup> Elevated H<sub>2</sub>O<sub>2</sub> concentrations are found during thunderstorms, implying formation through electrostatic discharge,<sup>[25–27]</sup> and near fire plumes.<sup>[28]</sup> Moreover, the reaction of hydroperoxyl radicals with each other (Eqn 1) is an important atmospheric radical termination, producing H<sub>2</sub>O<sub>2</sub>.<sup>[29]</sup>



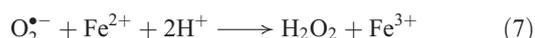
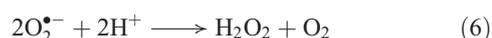
Another source for atmospheric H<sub>2</sub>O<sub>2</sub> is the reaction of ozone with isoprene, monoterpenes and alkenes by a Criegee biradical, expressed in Eqns 2 and 3 (R represents H, alkyl or acyl).<sup>[30]</sup>



Photochemical reactions are also a common source of H<sub>2</sub>O<sub>2</sub> in terrestrial<sup>[31]</sup> and marine<sup>[32]</sup> aqueous environments.<sup>[33]</sup> The underlying mechanism is the photo-ionisation or photo-excitation of dissolved organic matter by sunlight, producing free electrons or excited states that can reduce dissolved oxygen to superoxide (Eqn 4, OM, organic matter).<sup>[34]</sup> As shown in Eqn 5, superoxide may also be formed by metal-based reduction, involving iron<sup>[35–37]</sup> or manganese,<sup>[38]</sup> but this reaction is inhibited under acidic conditions and in the presence of chloride.<sup>[39–42]</sup>



Superoxide can disproportionate, yielding H<sub>2</sub>O<sub>2</sub> (Eqn 6)<sup>[43]</sup> or it may be reduced further to H<sub>2</sub>O<sub>2</sub> (Eqn 7).<sup>[44]</sup>



Other known biogenic H<sub>2</sub>O<sub>2</sub> sources in soil and aquatic systems are the release of H<sub>2</sub>O<sub>2</sub> by fungi<sup>[45]</sup> and brown algae.<sup>[46]</sup> H<sub>2</sub>O<sub>2</sub> also plays a significant role in bacterial metabolism.<sup>[47]</sup>

### *Halides in nature*

Weathering processes liberate large amounts of halides from primary rocks and minerals. These are dissolved in water and transported via rivers to the oceans as the final sink. One litre of ocean water contains 0.5 mol chloride, 1 mmol bromide

and 1 μmol iodide (the molar ratio of Cl<sup>-</sup>:Br<sup>-</sup>:I<sup>-</sup> is 500 000:1000:1).<sup>[48]</sup> Part of the halides is mobilised by sea-spray or as organohalogenes and enters the terrestrial environment. Therefore, the atmospheric deposition of halides is dependent on the distance from the ocean and on the amount of precipitation.

In addition, primary rocks and evapotranspiration contribute to the halide content of soils. The mean chloride content of soils in humid climates is in the range 100–300 mg kg<sup>-1</sup>; the corresponding bromide and iodide contents are 5–50 and 3–30 mg kg<sup>-1</sup> respectively.<sup>[2]</sup> The molar ratio of Cl<sup>-</sup>:Br<sup>-</sup>:I<sup>-</sup> in soil is ~100:5:1.<sup>[48]</sup> In conclusion, the molar ratio in soil is distinctly shifted relative to ocean water, especially for iodide, which is enriched by a factor of ~5000.

### Relevant oxidation reactions

#### *The reaction of halides with OH radicals and H<sub>2</sub>O<sub>2</sub>*

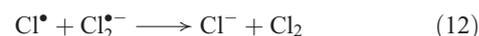
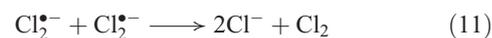
In the presence of Fe<sup>II</sup>, aqueous H<sub>2</sub>O<sub>2</sub> may produce OH radicals (see below). Halides are known to react with OH radicals, yielding reactive halogen species. A general reaction mechanism is shown in Eqns 8 and 9 with X = Br,<sup>[49]</sup> Cl<sup>[50,51]</sup> and I.<sup>[52]</sup>



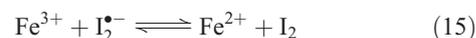
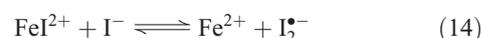
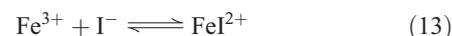
Owing to increasing electronegativity, the reactivity of OH radicals with halides decreases from iodide to chloride.<sup>[53]</sup> The recombination of halogen radicals is described in Eqn 10.<sup>[54–57]</sup>



Recently, the mechanism for Cl<sub>2</sub> evolution was summarised,<sup>[58]</sup> involving the reactions shown in Eqns 11 and 12.



The oxidative power of Fe<sup>III</sup> is high enough to oxidise iodide through a clock reaction directly to I<sub>2</sub>.<sup>[59]</sup>



Counteracting the formation of reactive halogen species is their reductive depletion by Fe<sup>II</sup><sup>[51]</sup> as well as by H<sub>2</sub>O<sub>2</sub><sup>[58]</sup> to halides.

The reaction of H<sub>2</sub>O<sub>2</sub> with halides is not restricted to an iron-catalysed Fenton-type reaction but halides are also directly oxidised by H<sub>2</sub>O<sub>2</sub>. H<sub>2</sub>O<sub>2</sub> reacts in the presence of iodide under acidic conditions to form hypoiodous acid, described by the modified ‘Iodine Clock’ reaction shown in Eqn 16,<sup>[60]</sup> which is based on the Landolt reaction.<sup>[61,62]</sup> This process is probably the main source of iodocarbons in the metabolism of brown algae.<sup>[63]</sup>

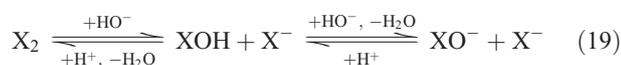


A similar mechanism was postulated for the reaction of bromide and chloride with  $\text{H}_2\text{O}_2$ , as illustrated in Eqns 17<sup>[64]</sup> and 18<sup>[65]</sup> respectively.



