An alginate-confined peroxygenase-CLEA for styrene epoxidation†

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Oxyfunctionalisation reactions in neat substrate still pose a challenge for biocatalysis. Here, we report an alginate-confined peroxygenase-CLEA to catalyse the enantioselective epoxidation of cis-β-methylstyrene in a solvent-free reaction system achieving turnover numbers of 96 000 for the biocatalyst and epoxide concentrations of 48 mM.

Biocatalytic oxyfunctionalisation reactions are enjoying an increasing interest in organic chemistry.1 Especially the often very high regio- and enantioselectivity of enzymatic oxyfunctionalisation reactions such as hydroxylations or epoxidations offers synthetic chemists straightforward access to chiral building blocks, which with traditional chemical means are difficult to prepare.

Next to the well-known P450 monooxygenases,2 in recent years also peroxygenases3 have been in the centre of attention. P450 monooxygenases reductively activate molecular oxygen to form the catalytically active oxyferyl-heme species. Peroxygenases form this species directly from partially reduced oxygen species (peroxides) and thereby circumvent the complex molecular architectures of P450 monooxygenases (Scheme 1).

The synthetic application of both enzyme classes, however, still suffers from the poor water solubility of the majority of starting materials, resulting in rather dilute reaction mixtures with an enormous water footprint. Therefore, increasing the starting material (and product) concentration is of utmost importance to increase the economic viability and environmental friendliness of such biocatalytic reactions.4

One common approach to increase the substrate loading is to use the so-called two liquid phase approach5 in which an aqueous, biocatalyst-containing layer is contacted with a hydrophobic, organic layer serving as substrate reservoir and product sink. To alleviate possible phase transfer rate limitations of this system, intensive mechanical stirring is needed, which however, also may impair the stability of the biocatalyst.6

The latter issue can be addressed by immobilising the biocatalyst to a heterogeneous carrier material and thereby physically protecting the enzyme. While a limited number of studies report immobilisation of peroxygenases, this technique is not fully explored yet for this enzyme class.7–12 In previous works, we could demonstrate that immobilised peroxygenases in principle can even be applied in neat (i.e. almost water-free) reaction media.9 A drawback of this approach, however, was the very poor specific activity of the immobilised enzyme, possibly due to a combination of activity losses of the enzyme during

Scheme 1 Comparison of (a) P450 monooxygenase-catalysed and (b) peroxygenase-catalysed oxyfunctionalisation reactions. (c) Both enzyme classes utilise Compound I as the oxygenating agent.

† Electronic supplementary information (ESI) available: Detailed information about synthetic and analytical procedures as well as additional experimental results. See DOI: 10.1039/d1cc01868j
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immobilisation and further activity losses originating from dehydratation of the enzyme surface.

Encapsulating enzymes in alginate matrices may represent an elegant compromise. The so-confined enzymes are mechanically stabilised while still situated in a micro-aqueous environment.8,11,13

We therefore set out to immobilise a peroxygenase in an alginate matrix and evaluate its catalytic activity under non aqueous reaction conditions. As model enzyme we chose the recombinantly expressed, evolved peroxygenase from Agrocybe aegerita (rAaeUPO)14–16 as catalyst for the epoxidation of styrene and cis-β-methylstyrene (Scheme 2). The biocatalyst was obtained from the supernatant of the fermentation broth of recombinant Pichia pastoris and used without further purification.

Confining rAaeUPO in Ca\(^{2+}\)-hardened alginites proved to be feasible. To our surprise, however, the resulting immobilisate showed low, and somewhat irreproducible catalytic activity (Fig. 1a), which most likely was due to leaching of the enzyme from the beads during the immobilisation procedure and storage. To improve the retention of the biocatalyst in the alginate beads, we decided to increase its molecular mass by covalent cross-linking (CLEA formation).17–19

Indeed, CLEA formation more than doubled the catalytic activity of the immobilised peroxygenase (Fig. 1a). Further improvements were achieved by using chitosan as coagulant20–23 and by increasing the enzyme load (Fig. 1a). Additional optimisation steps are reported in the ESL.† It is important to note that the size of the beads had a significant influence on the activity of the immobilised peroxygenase. The larger the beads, the lower the catalytic activity under otherwise identical conditions (Fig. 1b).

