The taming of oxygen: biocatalytic oxyfunctionalisations

Dirk Holtmann, a Marco W. Fraaije, b Isabel W. C. E. Arends, c Diederik J. Opperman d and Frank Hollmann* c

The scope and limitations of oxygenases as catalysts for preparative organic synthesis is discussed.

Introduction

Selective oxyfunctionalisation of non-activated hydrocarbons represents a contemporary issue of organic chemistry. The inertness of most C–H bonds requires powerful oxygen transfer agents.1 High activity, however, is frequently accompanied by poor selectivity, which is in contrast to the demands of modern chemical synthesis.2 Nature provides us with a class of catalysts that comprises both features: activity and selectivity: Oxygenases catalyse the introduction of oxygen atoms from molecular oxygen or hydrogen peroxide into (non-)activated C–H and C–C-bonds and to heteroatoms. Often, these oxyfunctionalisation reactions occur highly selectively. Many oxygenases are selective for only one position in structurally complex molecules and they introduce the oxygen atoms with high stereocontrol. Furthermore, overoxidation, which is a frequent problem in chemical oxyfunctionalisation, is far less observed in enzymatic oxyfunctionalisations. This unique combination of activity and selectivity stems from the embedding of reactive oxygen transfer reagents such as highly oxidised iron–oxo complexes or organic peroxides in the cavity of an enzyme’s active site. The well-defined and chiral environment not only positions the starting material precisely to the ‘hot’ oxygen atom transferred (accounting for selectivity) but also stabilises transition states thereby leading to, sometimes dramatic, rate accelerations as compared to the biomimetic analogues (Scheme 1).

Therefore, it is not very astonishing that the interest in biological oxyfunctionalisation chemistry has been steadily growing over the past decades. We are convinced that oxygenases,

Dirk Holtmann was born in Bremen, Germany, and has completed his diploma in chemical engineering/biotechnology in 1999. He obtained his PhD at the Otto von Guericke University of Magdeburg on the electrochemical measurement of the microbial activities in fermentations. He is group leader of the biochemical engineering group at the DECHEMA Research Institute in Frankfurt, Germany. His current research activities concentrate on biocatalysis and biotransformations, the development and evaluation of electro-enzymatic processes as well as microbial electrosynthesis.

Marco W. Fraaije obtained his PhD in Biochemistry in 1998 from Wageningen University, The Netherlands. After a long-term EMBO fellowship in protein crystallography in the group of Prof. Andrea Mattevi at the University of Pavia, Italy, he moved to the University of Groningen, The Netherlands. Since 2012 he is full professor, leading a Molecular Enzymology research group. His research interests cover many areas of biocatalysis, in particular the knowledge-based discovery, engineering and redesign of oxidative enzymes.
following the well-established hydrolases\textsuperscript{4–6} and the ever more popular dehydrogenases,\textsuperscript{5,7–10} will represent the next upcoming wave of biocatalysts used in chemical synthesis.\textsuperscript{11}

The aim of this perspective is to encourage organic chemists to consider oxygenases in their synthesis planning more often. For this, we will focus on the application of oxygenases for organic synthesis, giving an overview over the rich product spectrum available already today and discussing some recent preparative examples. In particular, we will cover the most-common oxygenases, \textit{i.e.} flavin-dependent monoxygenases as well as heme-dependent monoxygenases and -peroxygenases. Also some perceived and real limitations \textit{en route} to becoming truly practical catalysts, together with some promising solutions will be discussed. A detailed discussion of the catalytic mechanisms would be beyond the scope of this perspective; the interested reader is referred to some excellent reviews\textsuperscript{5,6,12–14} exhaustively covering our current mechanistic understanding.

It is also worth mentioning here that continuously new oxygenases are discovered as well as existing ones are improved to match with the requirements of chemical synthesis.\textsuperscript{1,10,12,14–35} Again, an in-depth discussion of these approaches, let alone the new enzymes obtained is not possible here, but some excellent recent contributions exhaustively cover this field.

\textbf{Flavin-dependent monoxygenases}

Flavin-dependent monoxygenases represent an extremely diverse class of enzymes catalysing an equally diverse range of synthetically useful oxyfunctionalisation reactions (Scheme 2).\textsuperscript{28–30,33,36–40}

The catalytic mechanism of the flavin-dependent monooxy-
genases comprises an oxidative and a reductive half reaction. The catalytic cycles start with the latter by NAD(P)H-mediated reduction of the enzyme-bound flavin group. The reduced flavin comprises highly reactive oxygenation agents such as (formal) Fe\textsuperscript{V}—oxyferryl—heme, or (hydro)peroxo—flavins embedded in the well—defined framework of an enzyme.\textsuperscript{3}

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flavin interacts with molecular oxygen to form an organic peroxide (C4a-(hydro)peroxoflavin), which acts as the actual oxygen transfer agent (oxidative half reaction). The resulting C4a-hydroxyflavin eliminates water and thereby returns to the oxidized resting form (Scheme 3). Only very recently an alternative mechanism for oxygenation by a flavoprotein has been revealed.41 It was shown that the bacterial enzyme EncM, involved in the biosynthesis of the antibiotic enterocin, performs an coenzyme-independent oxygen insertion via a reactive flavin N5-oxide. In this specific example, the reducing equivalents come from the substrate itself. It remains to be seen whether this is a rare example or whether there are more flavoproteins in nature that employ such a mechanism.