The reactivity between halides and  $\text{H}_2\text{O}_2$ , described in Eqns 17 and 18, decreases from  $\text{I}^-$  to  $\text{Cl}^-$ .<sup>[53]</sup> Furthermore,  $\text{H}_2\text{O}_2$  is able to reduce the hypohalous acids to hydrogen halides under evolution of oxygen, reducing the yield of  $\text{HOCl}$ <sup>[66]</sup> and  $\text{HOBr}$ .<sup>[67]</sup> Hypoiodous acid or iodine even catalyse the decomposition of  $\text{H}_2\text{O}_2$ , as illustrated in Fig. 2.<sup>[68,69]</sup>

This illustrates the complicated mechanisms of Fenton-type processes and the corresponding side reactions in the presence of halides, yielding reactive halogen species like  $\text{X}$ ,  $\text{X}_2^-$ ,  $\text{X}_2$ ,  $\text{XOH}$  and  $\text{XO}^-$ . In addition,  $\text{X}_2$ ,  $\text{XOH}$  and  $\text{XO}^-$  are in pH-dependent equilibria with one another (Eqn 19).<sup>[70]</sup>



#### Oxidants for the natural oxidation of organic matter

The oxidation chemistry of  $\text{Fe}^{\text{II}}$  in water has been studied extensively since Fenton's discovery that  $\text{Fe}^{\text{II}}$  salts in the presence of  $\text{H}_2\text{O}_2$  efficiently oxidise organic matter in acidic aqueous solution.<sup>[71–73]</sup> The involvement of OH radicals has been suggested and the OH radicals are often believed to be the

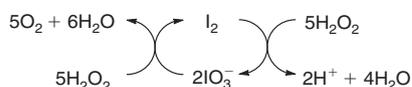


Fig. 2. Catalytic decomposition of  $\text{H}_2\text{O}_2$  by iodine.<sup>[68,69]</sup>

relevant oxidant.<sup>[74]</sup> However, on the basis of experimental observations in the 1930s, high-valent iron-oxo species have also been suggested to be involved in Fenton reactions,<sup>[75]</sup> and this was confirmed by density functional theory (DFT) calculations a decade ago.<sup>[76]</sup> At approximately the same time, the first reports of low-molecular-weight ferryl complexes and non-heme iron enzymes appeared.<sup>[54–57]</sup> Important milestones in this area are the first report of the spectroscopic<sup>[77]</sup> and structural<sup>[78]</sup> characterisation of intermediate-spin non-heme ferryl model complexes as well as a detailed mechanistic study of the  $\alpha$ -keto-acid-dependent enzyme TauD with a high-spin ferryl active site.<sup>[79–82]</sup> Especially interesting, therefore, are the observations of high-spin low-molecular-weight ferryl species<sup>[83–87]</sup> and the proposal of catalytically active intermediate-spin dihydroxo-iron(IV) complexes.<sup>[84]</sup> An important observation is that ferryl complexes can be trapped in pure water, prepared from the  $\text{Fe}^{\text{II}}$  precursor and  $\text{H}_2\text{O}_2$  under typical Fenton conditions. Therefore, in the first phase of the stoichiometric reaction, this Fenton-type process does not involve OH radicals (see Fig. 3).<sup>[88]</sup> Also of importance are reports on the halogenation of unactivated substrates with ferryl model systems.<sup>[89,90]</sup> It needs to be pointed out that non-heme iron enzymes generally activate dioxygen and that in most of the model reactions discussed here, the ferryl species are obtained from the  $\text{Fe}^{\text{II}}$  precursors by oxygen atom transfer, electron transfer or oxidation with  $\text{H}_2\text{O}_2$ . There are only few examples of direct oxidation by dioxygen, and recent results indicate that in at least one example, this is not based on oxygen activation but rather on radical-based autoxidation.<sup>[91]</sup>

There is no doubt that ferryl complexes such as that shown in Fig. 3 and, more generally, other high-valent metal complexes, are strong and very efficient oxidants and that they are available in natural abiotic aquatic systems – i.e. under Fenton-type conditions usually assumed in soils, water and aerosols – and therefore, they obviously play an important role in various environmental compartments. However, OH radicals are also produced in  $\text{Fe}^{\text{II}}/\text{H}_2\text{O}_2$  systems and there is no doubt either that

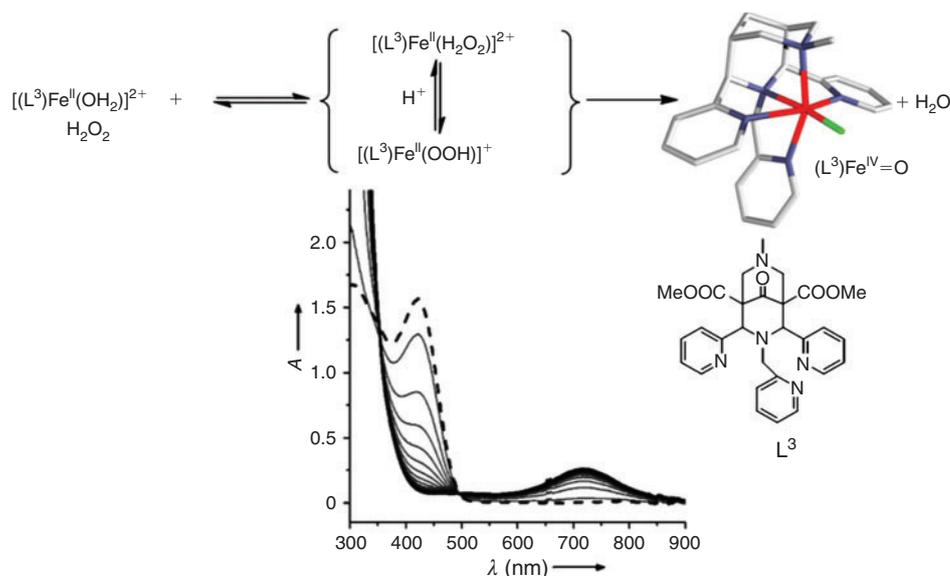
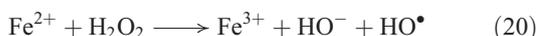


Fig. 3. UV-Vis spectra showing the oxidation of the  $\text{Fe}^{\text{II}}$  complex of the bispidine ligand  $\text{L}^3$  (chemical structure shown; bispidines are very rigid ligands that efficiently encapsulate metal ions and are known to form very reactive ferryl complexes, see also *Abiotic oxidation of organic matter* section below<sup>[57]</sup>) with  $\text{H}_2\text{O}_2$  in water (0 °C, citrate buffer, pH 5.4; the dotted line is the electronic spectrum of the ferric complex, the dark line corresponds to the ferryl complex, developed within 80 s),<sup>[88]</sup> adapted from Comba.<sup>[57]</sup>

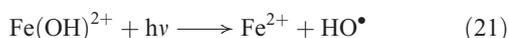
these are also of importance in the oxidation of organic matter. Although the product selectivity of in vitro oxidation reactions may indicate whether there is a preferred ferryl or OH radical-based process,<sup>[92]</sup> such differentiation seems to be difficult in environmental transformations.

The 'classical' mechanism of OH radical-based Fenton processes (aqueous  $\text{Fe}^{2+}/\text{H}_2\text{O}_2$  mixtures) was proposed by Haber and Weiss (Eqn 20).<sup>[74]</sup>



Another reaction of importance is the reduction of  $\text{Fe}^{\text{III}}$  by  $\text{H}_2\text{O}_2$ , and this completes the catalytic iron cycle of the Fenton reaction<sup>[93]</sup> (see Fig. 4).