Overall, approximately 19% of the enzyme was immobilised (as determined via quantification of the amount of active heme sites using CO-differential spectra) and 11.4% of the peroxidase activity, as judged by the ABTS oxidation activity, was found back in the immobilisates. It is worth mentioning here that rAaeUPO immobilisation also increased its storage stability. While the free enzyme completely lost its catalytic activity after 12 days storage at room temperature, the immobilised version exhibited at least 80% of its initial activity even after two weeks (Fig. S10, ESL†).

Having the immobilised rAaeUPO preparation at hand, we decided to compare its catalytic performance in the epoxidation of cis-β-methylstyrene with the free enzyme in a two liquid phase approach (Fig. 2) using ‘BuOOH as oxidant.

Very much to our surprise the immobilised enzyme outperformed the free enzyme under otherwise identical conditions (such as volumetric ratio of aqueous or alginate volume to...
the organic phase and enzyme concentrations). With the immobilised enzyme the product accumulation rate was approx. 10 mM h\(^{-1}\) (corresponding to the \(^1\)BuOOH feed rate) while with the free enzyme it was only 3 mM h\(^{-1}\). A plausible explanation for this may be the higher surface area of the reactions using alginate-immobilised \(\text{rAaeUPO}\), largely eliminating the diffusion rate limitation of \(^1\)BuOOH and/or cis-\(\beta\)-methylstyrene into the aqueous reaction phase (Fig. S15, ESI\(^\dagger\)).

Overall, in this experiment, approx. 30 mM of enantioselectively pure \((2R,3S)\)-2-methyl-3-phenyloxirane has been synthesised within 4 h corresponding to a turnover number \((TN = \text{mol}_{\text{product}} \times \text{mol}_{\text{rAaeUPO}}^{-1})\) for the enzyme of 60 000 and an average (over 4 h) turnover frequency of 4.1 s\(^{-1}\). It should be mentioned here, that under these reaction conditions several side products such as benzaldehyde and phenylacetone were observed (\emph{vide infra}).

Despite the promising results, the reactions stopped after approximately 5 h. We suspected the irreversible, oxidative inactivation of the heme-containing biocatalyst by the hydroperoxide to account for the low robustness of the reaction.

Therefore, we performed a series of experiments varying the \(^1\)BuOOH addition rate (Fig. 3). While the initial product formation rate decreased with decreasing \(^1\)BuOOH feeding rates, the long-term robustness of the reaction increased: at a \(^1\)BuOOH feeding rate of 20 mM h\(^{-1}\), product formation rates of 9 mM h\(^{-1}\) were observed but the product accumulation ceased after 4 h. Applying a \(^1\)BuOOH feeding rate of 1 mM h\(^{-1}\) approximately the same product formation rate was observed, albeit for at least 72 h. Also the formation of the undesired side products decreased considerably with lower \(^1\)BuOOH feeding rates (Fig. S19, ESI\(^\dagger\)). Both observations are most likely related to each other. At high \(^1\)BuOOH feeding rates, the peroxide availability exceeds the enzyme’s epoxidation capacity resulting in oxidative inactivation of the heme prosthetic group and release of iron ions. The latter catalyse Fenton-like transformations resulting in non-selective oxidation of the cis-\(\beta\)-methylstyrene starting material and formation of the undesired side-products.

In any case, lowering the \(^1\)BuOOH feeding rate not only increased the robustness of the reaction but also reduced the side-product formation. Under these conditions, 48 mM (6.4 g L\(^{-1}\)) of enantiomerically pure \((2R,3S)\)-2-methyl-3-phenyloxirane have been synthesised within 72 h. This corresponds to an excellent TN of 96 000 for the biocatalyst. This catalytic performance also favourably compares to other enzyme systems such as flavin-dependent monoxygenases.\(^{24–27}\) Admittedly, the current substrate scope of the proposed immobilised \(\text{rAaeUPO}\) preparation is rather limited, preliminary experiments on styrene epoxidation indicate a similar catalytic potential for this substrate (Fig. S21, ESI\(^\dagger\)). Future experiments will broaden the synthetic scope of the proposed \(\text{rAaeUPO}\) preparation.