In principle, the chemical versatility of flavins should also allow for H2O2-driven oxyfunctionalisation reactions as frequently demonstrated with N5-alkylated flavins as ‘chemical catalysts’.28 Recently, Fraaije and coworkers have demonstrated that flavoproteins can be engineered to act as peroxigenases by replacing the riboflavin cofactor in the riboflavin-binding protein with alkylated flavins. Overall the general feasibility of ‘flavoperoxigenases’ could be demonstrated (Scheme 4).42

Organic chemists are probably most acquainted to the enzymatic Baeyer–Villiger oxidation mediated by so-called Baeyer–Villiger monooxygenases (BVMOs, Scheme 2, 2). Since some early contributions from the mid-20th century43–45 and the pioneering work by Trudgill and coworkers46,47 the scope of enzymatic Baeyer–Villiger reactions has been expanded significantly in the last two decades31,48–50 and a range of synthetically useful transformations have been reported (Table 1). Also, the first crystal structure of a BVMO51 has significantly contributed to the mechanistic understanding of BVMOs52,53 and enabled rational approaches to engineer tailored new BVMOs.54–64 Today, the enzymatic Baeyer–Villiger oxidation (in the form of whole cell biotransformation, *vide infra*) has reached the multi-kg scale65–68 and further scale-ups and industrial applications may be expected in the nearer future.

A special case of BVMO-catalysed Baeyer–Villiger oxidations is the oxygenation of aldehydes (Scheme 2, 5). In most cases, BVMOs convert aldehydes into the corresponding formyl esters (following the migration rules of the chemical Baeyer–Villiger oxidation). However, recently Bisagni and coworkers reported...
on a novel BVMO from *Dietzia* sp. preferentially catalysing acid formation of e.g. profene aldehydes.69

Many of the aforementioned BVMOs are also capable of heteroatom oxygenation (Scheme 2, 4). Enantiospecific sulfoxidation here clearly represents the reaction most frequently investigated.30,70–74 Next to the often high enantioselectivity of this reaction, also its high chemoselectivity is valued as the ‘overoxidation product’ i.e. the corresponding sulfone is usually not observed in enzymatic sulfoxidation reactions. Next to sulphur also other heteroatoms such as selenium,75–78 boron,77,79 or nitrogen48 can be oxygenated using flavin-dependent monoxygenases. Recently, Codexis evolved cyclohexanone monoxygenase for the selective sulfoxidation to yield enantiopure (S)-pantoprazole (Scheme 5),74,80 thereby impressively demonstrating the potential of protein engineering to tailor a monoxygenase to meet the requirements of industrial-scale synthesis.

Also the regioselective hydroxylation of phenols (Scheme 2, 3) either in the *ortho-* or *para*-position represents a principally highly interesting reaction for organic synthesis as the repertoire of chemical aromatic hydroxylations (apart from Dakin-, Sandmeyer- and Baeyer–Villiger-type reactions as well as boronic acid oxidations) is rather limited. However, at present also the number of phenol hydroxylases is rather restricted as well.81 Nevertheless for example, 2-hydroxy biphenyl-3-monooxygenase (HbpA) has been used at up to kg-scale synthesis of catechols.82–89 But also phenol hydroxylase (PheA1),90–93 and the benzoate hydroxylases94–96 have been reported and might exhibit some synthetic potential.

Steroselective epoxidation of C=C-double bonds (Scheme 2, 1) is an emerging field in flavoprotein- monoxygenase chemistry. Especially the so-called styrene monoxygenases are enjoying increased popularity. For example the styrene monoxygenase from *Pseudomonas* sp. VLB 120 has been investigated intensively by Schmid and coworkers.97–114 But also new styrene monoxygenases from other sources are constantly added to the portfolio.115–121

Currently, the styrene monoxygenases available appear to have a clear preference for vinyl aromatic substrates even though also aliphatic alkenes have been reported as substrates.119,120 The more severe limitation of the present portfolio is that exclusively (S)-selective styrene monoxygenases are known. Hopefully, screening of natural diversity and/or protein engineering will close this gap in the nearer future.