Alternatively to the  $\text{Fe}^{\text{II}}$  catalysed decomposition of  $\text{H}_2\text{O}_2$ , photolysis by UV radiation ( $\lambda < 400$  nm) can generate OH radicals. Radiation at 290–400 nm enhances Fenton-like reactions by reduction of  $\text{Fe}^{\text{III}}(\text{OH})^{2+}$  to  $\text{Fe}^{\text{II}}$  and the concomitant generation of free OH radicals in this light-induced Fenton or photo-Fenton reaction (Eqn 21).<sup>[94]</sup>



Importantly, metal complex-based Fenton chemistry is not limited to iron as redox catalyst. The amount of oxidised species formed in Fenton-like reactions at circumneutral pH increases according to the order  $\text{Ni}^{\text{II}} < \text{Mn}^{\text{II}} < \text{Fe}^{\text{III}} < \text{Co}^{\text{II}} < \text{Cr}^{\text{III}} < \text{Cu}^{\text{II}}$ .<sup>[95]</sup> In reactions of  $\text{Cu}^{\text{II}}$  with  $\text{H}_2\text{O}_2$ , OH radicals are believed to only play a minor role, and  $\text{Cu}^{\text{II}}$  is proposed to be of major importance.<sup>[96,97]</sup>

In summary, it appears that, depending on the conditions, the active species may involve OH radicals, but in the presence of suitable ligands, high-valent metal complexes may be the more relevant oxidant. Specifically, an  $\text{Fe}^{\text{II}}$  complex may be oxidised to  $\text{Fe}^{\text{III}}$  and then coordinate  $\text{H}_2\text{O}_2$ . The resulting  $\text{Fe}^{\text{III}}$  hydroperoxido complexes themselves are known to be strong oxidants<sup>[98]</sup> but may also produce ferryl species and OH radicals (homolytic cleavage of the O–O bond).<sup>[99,100]</sup> Moreover, coordination of  $\text{H}_2\text{O}_2$  to the  $\text{Fe}^{\text{II}}$  precursor and subsequent homolytic cleavage of the O–O bond may lead to an  $\text{Fe}^{\text{IV}}(\text{OH})_2$  complex, a tautomer of the reactive ferryl complex.<sup>[84,101]</sup> Which of these pathways and which of the resulting oxidants leads to the observed oxidation of organic matter in soils is not clear in most of the reactions studied so far (see sections below), but it obviously depends on the reaction conditions, most importantly on the ligands available.<sup>[75,102,103]</sup>

#### Abiotic oxidation of organic matter

A key initial reaction in the context of abiotic natural environments is the degradation of humic acid, and it is believed that the

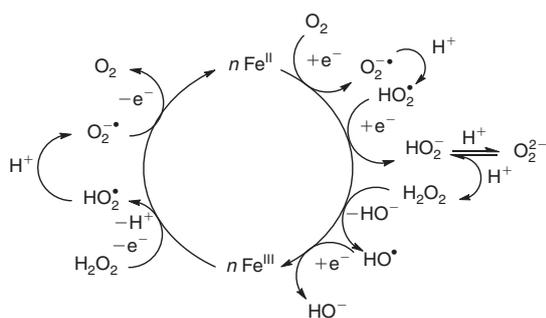


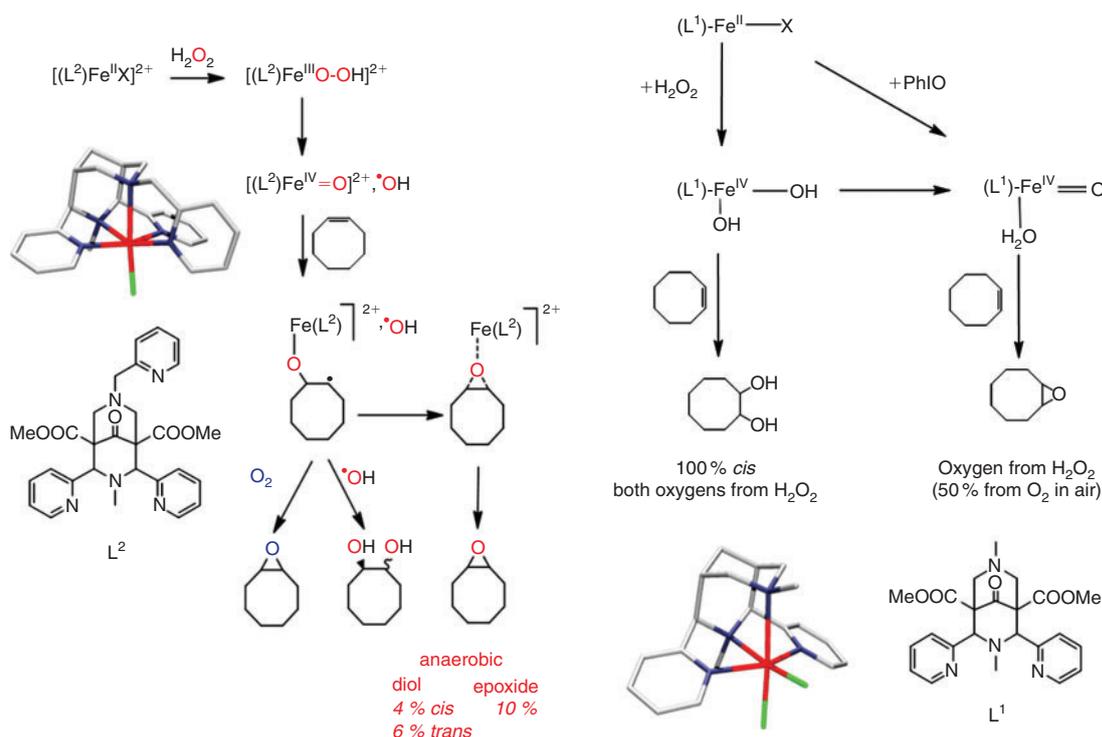
Fig. 4. Schematic iron cycling in Fenton and Fenton-like chemistry.<sup>[93]</sup>

iron-catalysed oxygenation of catechol- and hydroquinone-derived subunits is of importance. The biochemistry of the relevant iron-based catechol dioxygenases (mononuclear non-heme iron enzymes) has been studied extensively.<sup>[104–107]</sup> Three different reactions are possible when dioxygen reacts with a catecholate derivative bound to a non-heme iron centre, (1) the oxidation to the *ortho*-quinone (catecholase activity, i.e. a simple two-electron oxidation), and dioxygenation, (2) leading to intradiol cleavage, or (3) leading to extradiol cleavage. Various biomimetic systems with dioxygenase reactivity have been investigated, and these have helped to elucidate the biologically relevant catalytic mechanisms.<sup>[108–113]</sup>

