A Peroxygenase-Alcohol Dehydrogenase Cascade Reaction to Transform Ethylbenzene Derivatives into Enantioenriched Phenylethanols

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In this study, we developed a new biocatalytic reaction to produce enantioenriched phenylethanols. In a first step, the recombinant, unspecific peroxygenase from Agrocybe aegerita (rAaeUPO) was used to oxidise ethylbenzene and its derivatives to the corresponding ketones (prochiral intermediates) followed by enantioselective reduction to the desired (R)- or (S)-phenylethanols using the (R)-selective alcohol dehydrogenase (ADH) from Lactobacillus kefir (LkADH) or the (S)-selective ADH from Rhodococcus ruber (ADH-A). In a one-pot two-stage cascade, 11 ethylbenzene derivatives were converted into the corresponding chiral alcohols at acceptable yields and often excellent enantioselectivity.

Introduction

Oxyfunctionalisation reactions (i.e. the insertion of O-atoms into C–H, C–C-bonds) represent a central theme in organic synthesis and particularly in the manufacture of pharmaceutically active ingredients[1] and the quest for efficient (economically viable and environmentally acceptable) syntheses continues. The synthesis of chiral 1-phenylethanol derivatives for example has been the focus of various research groups. Chiral, α-functionalised benzene derivatives are found in approximately 15% of the 2020 top selling small molecule drugs[2] and various synthetic routes such as the enantioselective reduction of prochiral acetophenone derivatives[3] or the (dynamic) kinetic resolution of racemic 1-phenylethanols[4] have been established. Envisioning ethylbenzene derivatives as starting materials (i.e. obtaining chiral 1-phenylethanols through selective benzylic hydroxylation), heme-dependent enzymes appear to be the catalysts of choice.[5] One shortcoming of current enzymatic enantioselective hydroxylation, however, is a lack of enantio-complementary oxygenases, often limiting access to only one enantiomer. Inspired by recent contributions from the groups of Flitsch[6] and Kroutil[7] we envisioned a biocatalytic cascade to give access to both enantiomers of 1-phenylethanol and its derivatives. Particularly, we propose to combine peroxygenase-catalysed oxyfunctionalisation yielding prochiral ketones followed by enantioselective alcohol dehydrogenase-catalysed reduction to the corresponding alcohols. In particular, we used the recombinant, evolved peroxygenase from Agrocybe aegerita (rAaeUPO)[8] for the benzylic oxidation via (R)-1-phenylethanol (derivatives) to the acetophenones of interest. To catalyse the stereoselective ketoreduction reaction we used either the (R)-selective alcohol dehydrogenase from Lactobacillus kefir (LkADH) or the (S)-selective alcohol dehydrogenase from Rhodococcus ruber (ADH-A) (Scheme 1).[9]

Results and Discussion

In a first set of experiments we established the ‘thorough oxidation’ of various ethylbenzene derivatives to the corresponding acetophenone derivatives (Table 1). Expectedly, the first oxidation step proceeded highly enantioselectively yielding the

Scheme 1. Envisioned biocatalytic cascade to access both enantiomers of phenylethanols from non-functionalised ethylbenzenes. The first step comprises a peroxygenase from Agrocybe aegerita, rAaeUPO-catalysed double hydroxylation to the prochiral acetophenones followed by stereoselective reduction to (R)-phenylethanol (catalysed by the alcohol dehydrogenase from Lactobacillus kefir, LkADH) or to the (S)-alcohol (catalysed by the alcohol dehydrogenase from Rhodococcus ruber, ADH-A).
Having established the individual components of the envisioned cascade, we further combined both enzymatic steps in one pot. In a first try, we tested both enzymatic steps concurrently (one-pot one-step) using ethyl benzene as starting material. At first sight, the cascade was successful producing significant amounts of the desired phenylethanol (Table 2). However, a closer inspection of the optical purity of the alcohol products revealed a poor ee-value of the (ADH-A-derived) (S)-phenylethanol 3a of 19% ee. We observed a significant amount of rAaeUPO-derived (R)-phenylethanol had not been thoroughly oxidised to the ketone, thereby contaminating the ADH-A-derived (S)-enantiomer product. A plausible explanation for the decreased rAaeUPO-activity is the presence of isopropanol in the reaction, which competes with phenylethanol for rAaeUPO-catalysed oxidation thereby slowing down the oxidation steps of the cascade. Furthermore, the accumulating acetone decreases the thermodynamic driving force for the ADH-catalysed reduction step. Apparently, the oxidative and reductive partial steps are not compatible for a one-pot one-step procedure.