An interesting cascade reaction producing enantiomerically pure (S)-styrene oxide from (renewable) phenylalanine in a cascade of amino lyase, decarboxylase and styrene monoxygenase was reported recently by Nielsen and coworkers (Scheme 6).122 Also, flavoprotein monoxygenase-catalysed oxidative halogenation reactions (Scheme 2, 6) are worth mentioning here. In the stricter sense, these reactions are not oxyfunctionalisation reactions as a halogen is incorporated instead of an oxygen atom.123–133 According to our present knowledge, flavin-dependent halogenases primarily catalyse the oxidation of halogenides to hypohalous acids (HOCl, HOBr). These are guided by the protein backbone directly and exclusively to the substrate performing the electrophilic halogenation reaction. Even though, flavin-dependent halogenases seem to be limited to activated (aromatic) substrates, their exclusive regioselectivity should make them highly interesting tools not only for pharmaceutical applications. However, *en route* to preparative application their still comparably poor catalytic activity (*k*<sub>cat</sub> being in the range of < 1 min<sup>−1</sup>) needs to be addressed.

Very recently, an interesting cascade of tryptophan synthase and tryptophane-7-halogenase was reported giving access to a broad range of tryptophan derivates from simple indole starting materials (Scheme 7).134

Finally, also a newly discovered long-chain alkane degrading flavoprotein monoxygenase (LadA) should be mentioned here.135,136 So far, this is the only flavin-dependent monoxygenase reported capable of hydroxylating non-activated hydrocarbons (being largely the domain of (non)-heme iron monoxygenases, *vide infra*). At present, only a few reports deal...
### Table 1: Representative examples of oxyfunctionalisation reactions mediated by flavin-dependent monooxygenases

| Substrate | Product | R | % Conv. (% yield) | Catalyst | ee (%) | Volumetric scale | Remarks | Ref. |
|-----------|---------|---|-------------------|----------|--------|------------------|---------|------|
| (1) Epoxidation reactions | | | | | | | | |
| | | R1 = H, R2 = Me | (87) | SMO (rec in growing E. coli) | > 99 (S) | 1 L | [S]₀ = 695 mM; t = 8 h | 100 |
| | | R1 = H, R2 = Me | 95 (87) | SMO (crude cell extract) | 99.7 (S) | 100 mL | [S]₀ = 50 mM; t = 10 h; TON(SMO) = 1844 | 114 |
| | | R1 = R2 = H, R3 = F, Cl, Br, Me | (90, 70, 31, 62) | SMO (rec in resting E. coli) | All > 99.9 (S) except 62.8 (S) for Me | 1 mL | [S]₀ = 200 mM; t = 24 h | 119 and 120 |
| | | R1 = R3 = H, R2 = Cl | 91 (73) | SMO (crude cell extract) | > 99.9 (S) | 100 mL | [S]₀ = 50 mM; t = 10 h; TON(SMO) = 2171 | 114 |
| | | R1 = R2 = H, R1 = Et, Me | (40, 10) | CHMO (partially purified enzyme) | > 98 (R) | 10 mL | [S]₀ = 12 mM; t = 48 h | 139 |
| (2) Baeyer–Villiger oxidations | | | | | | | | |
| | | R1 = R2 = Me, Et, nPr, iPr, nBu, allyl (independently) | 47 | HAPMO (partially purified enzyme) | > 98% (product) | 50 mL | 900 g; [S]₀ = 0.1 M; t = 20 h | 65 and 66 |
| | | R1 = R2 = Me, Et, nPr, iPr, nBu, allyl (independently) | 50 | CHMO (partially purified enzyme) | E > 100 | 13 mL | [S]₀ > 20 mM; t = 24 h; DKR | 70 |
| | | R1 = R2 = Me, Et, nPr, iPr, nBu, allyl (independently) | | CHMO (partially purified enzyme) | E > 200 | 50 mL | KR; [S]₀ = 5.4 mM | 141 |
| | | R1 = R2 = Me, Et, nPr, iPr, nBu, allyl (independently) | | CHMO (partially purified enzyme) | E > 200 | 1 mL | KR or desymmetrization; [S]₀ = 2 mM; t = 2 h | 142 |
with this interesting enzyme and future will tell the preparative potential of LadA.

A representative selection of examples ranging from analytical proof-of-concept contributions to (near) industrial scale implementations is shown in Table 1.

Overall, flavin-dependent monooxygenases have great potential for organic synthesis. They enable highly selective introduction of molecular oxygen into organic compounds. Very often, a comparable chemical route is yet unknown. Unfortunately, at present only a few of these promising catalysts are commercially available (e.g. some BVMOs).