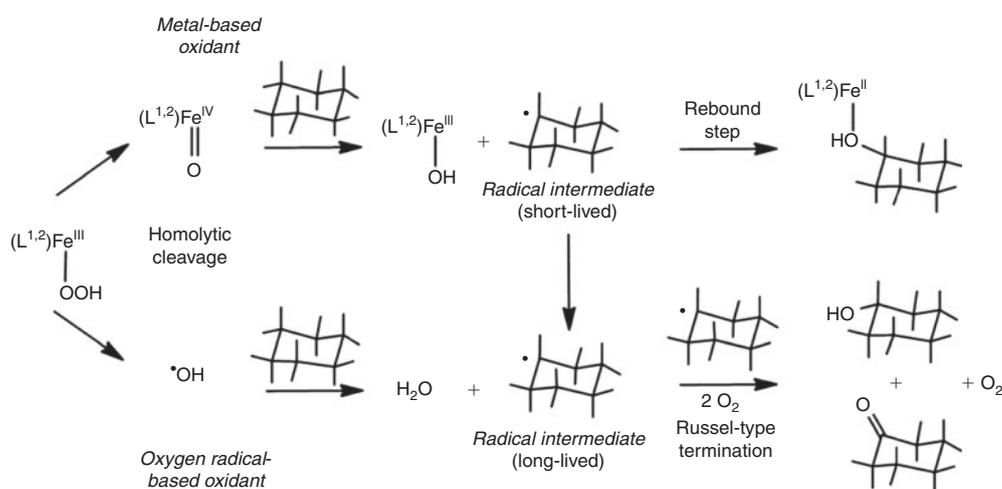
A wide variety of published work on the stoichiometric and catalytic oxidation of organic molecules with low-molecular-weight non-heme iron model complexes is available,<sup>[57,114,115]</sup> and this includes oxygen-transfer reactions, e.g. sulfoxidation,<sup>[91,116]</sup> oxidative demethylation,<sup>[117]</sup> and methane formation<sup>[118]</sup> as well as the oxidation of alkanes and alkenes,<sup>[91]</sup> which are of specific interest in the degradation of organic matter in nature. An interesting recently described reaction, related to published work on demethylation and well-studied sulfoxidation reactions, is methane formation from methionine under oxidative conditions.<sup>[118]</sup>

As an example of these biomimetic studies with well-defined systems and their complexes, we describe a few processes of bispidine-type ligands relevant to environmental transformations, also because some of the environmentally relevant mechanistic work has been done with these ligands. Note that in soils, the relevant organic matter is humic substances, and these are believed to coordinate to  $\text{Fe}^{\text{II}}$  and  $\text{Fe}^{\text{III}}$  to enable chemical reactions similar to the structurally well-defined model systems described here. With bispidine-type ligands, the formation of ferryl complexes has been confirmed in some detail (see also Fig. 3),<sup>[57,88,101,119]</sup> and the mechanism of olefin epoxidation and dihydroxylation has been studied, both experimentally and by quantum-chemical methods.<sup>[120,121]</sup> Careful product analyses, including  $^{18}\text{O}$  labelling studies (separately with  $\text{H}_2^{18}\text{O}$ ,  $^{18}\text{O}_2$  and  $\text{H}_2^{18}\text{O}_2$ ) led to proposing the mechanisms shown in Fig. 5, and these were confirmed by DFT calculations. The most interesting features are that (i) the attack by the ferryl oxygen at the double bond is asymmetrical, leading to a carbon-based radical intermediate, which may be quenched by  $\text{O}_2$  in ambient atmosphere to selectively yield an epoxide with cyclooctene as substrate.<sup>[122]</sup> (ii) With the tetradentate ligand system, the initial  $\text{Fe}^{\text{IV}}$  species is the novel intermediate-spin  $\text{Fe}^{\text{IV}}(\text{OH})_2$  complex (Fig. 5),<sup>[84,101]</sup> and this may tautomerise to the high-spin ferryl complex. The ferryl complex oxidises the double bond to the epoxide with the same mechanism described above for the pentadentate bispidine ferryl complexes, and the dihydroxo complex yields the *cis*-diol products (see Fig. 5).<sup>[84,101]</sup>

The very high  $\text{Fe}^{\text{IV/III}}$  redox potentials<sup>[123,124]</sup> suggest that the bispidine-based ferryl complexes should even be able to oxidise the strong C–H bonds of alkanes.<sup>[89,124]</sup> With bispidines and several other ligand systems,<sup>[125–127]</sup> various possible high-valent iron species were proposed to be responsible for substrate activation, i.e.  $\text{Fe}^{\text{V}}=\text{O}$  (heterolytic O–O cleavage in the  $\text{Fe}^{\text{III}}\text{-OOH}$  intermediate),  $\text{Fe}^{\text{IV}}=\text{O}$  together with OH radicals (homolytic O–O cleavage in the  $\text{Fe}^{\text{III}}$  precursor) or the products of direct oxidation of the  $\text{Fe}^{\text{II}}$  precursor to the catalytically active  $\text{Fe}^{\text{IV}}$  oxidant (see above).<sup>[89,92,128,129]</sup> In the catalytic oxidation of alkanes, it is believed that metal-based oxidants (either  $\text{Fe}^{\text{V}}=\text{O}$  or  $\text{Fe}^{\text{IV}}=\text{O}$ ) predominantly yield the alcohol products, i.e. hydrogen abstraction by the ferryl oxidant leads to carbon-based



**Fig. 5.** Pathways for the oxidation of cyclooctene with  $H_2O_2$ , catalysed by iron complexes of the pentadentate bispidine ligands  $L^2$  and  $L^3$ <sup>[120,121]</sup> (left). Mechanism of the  $[Fe^{II}(L^1)(X)]^{n+}$  (tetradentate bispidine)-catalysed oxidation of cyclooctene<sup>[84]</sup> (right), where X represents any ligand. See text for a detailed description of the reactions; adapted from Comba.<sup>[57]</sup>

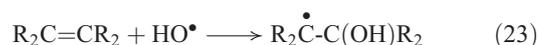
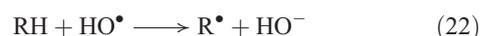


**Fig. 6.** Mechanism of the iron-bispidine-catalysed oxidation of cyclohexane (the ligands are the same as those in Fig. 5)<sup>[92]</sup>; adapted from Comba.<sup>[57]</sup>

radicals that are rebound to the  $Fe^{III}-OH$  intermediate to produce the alcohol (see Fig. 6 and Fig. 7 below).<sup>[130]</sup> In contrast, OH radical-based processes lead to carbon-based substrate radicals that are trapped by  $O_2$  to generate equimolar amounts of alcohol and ketone (Fig. 6).<sup>[131,132]</sup> Product analyses of oxidation reactions initiated by the bispidine complexes, including  $^{18}O$  labelling studies, the determination of kinetic isotope effects and experiments with adamantane as substrate to determine the preference for tertiary over secondary alcohol formation (stabilisation of the tertiary radical intermediate), supported by DFT calculations, lead to the proposed mechanism shown in Fig. 6.<sup>[92]</sup>