To obtain a first overview over the environmental impact of the reaction system established in this study, we used Sheldon’s E-factor\(^{28,29}\) to estimate the wastes generated in the formation of \((2R,3S)\)-2-methyl-3-phenyloxirane. As shown in Table 1, a total of 153.3 kg of waste was generated per kg of the desired product. 70% of the E-factor contribution stems from non-reacted starting material, which in a putative preparative-scale reaction can be recovered \emph{via} distillation. The second-largest contributor (24%) is the enzyme preparation. The latter is mostly comprised of the alginate beads and buffer (making 99% of the total mass of the immobilised enzyme).

We are convinced that further optimisation of the immobilisation protocol will improve the \(\text{rAaeUPO}\) loading in the alginate beads. For example using alginate-in-oil emulsions for the bead preparation will certainly improve the \(\text{rAaeUPO}\) loading.\(^{30}\) Also the E-factor contribution of the oxidant and its by-product \(^1\)BuOH, respectively, can be reduced significantly when co-immobilising the formate oxidase from \emph{Aspergillus oryzae} (\(\text{AOxFOX}\)) to use methanol as sacrificial electron donor for the \emph{in situ} generation of \(\text{H}_2\text{O}_2.\)^{31–34} Implementing this

![Fig. 3](image-url)  
**Fig. 3** Initial rate, maximal product concentration and reaction robustness of the epoxidation of cis-\(\beta\)-methylstyrene catalysed by imm-\(\text{rAaeUPO}\) at different \(^1\)BuOOH feeding rates. Reaction set-up: 570 \(\mu\)l cis-\(\beta\)-methylstyrene, supplemented with 180 mg immobilate and continuously fed with the indicated \(^1\)BuOOH rate. General reaction conditions: [\(\text{rAaeUPO}\)] = 0.5 \(\mu\)M, room temperature, shaking at 99 rpm with 60\(^\circ\) angle in an overhead rotator. Data represents the average of duplicates.

| Products                  | E-factor Analysis of the Epoxidation of cis-\(\beta\)-methylstyrene to (2R,3S)-2-methyl-3-phenyloxirane |
|---------------------------|------------------------------------------------------------------------------------------------------|
| (2R,3S)-2-methyl-3-phenyloxirane | 4.8                                                                                                   |
| \(^1\)BuOH\(^\dagger\)          | 41.0                                                                                                 |
| Various side products\(^\dagger\) | 0.9                                                                                                  |
| cis-\(\beta\)-Methylstyrene\(^\dagger\) | 515.9                                                                                               |
| \(^1\)BuOOH\(^\dagger\)        | 0.0                                                                                                   |

\(^\dagger\) It is assumed that all added \(^1\)BuOOH converted to \(^1\)BuOH. The indicated \(^1\)BuOH mass includes decane which was used for dilution of \(^1\)BuOH. \(^\dagger\) Concentrations and masses of side products were estimated based on the GC calibration line and response factor of \((2R,3S)\)-2-methyl-3-phenyloxirane. \(^a\) Mass of cis-\(\beta\)-methylstyrene after reaction stop is estimated based on formation of epoxide and side products. \(^{30}\) imm-\(\text{rAaeUPO}\) includes imm-\(\text{rAaeUPO}\) beads.
system will eliminate the 1BuOH contribution to the E-factor (8.5 kg kg⁻¹) and reduce it to approx. 0.11 kg CO₂ kg⁻¹ Product⁻¹. Overall, in this contribution we have established alginate-confined peroxygenase-CLEAs as practical enzyme preparations for the selective epoxidation of styrene derivates such as cis-β-methylstyrene to synthesise enantiomerically pure epoxides. In terms of catalyst efficiency (more than 90,000 catalytic cycles observed), the current system outperforms comparable reaction systems using chemical catalysts,³⁵ P450 monooxygenases or other established enzymatic systems,²⁶,²⁷,³⁷ also compared to our previous efforts using immobilised AaeUPO.⁹ We are convinced that further optimisation will bring this approach to maturity and will establish an economically and environmentally feasible reaction system.

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F. E. H. N., Y. W. and M. P. have performed the experiments and analysed the results. The study was conceptualised by M. H., M. A. and F. H. All authors contributed to the manuscript writing.

Conflicts of interest

There are no conflicts to declare.

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