**Heme-iron-monooxygenases and -peroxygenases**

Heme-iron-monooxygenases, also called P450- or CYP-monooxygenases, exhibit an even higher oxyfunctionalisation
potency than most of the flavoprotein monooxygenases discussed above. P450 monooxygenases can also abstract non-activated C–H bonds such as in alkanes. Obviously, this has inspired many research groups worldwide to explore the catalytic potential of this enzyme class (Scheme 8).20,21,144–147

P450 monooxygenases comprise a somewhat more complicated mechanism than flavoprotein monooxygenases. Molecular oxygen is activated by coordination to a highly oxidized (formally FeV) iron species enabling electrophilic O-transfer. To achieve this, two additional reducing equivalents are necessary, which are delivered in two individual single electron transfer steps (Scheme 9). Again, NAD(P)H serves as a source for the reducing equivalents needed. However, since NAD(P)H is an obligate hydride donor, it is not capable of interacting directly with the iron centre (being an obligate single electron acceptor). To overcome the mechanistic incompatibility of NAD(P)H and Fe3+, nature uses e.g. NAD(P)H-ferredoxin oxidoreductases as relay systems. These enzymes contain flavins, which due to their mechanistic versatility, can accept a hydride from NAD(P)H and pass on the two electrons in two subsequent steps either to the monooxygenase directly or via electron transport proteins such as Fe2S2 ferredoxin (Scheme 10).

It is worth mentioning here that some P450 monooxygenases are capable of forming the catalytically active oxyferryl species from the resting state using hydrogen peroxide (Scheme 9). However, usually, their efficiency with H2O2 is relatively poor so that oxidative inactivation of the heme-prosthetic group (and the protein backbone) dominates. In contrast, the so-called peroxygenases utilise this hydrogen peroxide shunt pathway very efficiently enabling the H2O2-driven P450-oxyfunctionalisation chemistry. In fact, it has been hypothesised that the P450 monooxygenases have evolved from H2O2-dependent ancestors.158

P450 monooxygenases have received tremendous attention due to their capability to hydroxylate non-activated C–H bonds. For example, the selective and mild hydroxylation of (cyclo)alkanes represents a focus of research. The promise here lies in the high selectivity of the enzymatic hydroxylation avoiding undesired overoxidation of the (more reactive) reaction products as frequently encountered in (industrial) oxidation methods.159 A very recent contribution by Groger and coworkers nicely demonstrates the synthetic potential of biocatalytic oxyfunctionalisation (Scheme 11).160,161 By combining a P450-monooxygenase with an alcohol dehydrogenase, the authors achieved clean aerobic oxidation of cyclohexane to cyclohexanone with absolute selectivity.
The overall low yield of the reaction (<10%) is most probably attributed to the volatility of the reagents and the non-optimised reaction conditions. Nevertheless, the high selectivity of this reaction convinces especially compared to chemical processes, where frequently by-products originating from overoxidation and ring-cleavage are observed.159
Similar examples comprise the selective transformation of (cyclo)alkanols into the corresponding esters (e.g. cyclohexanol to ε-caprolactone).\textsuperscript{162,163}

Industrial interest in P450 monooxygenases today mainly stems from the pharmaceutical industry for the generation of drug metabolites and the production of active pharmaceutical ingredients (APIs) such as steroids.\textsuperscript{26,146,147,164,165}

But also selective oxyfunctionalisation of terpenes is of great interest.\textsuperscript{152,166–173}

A very elegant approach was reported by Keasling and coworkers who used an engineered \textit{Saccharomyces cerevisiae} overexpressing a P450 monooxygenase to produce artemisinic acid (basically from sugar) (Scheme 12).\textsuperscript{174,175}

Often, P450 monooxygenase-catalysed reactions are still somewhat too slow and yield too low product titers (\textit{vide infra})\textsuperscript{26} to meet the economic requirements for bulk chemicals.\textsuperscript{176}

Nevertheless, oxyfunctionalisation of fatty acids to yield ω,ω-dicarboxylic acids (as polymer building blocks) has been demonstrated at appreciable product titres of more than 100 g L\textsuperscript{-1} (ref. 177–180) pointing towards large-scale applicability of these biocatalysts.

For a long time, methane hydroxylation was believed to be limited to non-heme iron monooxygenases and out of scope for P450-monooxygenases. Especially the higher bond-strength of the methane C–H bond as compared to higher homologues was thought to be the major reason for this.\textsuperscript{154} However, recently Reetz and coworkers have demonstrated that inert decoy molecules such as perfluorinated acids enable the P450BM3-catalysed hydroxylation of even methane.\textsuperscript{155} It is thought that the perfluorinated alkyl chain ‘fills up’ the large cavity around the active site and thereby facilitates methane binding. The same approach (decoy molecules) was also successful in enhancing P450BM3-catalysed hydroxylation of e.g. benzene.\textsuperscript{156,181} It is also interesting to note that such decoy molecules may have an influence on the stereoselectivity of P450-catalysed oxyfunctionalisation reactions.\textsuperscript{182}

Next to protein engineering\textsuperscript{20,158,164,183–189} also substrate engineering may be a promising approach to improve P450-monooxygenase-catalysis as demonstrated by Griengl and coworkers.\textsuperscript{190–193} For example \textit{Beauveria bassiana} cannot convert cyclopentanone whereas the corresponding N-benzyloxyxazolidine was converted smoothly by the same organism (Scheme 13).