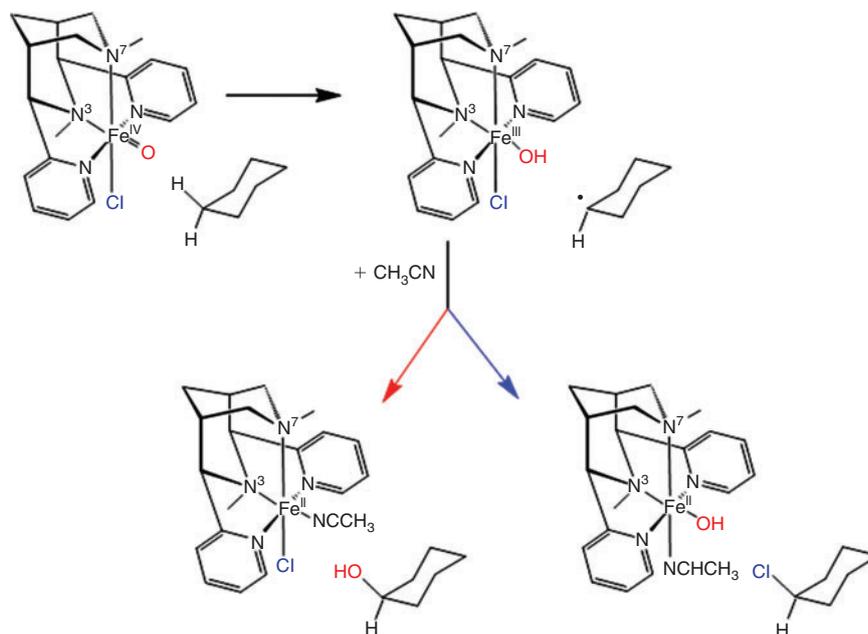
The more classical analysis of Fenton reactions describes the oxidation of organic matter by an initial abstraction of a H atom

by an OH radical (Eqn 22),<sup>[103]</sup> and radicals are also known to react with unsaturated C=C bonds (Eqn 23).<sup>[133]</sup>

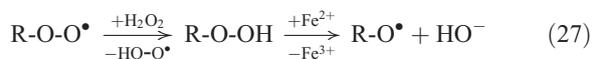
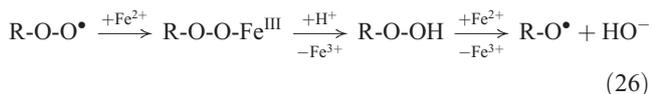


The propagation of radical chain reactions is summarised in Eqns 24–28.<sup>[133]</sup>

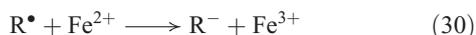
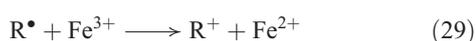




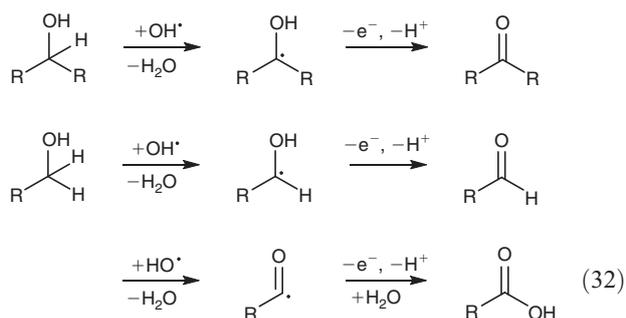
**Fig. 7.** Mechanism of the iron-bispidine-catalysed halogenation of cyclohexane,<sup>[89]</sup> see text for a detailed description of the mechanism; adapted from Comba.<sup>[57]</sup>



The chain reactions are terminated by iron oxidation or reduction as well as possible dimerisation of carbon radicals (Eqns 29–31).<sup>[103,133]</sup>



Eqn 32 shows the  $\text{Fe}^{\text{III}}$ -mediated pathway for the oxidation of primary and secondary alcohols. Secondary alcohols are oxidised to ketones<sup>[134]</sup> whereas the less-reactive primary alcohols are converted to aldehydes and further to carboxylic acids (Eqn 32).<sup>[135]</sup>

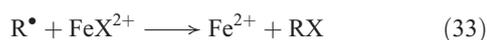


There are two pathways for biological iron-catalysed halogenation processes,<sup>[10,55,57,89,136–138]</sup> involving heme-based chloroperoxidases or non-heme halogenases (as with other redox-active metal centres, e.g. in vanadium-based haloperoxidases). Chloroperoxidases generate a metal-bound hypochlorite ion and hypochlorous acid that are capable of halogenating electron-rich organic substrates. Owing to their high-spin ferryl centres, spectroscopically characterised as reactive intermediates, the  $\alpha$ KG-dependent non-heme halogenases can also halogenate less reactive electron-poor alkanes.<sup>[136]</sup> Similarly to the hydroxylation reactions discussed above, the ferryl intermediates abstract a hydrogen atom from the substrate and the rebound step then transfers a halogen atom from the  $\text{Fe}^{\text{III}}\text{-Cl}$  intermediate to the substrate radical (see Fig. 7).

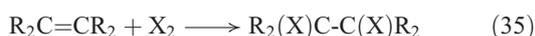
Owing to the similarity of the enzyme active sites and relevant intermediates, it appears that the radical intermediate in the halogenases may compete in the rebound step with the  $\text{Fe}^{\text{III}}\text{OH}$  and  $\text{Fe}^{\text{III}}\text{Cl}$  sites. However, attempts to detect alcohol products in halogenases failed, and the selectivity required in biological reactions seems to be accomplished by the enzyme-enforced substrate positioning.<sup>[137,138]</sup> Low-molecular-weight non-heme iron model systems have been shown to be able to halogenate alkanes and alkenes in stoichiometric<sup>[89,139]</sup> and catalytic processes.<sup>[89,140]</sup> With the tetradentate bispidine  $\text{L}^1$  (Fig. 7), the mechanism was studied in some detail, and the kinetic isotope effect as well as the product distribution with adamantane as substrate (relative stability of secondary and tertiary carbon-based radicals) indicated that the rate-determining step indeed is hydrogen atom abstraction, a scenario that is also supported by DFT calculations.<sup>[89]</sup> It appears that the high halogenation selectivity ( $\sim 90\%$ ) is due to a lower activation barrier for the  $\text{Fe}^{\text{III}}\text{-Cl}$  v.  $\text{Fe}^{\text{III}}\text{-OH}$  rebound, and it is proposed that this is related to the relative redox potentials of  $\text{OH}^-$  v.  $\text{Cl}^-$ , i.e. to electronic effects.<sup>[89,139]</sup> These mechanistic interpretations were challenged in a recent study of another low-molecular-weight non-heme iron halogenase model system,

where the first step of the halogenase process, i.e. hydrogen atom abstraction, was characterised unambiguously, but did not produce any halogenated alkanes.<sup>[90]</sup> Preliminary DFT calculations indicate that this may be related to the thermodynamics of the rebound step, i.e. that halogenation is thermodynamically an uphill process whereas hydroxylation is a downhill process. Because the preliminary DFT calculations indicate that halogenation as well as hydroxylation are thermodynamically possible with the bispidine catalyst, it appears that the first step in the proposed mechanism in Fig. 7 (formation of a carbon-based radical and an Fe<sup>III</sup>-chlorido-hydroxy intermediate, ready for the rebound step) is unambiguous. Whether or not the product-forming second step is a rebound or a radical-based reaction is not easy to prove experimentally. Alternatives may involve halide oxidation, as recently studied with two non-heme iron model complexes,<sup>[141]</sup> or typical Gif chemistry as discussed below.<sup>[142]</sup> Importantly, there are recently published observations that the so-far generally assumed rebound mechanism for non-heme iron model systems (see Fig. 7) is at least in one case not relevant.<sup>[143]</sup>

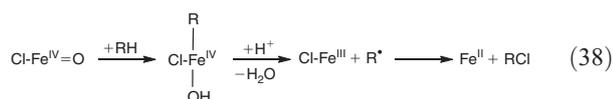
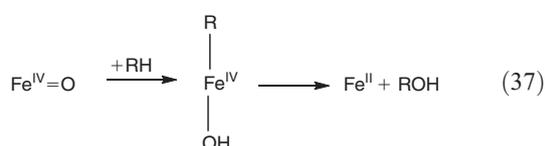
In the presence of halides, several halogenation mechanisms are conceivable. Eqn 33 shows the iron-mediated ligand transfer of a halide to an organic radical,<sup>[144]</sup> whereas the reaction in Eqn 34 is based on halogen radicals.<sup>[145]</sup>



Further important reactions are the electrophilic addition of halogens to alkenes (Eqn 35)<sup>[146–148]</sup> and, in analogy to OH radicals, the addition of free halogen radicals to unsaturated carbon bonds (Eqn 36).



Apart from oxidation by radicals, there is another Fe<sup>IV</sup>-based process. Postulated mechanisms for the hydroxylation and halogenation of hydrocarbons by Gif chemistry are shown in Eqns 37 and 38.<sup>[142,149]</sup>



## Model reactions

Chemical reactions in soil and natural aqueous systems are complicated by heterogeneity and poorly defined environmental parameters (temperature, pH, concentrations, as well as type and concentrations of relevant species present). To decipher natural abiotic processes, it is inevitable that the reactions must be

mimicked under constrained laboratory conditions with a reasonable amount of reactants and parameters. In the last two decades, degradation mechanisms of organic model compounds under Fenton-like conditions with a variety of iron species have been elucidated. Some of the results, which partially redefine the production and flow of small organic compounds in environmental compartments, are discussed in the final sections of the present account.

## Organic model compounds

Organic matter in the environment is an umbrella designation for a multitude of organic molecules, resulting from the metabolism of residues of plants and animals, as well as cells and tissues of various organisms. These compounds are found at different stages of degradation. The major fraction of natural organic matter is classified as humic acid and comprises compounds of high molecular weight with a complex structure with numerous carboxylic and phenolic groups. Humic acids are closely related to the lower-molecular-weight fulvic acids. A proposed model of humic substances is shown in Fig. 8, and this is composed of lignin, peptides, cellulose and chitin groups with various metal coordination sites.<sup>[150]</sup>

Because organic matter in soil has a highly complex and ill-defined structure, chemical reactions are generally studied with well-defined small molecular model compounds with the relevant structural elements and redox properties. Widely accepted models are, for example, catechol, hydroquinone, guaiacol, resorcinol and 2,3-dihydroxybenzoic acid.

## Modelling of the catalytically active iron species

The most relevant form of iron species in soil model systems are soluble Fe<sup>II</sup> and Fe<sup>III</sup> salts, e.g. sulfates, chlorides or carbonates. Several experiments have also been done with iron minerals.<sup>[151,152]</sup> In a recent series of studies, biomimetic non-heme iron complexes were used to model the coordination of iron cations to natural organic matter in soils. Iron bispidine complexes were chosen for these experiments because they provide a well-defined coordination sphere, enforced by the rigid adamantane-derived backbone (see Figs 3, 5 and 7 above),<sup>[123,153,154]</sup> and the Fe<sup>II</sup>-bispidine-H<sub>2</sub>O<sub>2</sub> system has been studied extensively and thoroughly with trapped and well-characterised metastable intermediates.<sup>[57,155,156]</sup>

## Environmentally relevant organic reaction products

Although oxidation processes under Fenton- or Fenton-like conditions were intensively studied for hazardous waste treatment,<sup>[157,158]</sup> their relevance for natural abiotic chemistry was not appreciated until the abiotic formation of halomethanes was studied in detail (Fig. 9).<sup>[151]</sup> A key feature was the observation that guaiacol is oxidised by Fe<sup>III</sup> to chloromethane among other products.

The detailed investigation of the degradation of catechol derivatives under Fenton-like conditions led to the identification of the environmentally relevant series of abiotically formed products shown in Fig. 10.

A closer look at the oxidative capabilities of Fe<sup>III</sup> demonstrated the mineralisation of catechol to CO<sub>2</sub>,<sup>[159]</sup> and the formation of chloroethene and chloroalkanes from catechol under Fenton-like conditions in the presence of chloride.<sup>[160]</sup> The degradation of catechol to mono- and dicarboxylic acids