It was suggested that the starting material itself was not efficiently recognised by the monoxygenase. Also the nature of the temporary protecting group had an influence on the stereoselectivity of the hydroxylation reaction. So far, this approach has not found widespread and systematic investigation.

Another exciting new development in P450-chemistry is the recent finding by Arnold and coworkers that reduced (Fe\textsuperscript{II}) P450
monooxygenases are efficient cyclopropanation catalysts (Scheme 14), opening up new avenues for P450-chemistry.\textsuperscript{157}

Table 2 gives a representative, yet naturally incomplete, overview over the diversity of P450 monooxygenase-catalysed oxyfunctionalisation reactions.

Peroxygenases entail the chemical versatility of P450 monooxygenases without being dependent on the complicated electron transport chains (\textit{vide infra}). Instead of relying on reductive activation of molecular oxygen, peroxygenases utilise H₂O₂ to form the catalytically active oxyferryl species (hydrogen peroxide shunt in Scheme 9).\textsuperscript{197}

For many decades chloroperoxidase from \textit{Caldariomyces fumago} (CPO) has been the role model and only representative of this highly interesting enzyme class.\textsuperscript{198–227} However, more recently a range of new (and potentially more useful) members of this enzyme class have gained interest.\textsuperscript{228–244} For example a peroxygenase from the basidomycetous fungus \textit{Agrocybe aegerita} is capable of cyclohexane hydroxylation, a reaction that has never been observed for CPO.\textsuperscript{228} If developed further, this reaction might become a viable alternative to the existing, selectivity-wise highly challenging chemical cyclohexane oxygenation reactions.\textsuperscript{159}

Even though peroxygenases are most valuable for the organic chemist due to their oxygen transfer capability (yielding \textit{e.g.} enantiomerically pure epoxides or sulfoxides), some other – potentially very useful – applications have been reported recently. Haloperoxidases, for example, catalyse the oxidation of halogenides and release of the corresponding hypohalogenide into the reaction medium. Recently, Le Nôtre, Scott and coworkers reported a ‘biocatalytic’ oxidative decarboxylation of natural amino acids such as phenyl alanine yielding the corresponding nitriles as the major product (Scheme 15).\textsuperscript{245} The role of the vanadium peroxidase was restricted to \textit{in situ} formation of hypochloride, which mediated the oxidative decarboxylation of the \textit{z}-amino acid. Compared to a stoichiometric use of bleach, this catalytic method excels by its catalytic use of chloride thereby significantly reducing salt wastes.

Some of us have applied CPO recently for the chemoenzymatic halogenation of thymol. The hydrogen peroxide needed for the enzymatic reaction was generated by electrochemical reduction of molecular oxygen (Scheme 16) thereby providing H₂O₂ in sufficient amounts to sustain the catalytic cycle while minimising H₂O₂-related inactivation of the enzyme.

Overall, P450-enzymes (monooxygenases and peroxygenases) exhibit enormous potential for preparative organic synthesis.

### Regeneration strategies

As mentioned above, reduced nicotinamides serve as universal electron donors for the reductive activation of molecular oxygen. Therefore, it is not very astonishing that the majority of published applications include NAD(P)H. Due to its fairly high costs, NAD(P)H cannot be applied in stoichiometric amounts but rather in catalytic amounts together with a suitable cofactor regeneration system (Table 3). Overall, oxidation of a simple sacrificial cosubstrate is utilised to promote monooxygenase catalysis.

One obvious approach is to utilise the microbial metabolism to provide the reducing equivalents needed.\textsuperscript{65,97,98,106,103–105,111–113,117,138,140,246–250} The advantages of this approach are: (1) the enzyme(s) are not isolated thereby significantly reducing the catalyst preparation costs;\textsuperscript{176} the same is true for the nicotinamide cofactor, which is supplied by the microbial cell; (2) generally, enzymes within their natural environment (the microbial cell) are more stable than as isolated preparations, also the microbes can constantly replace inactivated enzymes; (3) the growth substrate (\textit{e.g.} glucose) for the microorganism also serves as a sacrificial electron donor for the biotransformation reaction thereby theoretically providing the maximal amount of reducing equivalents available from complete mineralisation. These advantages explain why fermentative processes still dominate the field of biocatalytic oxyfunctionalisation chemistry. There are, however, also a range of challenges that have fostered research on the use of isolated enzymes. Amongst them are the frequently observed toxicity of the reagents to the microbial cells, transport limitations of reagents over the cell membranes, as well as issues related to undesired side reactions catalysed by the many other enzymes present in the microbial cells. Also, it is not always easy to balance the microorganism’s redox needs with the demands of the desired biotransformation.