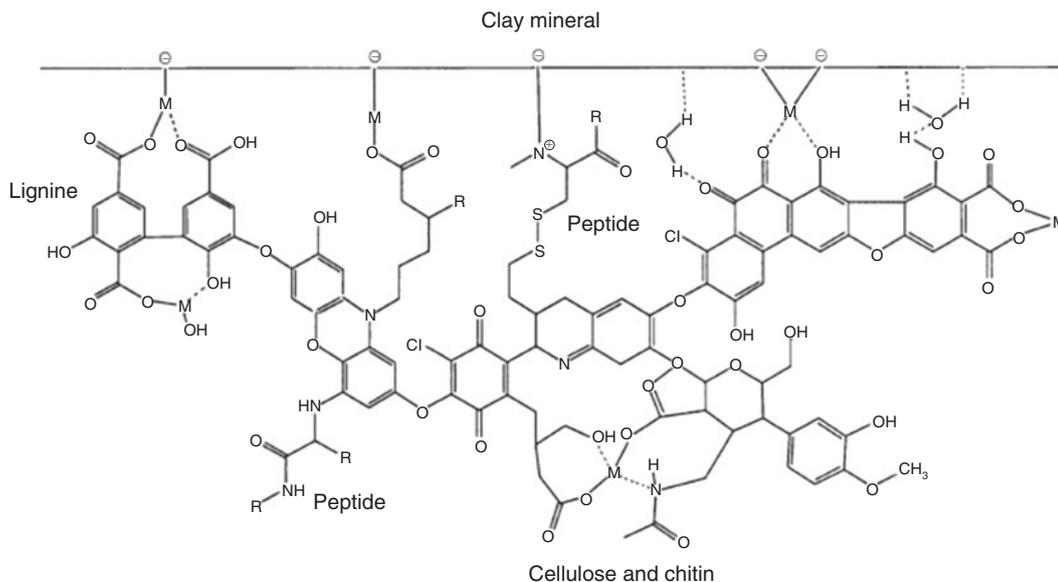


Fig. 8. Proposed structure of humic acid.<sup>[150]</sup>

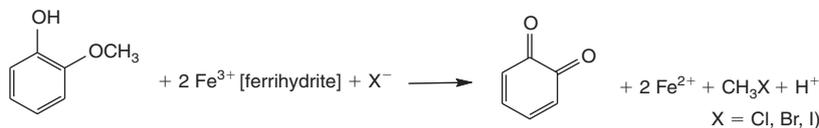


Fig. 9. Schematic formation of methyl halides from guaiacol.<sup>[151]</sup>

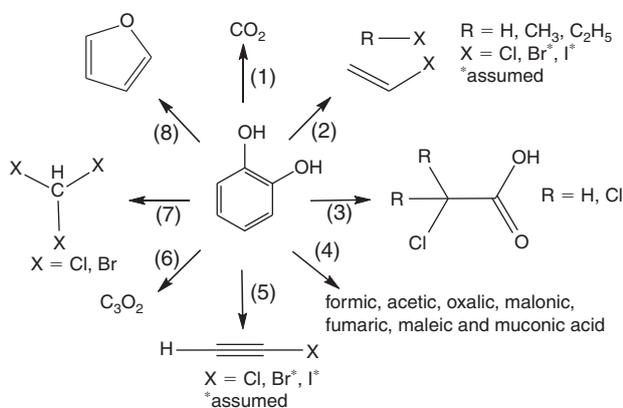


Fig. 10. Degradation of catechol under Fenton and Fenton-like condition to (1) carbon dioxide,<sup>[159]</sup> (2) chloroethene and chloroalkanes,<sup>[160]</sup> (3) chlorinated acetic acid,<sup>[118,161]</sup> (4) muconic, formic, acetic, oxalic, malonic, fumaric and maleic acids,<sup>[162–164]</sup> (5) chloroethyne,<sup>[165]</sup> (6) carbon suboxide,<sup>[166]</sup> (7) trihalomethanes,<sup>[167]</sup> (8) furan.<sup>[168,169]</sup>

was observed,<sup>[162,163,164]</sup> and chloroethyne,<sup>[165]</sup> carbon suboxide<sup>[166]</sup> and trihalomethanes<sup>[167]</sup> were also detected. All reaction channels in Fig. 10 may have similar probabilities, and the product yields in the terrestrial environment are in the parts per million or up to percentage range, depending on the substrate concentration and environmental parameters such as pH, Eh and humidity.

For the liberation of chloromethane from guaiacol,<sup>[151]</sup> a mechanism for the formation of halogenated alkanes was proposed,<sup>[170]</sup> based on nucleophilic substitution promoted by Fe<sup>III</sup> and formation of 1,2-benzoquinone. The latter is assumed to be an intermediate in the mineralisation process<sup>[159]</sup> and the

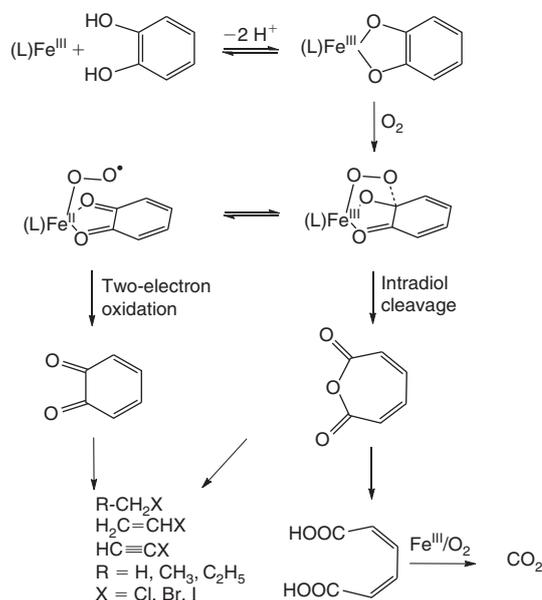
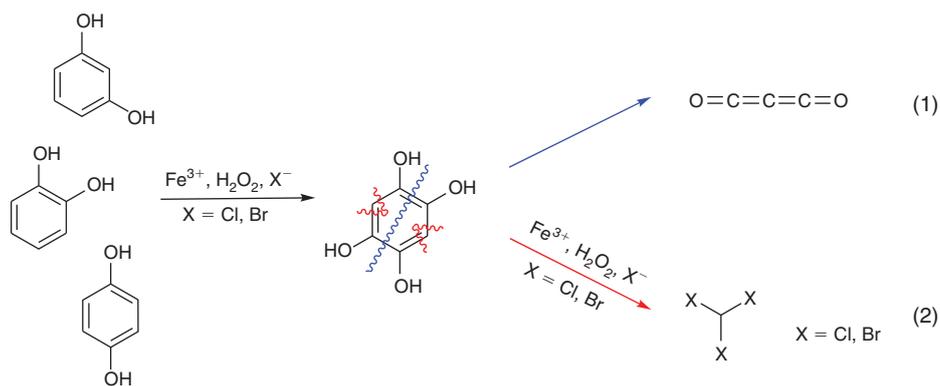


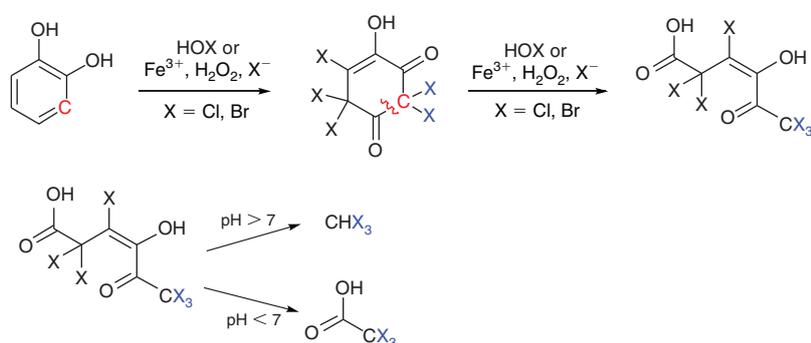
Fig. 11. Iron-catalysed oxidation of catechol to 1,2-benzoquinone (left, electron transfer), muconic anhydride (right, eventually forming muconic acid). In the corresponding enzymes and model systems, the iron species are transformed to the resting state, top left. Further reactions to CO<sub>2</sub> and volatile halocarbons also shown in the scheme are not mechanistically studied in detail but may follow mechanisms discussed elsewhere in this review.<sup>[89,113,159,160,165]</sup>

formation of saturated and unsaturated halocarbons,<sup>[160,165]</sup> see Fig. 11 and *Abiotic oxidation of organic matter* section.