Using isolated monooxygenases circumvents some of the aforementioned challenges: by utilising isolated enzymes, the...
biotransformation is uncoupled from the fermentation step and therefore can be controlled more easily. Also, undesired side reactions are generally observed to a lesser extent than in whole-cell systems. The major challenge of using isolated enzymes is that the supply of the monooxygenase with reducing equivalents does not anymore come along with the microbial metabolism. Hence, the nicotinamide cofactor (in substoichiometric amounts) has to be applied together with a suitable in situ regeneration system. Table 3 gives an overview on common enzymatic NAD(P)H regeneration systems used to promote
monooxygenase reactions. To estimate the efficiency of a given regeneration system the total turnover number (TTN) of the nicotinamide cofactor can be used. As a rule of thumb, TTN of greater than 1000 are generally considered to be sufficient for an economically reasonable process (even though it must be mentioned here that this very much depends on the price of the product amongst others).

Recently, so-called designer cells have gained significant attention. This approach combines the advantages of whole cell biocatalysis and the regeneration approaches outlined in Table 3 by coexpressing the production enzyme together with a suitable regeneration system and using the whole cells as catalysts. On the one hand the enzymes are protected in their natural environment and also protein-isolation and -purification is not applied. On the other hand, the cells are usually not metabolically active thereby largely eliminating toxicity issues as well as undesired side reactions. Overall, the designer-cell approach appears to be a very promising catalyst concept for future biocatalytic oxyfunctionalisation reactions.

The regeneration approaches outlined before all are based on the enzyme-coupled regeneration concept: regeneration reaction and production reaction are linked via the nicotinamide cofactor only. Hence, the cofactor regeneration consumes another substrate (cosubstrate) and produces a stoichiometric coproduct. Another interesting approach is the so-called intrasequential cascade, wherein the NAD(P)H-consuming (oxyfunctionalisation) reaction is also productively coupled to the NAD(P)H-regenerating reaction via an intermediate product (Scheme 17). Their use elegantly circumvents the need for the additional cosubstrate–coproduct couple by double transformation of only one substrate but naturally is rather limited in scope. However, the self-sufficient nature of these reactions as well as the apparent non-generation...
of wastes might point towards bulk-scale application such as ε-caprolactone or cyclohexanone from simple starting materials.

**Direct regeneration approaches**

Many monooxygenases rely on rather complicated, multi-enzyme electron transport chains to deliver the reducing equivalents from NAD(P)H to the flavin- or heme-prosthetic group. While this architecture makes sense for the (microbial) cell as it adds further levels of control over the cellular redox metabolism, it adds further complexity to the application of monooxygenases for chemical synthesis. Often, only the reducing equivalents are needed to sustain the monooxygenases’ catalytic cycles; therefore in recent years a growing number of research efforts have been dedicated to delivering the reducing equivalents directly to the monooxygenases and circumventing the electron transport chains (Scheme 18).

The potential benefit of such direct regeneration approaches is that complicated electron transport chains comprising up to 2 additional enzymes and 2 additional cofactors can be substituted by only one regeneration catalyst, resulting in highly simplified (and more easily controllable) reaction schemes. Table 4 summarises some representative examples of oxyfunctionalisation reactions performed by direct regeneration.

It becomes clear from Table 4 that the immense potential of direct regeneration of monooxygenases still remains to be exploited. The major limitation is the regeneration catalysts, which in most cases do not appear to act as true catalysts. We believe that the reason lies in the high reactivity of most mediators with molecular oxygen. Hence, futile reoxidation of the reduced regeneration catalysts by molecular oxygen competes with the desired monooxygenase regeneration thereby lowering the productive catalytic turnover of the regeneration catalysts. Furthermore, the futile cycle leads to the generation of reactive (partially reduced) oxygen species (ROS), which impair enzyme stability and lead to undesired side reactions.

The molecular reason for this undesired side reaction probably lies in the redox properties of the regeneration catalysts used. With the exception of \([\text{Cp*Rh(bpy)(H}_2\text{O)}]^+\) and deaza-flavin, all regeneration catalysts are obligate one electron donors; hence their reaction with the predominant triplet oxygen \((\text{^3O}_2)\) is spin-allowed (and fast) whereas the reactions of the two-electron donors \([[\text{Cp*Rh(bpy)}^+\text{H}]]\) and deaza-flavin\(^{\text{red}}\) with \(^3\text{O}_2\) are spin-forbidden (and therefore slow). Also the natural redox mediators such as putida redoxin (Pdx) are single electron mediators and therefore prone to fast aerobic reoxidation. The same is true to some extent for reduced flavins. Even though they are traditionally denoted as two-electron donors (in the classical mechanisms) they are also able to form semiquinones e.g. during sequential reduction of FeS-redoxproteins or during fast synproportionation with oxidised flavins.\(^{274}\) This also explains the exceptionally high turnover numbers observed by Schmid and coworkers (Table 4).\(^{101}\)
By using very low flavin concentrations they could efficiently shift the flavin synproportionation equilibrium away from the reactive flavin semiquinones. Furthermore the advanced electrochemical reactor setup enabled minimising the contact time of reduced flavins and molecular oxygen.

Unfortunately, so far this undesired uncoupling reaction (also observed quite frequently with the ‘traditional’ regeneration approaches) has not been addressed very much and a general awareness of this oxygen dilemma is missing.

Overall, it can be asserted that on the one hand undesired, spontaneous reduction of molecular oxygen leads to a waste of reducing equivalents and concomitant of toxic ROS. On the other hand, molecular oxygen, as an integral part of the catalytic cycle of monooxygenases, cannot be omitted from the reaction schemes, resulting in the ‘oxygen dilemma’. Practical solutions to the oxygen dilemma are urgently needed in order to make monooxygenase-catalysis truly practical for organic synthesis.

Supply with H$_2$O$_2$ to promote peroxynasate catalysis

The dependence of peroxynasases on simple peroxides only at first sight offers a trouble-free catalyst system to be used in organic synthesis. The major challenge of using peroxides as a source of oxygen lies in their reactivity, especially with the prosthetic heme group itself. The exact inactivation mechanism is still under debate but it is clear by now that already small concentrations of hydrogen peroxide irreversibly inactivate the heme group (most probably oxidatively).

The simplest approach to circumvent the undesired oxidative inactivation of peroxynasases is to supply H$_2$O$_2$ in various, small portions. This approach is, however, work-intensive and also leads to significant volume increases which will complicate downstream processing. Alternatively, organic hydroperoxides have received some attention as milder alternatives to H$_2$O$_2$. More recently, various in situ O$_2$ reduction methods have been evaluated to generate H$_2$O$_2$. The principle behind is that these methods enable to generate H$_2$O$_2$ in situ in just the right amounts to sustain peroxynasate catalysis while minimising the H$_2$O$_2$ related inactivation. Table 5 gives an overview of the different sources of reducing equivalents needed for O$_2$ reduction and catalysts used.

| Product | Monooxygenase | Regeneration catalyst | Source of reducing equivalents | TTN (regeneration catalyst) | Ref. |
|---------|---------------|-----------------------|-------------------------------|-----------------------------|------|
| P450 cam | Pdx | Cathode | 0.06 | 259 |
| StyA | FAD | Cathode | 0.51 | 263 |
| StyA | [Cp*Rh(bpy)(H$_2$O)$_2$] | NaHCO$_3$ | 10 | 110 |
| Myoglobin | None | Cathode | — | 261 and 262 |
| P450 cam | Pdx | Cathode | 0.51 | 263 |
| P450rFP45004A1 | Co(sep) | Cathode | 0.016 | 264 |
| P450BM3 | Co(sep) | Zn | <1 | 265 and 266 |
| P450BM3 | [Cp,Co]$^+$ | Zn | 0.05 | 267 |
| P450BM3 | Co(sep) | Sodium diethylthiocarbamate | 140 | 153 and 268 |
| P450BM3 | Deazaflavin | EDTA | 7 | 269 |
| P450BM3 | Co(sep) | n.d. | Cathode | 168 and 270–272 |
| P450 cin | Co(sep), phenosafranine T, neutral red, flavins | n.d. | Cathode | 273 |

How green/environmentally friendly are biocatalytic oxyfunctionalisation reactions?

Today, biocatalysis is generally accepted as a ‘green technology’. Often, one or a few of the famous Twelve Principles of Green Chemistry are used to substantiate the green touch of a given reaction.
biocatalytic reaction. However, we are convinced that authors should be more careful with green claims as a critical evaluation of the environmental impact might actually result in nasty surprises. The Twelve Principles of Green Chemistry are a wonderful framework for the design of environmentally more friendly processes but simple adherence to some of these principles does not make a given reaction/process ‘green’. Therefore, a more quantitative (and critical) evaluation is a prerequisite en route to truly Green Chemistry. Today, full life cycle assessment, taking into account as many parameters as possible, represents the ‘golden standard’ of environmental evaluation. However, the data basis required for LCAs is enormous, making LCAs time-consuming and too expensive for academics to perform.

We believe that simple, mass-based metrics such as the E-factor ($E$ being the amount of waste generated per kg of product)\(^{289}\) may be a valuable tool especially for academic researchers to estimate the ‘greenness’ of a given reaction.\(^{290-293}\) The E-factor concept is easily understood and the calculations easily and quickly done. Of course, such a simple mass-based tool neglects important contributors to the environmental impact such as energy consumption and does not weigh the quality of the different mass flows (scarce starting materials, hazardous wastes).\(^{294,295}\) Nevertheless, the E-factor frequently qualitatively points into the same direction as more advanced analyses and thereby can give valuable hints to optimise a reaction.\(^{100,290,296}\) Therefore, we would like to encourage especially academic researchers to use this simple tool more often to critically assess the environmental impact of their reactions.