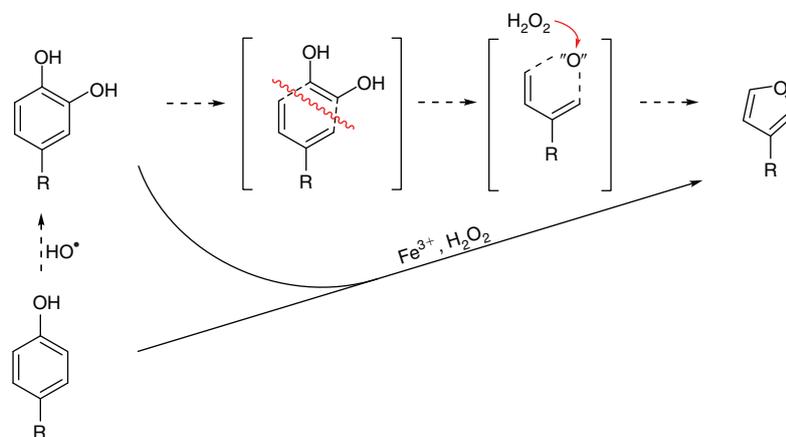
Based on studies with several phenolic derivatives (catechol, hydroquinone, and recorcinol),<sup>[166,167]</sup> the formation of 1,2,4,5-



**Fig. 12.** Formation of 1,2,4,5-tetrahydroxybenzene followed by ring cleavage to (1) carbon suboxide,<sup>[166]</sup> and (2) trihalomethanes.<sup>[167]</sup>



**Fig. 13.** Postulated formation of trihalomethanes and halogenated acetic acids.<sup>[161,167,172]</sup>



**Fig. 14.** Proposed catechol degradation to furan.<sup>[168]</sup>

tetrahydroxybenzene and, depending on where the C–C bonds in this intermediate is cleaved, the release of carbon suboxide and trihalomethanes were postulated (Fig. 12).

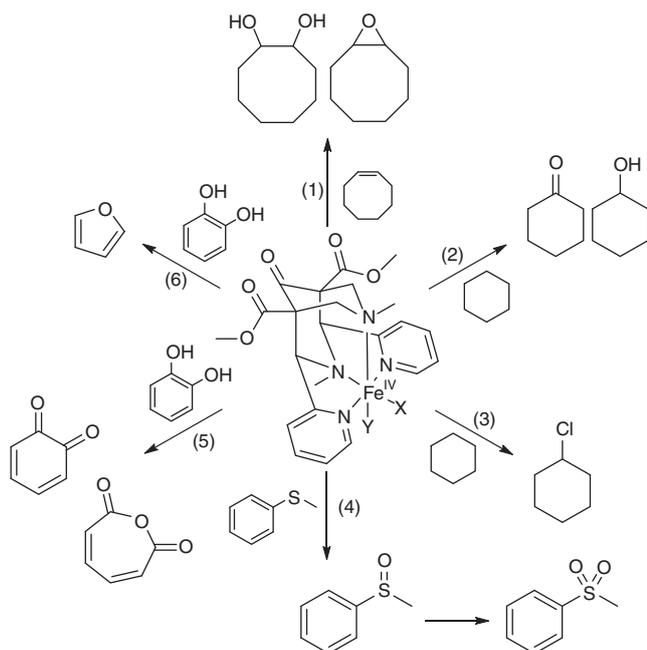
The well-known haloform reaction<sup>[171]</sup> of methyl ketones in alkaline conditions yields trihalomethanes after ring cleavage. Alternatively, the degradation of 1,3-dihydroxybenzene (resorcinol) by direct chlorination of aromatic residues is proposed to produce trichloromethane and trichloroacetic acid (Fig. 13).<sup>[172]</sup>

This mechanism can explain the formation of haloacetic acid<sup>[161]</sup> but, in contrast to the experimental conditions, it assumes basic conditions for the release of trihalomethanes.<sup>[167]</sup> A review of the literature on natural trichloromethane formulation in peatlands, tundra and forest soils found strong evidence

that also in acidic environments the liberation of trichloromethane is conclusive.<sup>[173]</sup>

A non-halogenated volatile compound emerging from catechol is furan. By isotopic labelling,<sup>[168]</sup> it was demonstrated that the oxygen atom in furan arises from H<sub>2</sub>O<sub>2</sub>, leading to the degradation pathway proposed in Fig. 14.

The degradation of catechol to furan was also studied with bispidine model systems. Several the thoroughly studied reactions with bispidine–ferryl complexes are shown in Fig. 15 (epoxidation and *cis*-dihydroxylation of alkenes,<sup>[84,121]</sup> oxidation<sup>[92,120]</sup> and halogenation<sup>[89]</sup> of cyclohexane, sulfoxidation<sup>[116]</sup> and catechol oxidation<sup>[113]</sup>). Although these earlier mechanistic studies were generally performed in organic



**Fig. 15.** Reactions catalysed by an iron(II) bispidine complex (see Figs 3 and 5–7; one of the coligands X,Y is the oxo group, the other is part of the bispidine backbone (i.e. a further pyridine), a monodentate coligand (e.g.  $\text{Cl}^-$  or a species derived from  $\text{H}_2\text{O}$ , e.g.  $\text{OH}^-$ ): (1) olefin epoxidation and *cis*-dihydroxylation,<sup>[84,121]</sup> (2) cyclohexane oxidation,<sup>[92,120]</sup> and (3) halogenation,<sup>[89,118]</sup> (4) sulfoxidation,<sup>[116]</sup> (5) catechol oxidation<sup>[113]</sup> and (6) furan formation.<sup>[169]</sup>

solvents (usually acetonitrile), more recent work has also involved aqueous chemistry and in particular also the environmentally relevant conditions described above, and this confirmed the formation of furan by a ferryl oxidant.<sup>[169]</sup>

## Conclusions

Iron-induced and iron-catalysed oxidation of organic substrates in nature, in biotic and abiotic systems, leads to alkanes and alkenes as well as oxygenated and halogenated hydrocarbons. From abiotic systems, these volatile products are liberated into the atmosphere, and a large number of related interesting and novel products have been found in recent years. Field and laboratory studies have helped to trace them back to degradation processes of humic substances as one of the main contributors of organic matter in the soil. Inorganic model chemistry of biological processes (biomimetic chemistry) has helped to solve important mechanistic problems in the area of high-valent metal-oxo, in particular iron-oxo, chemistry in the last decade. It is therefore attractive to transfer some of these important and novel results from bioinorganic to environmental chemistry. Although one needs to be very cautious in reinterpreting earlier mechanistic interpretations that are primarily based on OH radical and ‘swimming pool’ chemistry, it appears that ferryl-based as opposed to OH radical-driven processes are in general more important than so far appreciated in environmental science.

## Acknowledgements

We are grateful for the financial support of the German Science Foundation (DFG Forschergruppe 763, HaloProc), to our coworkers for their excellent contributions and to our HaloProc colleagues for inspiring discussions.

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