In the following, we highlight and discuss two Green Chemistry issues that – to our mind – are notoriously underestimated in the scientific literature dealing with (bio)catalytic oxyfunctionalisation chemistry: substrate loading and downstream processing.

Substrate loading has a very significant impact on the economic feasibility and environmental impact of a reaction. However, the majority of reactants of interest is poorly water soluble. Unfortunately, the general solution to this challenge is to apply low substrate concentrations (often in the lower millimolar range). A simple E-factor estimation however demonstrates the dimensions of the water ballast resulting from this (Fig. 1). Producing tons of contaminated waste water per kg of product cannot be the ultimate green (not to mention economical) solution.

Increasing the overall substrate concentration can significantly reduce the water ballast of any given reaction and therefore should be more often be strived for. To cope with the poor substrate solubility, the two-liquid-phase-system (2LPS) approach seems to be a viable solution. Here, a water-immiscible apolar organic phase serves as the substrate reservoir and product sink enabling overall high payloads (Scheme 19).

Table 5 \textit{In situ} \text{H}_2\text{O}_2\text{ generation methods to promote peroxygenase reactions}

\begin{tabular}{|c|c|c|c|}
\hline
Catalyst & Cosubstrate & Coproduct & Ref. \\
\hline
GOx & Glucose & Gluconolactone & 197, 211 and 276–279 \\
Cathode & — & — & 201 and 280–284 \\
Pd & H\textsubscript{2} & — & 285 \\
Flavin/h\textsubscript{ran} & EDTA & Ethylene diamine, CO\textsubscript{2}, formaldehyde & 228, 286 and 287 \\
\hline
\end{tabular}

GOx: Glucose oxidase.

Additional benefits from the 2LPS concept may be alleviation of reactant toxicities and inhibitory effects (especially for whole cell biocatalysts),\(^{106,297}\) prevention of over-oxidation (e.g. of aldehydes into carboxylic acids)\(^{11,106,246,297–303}\) and prevention of hydrolytic degradation of e.g. epoxide or lactone products.\(^{14,111,112,114,304–306}\) Furthermore, high product concentrations in easily water separable organic phases will also facilitate DSP (\textit{vide infra}).

Of course, the selection of the organic solvent should – next to practical issues such as partitioning coefficients and bio-catalyst stability – also take its potential environmental impact into account.\(^{307-309}\)
One issue of 2LPS arises from the rather hydrophilic character of many sacrificial electron donors used such as formates, phosphites or glucose making them incompatible with 2LPSs exhibiting high volumetric ratios of organic to aqueous phase. To solve this challenge, some of us have recently proposed using hydrophobised formates as the organic phase for biocatalytic oxyfunctionalisation reactions (Scheme 20).251

Downstream processing (DSP) is an issue that is not very frequently addressed in typical publications dealing with (bio)catalysis. However, DSP is an integral part of the production system as ‘it is no product unless it is in a bottle’ (C. Wandrey). From an environmental point-of-view, DSP can contribute very significantly to the overall environmental impact of a production system.290,310 Therefore, an increased focus on DSP issues also at an early stage of development is highly desirable. This should include ‘smart by design’ reaction systems enabling facile product isolation e.g. by filtration or 2LPSs enabling low-energy distillation DSP.

Another very promising line of research comprises so-called cascade reactions,311,312 wherein complex reaction sequences are performed without isolation of the intermediate reaction products. A very elegant cascade was reported recently by Bühl and coworkers reporting a formal terminal amination of fatty acids by combining a sequence of two hydroxylase- and one transaminase-reaction (together with the corresponding cofactor regeneration reactions) in one engineered E. coli production strain (Scheme 21).313,314

Today, still too many research projects on biocatalytic oxyfunctionalisation focus on the biocatalyst only while accepting low substrate loadings and completely neglecting the DSP part.

Conclusions

Biocatalysis has a lot to offer for the organic chemist. Simple and robust catalysts such as lipases for chirotechnology applications are well-established already. Oxygenases are on the go to follow them. This will significantly broaden the chemist’s toolbox for selective oxidation/oxyfunctionalisation reactions. Especially the high selectivity of enzymes will enable shorter
synthesis routes and yield higher quality products. Another interesting feature of biocatalysis (in general) is its potential for environmentally more benign syntheses. However, being biobased alone does not make an enzymatic route green, a more self-critical evaluation of contributors is highly desirable. In this respect, already simple metrics such as the E-factor may be valuable and simple tools.

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