We therefore drew our attention to a one-pot two-step procedure, in which first the rAaeUPO-catalysed conversion of ethylbenzenes to the corresponding acetophenone derivatives occurs, followed by the ADH-catalysed reduction to the chiral alcohols. Concretely, in a first phase the rAaeUPO-catalysed ethylbenzene (50 mM) oxyfunctionalisation was conducted for 6 h with a H2O2-addition rate of 20 mM h⁻¹. This was followed by the addition of the ADH catalysts together with isopropanol (as sacrificial reductant) and incubation overnight. A first experiment combining rAaeUPO with ADH-A (Figure 2) gave promising results converting initial 55 mM of ethyl benzene into 1-phenylethanol (35.8 mM final concentration).

As this strategy proved to be successful, we further applied it for the conversion of the starting materials evaluated previously (vide supra). As shown in Table 3, the majority of ethylbenzene starting materials 1 was successfully converted into the corresponding (R)- or (S)-phenylethanol 3 at reasonable yields and generally good optical purities (Table 3). One notable exception was the methoxy derivative 11 where in both cases low alcohol concentrations of the (R)-alcohol were observed. Although a better understanding of the issue with this substrate necessitates further experiments, it may be assumed that the LkADH and ADH-A exhibited low to no activity towards the ketone intermediate 21. Overall, we have established a biocatalytic cascade reaction to obtain both enantiomers of a range of phenylethanol.

Table 2. Results from the one-pot one-step system. [a]

| ADHs   | Phenylethanol 3a [mM] | ee [%] |
|--------|-----------------------|--------|
| LkADH  | 11.3 ± 0.1            | 98 (R) |
| ADH-A  | 15.1 ± 1.2            | 19 (S) |

[a] Reaction conditions: [ethylbenzene 1a] = 50 mM, [NAD(P)H] = 0.1 mM, 10% v/v 2-propanol, [MgCl2] = 2 mM, LkADH/ADH-A: 50 μl cell free extract or 20 mg lyophilised cells, 50 mM KPi buffer pH 7, 30°C, 600 rpm, 24 h.

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Figure 1. Stereoselective reduction of acetophenone using two enantiocomplementary ADHs. Conditions: [acetophenone] = 15 mM, [NAD(P)H] = 0.1 mM, 10% v/v 2-propanol, [MgCl2] = 2 mM, LkADH/ADH-A: 50 μl cell free extract or 20 mg lyophilised cells, 50 mM KPi buffer pH 7, 30°C, 600 rpm, 24 h.
we performed an E-factor analysis of the reaction (at the example of p-chloroethylbenzene 1c, Figure 3).

The wastes generated in the current setup correspond to approx. 262 kg wastewater/kt of which 99% are caused by the (co-)solvents. Non reacted starting material and ketone intermediates contribute to less than 0.5% (E-factor contribution of 0.37 kg × kg⁻¹), and the contribution of the catalysts (AaeUPO, ADH-A, NAD: approx. 0.02 kg × kg⁻¹) or of the buffer salts are negligible. Evidently a simple E-factor analysis does not give a complete picture as it neglects the pre-history of the reagents and catalysts used as well as energy requirements and therefore can only give a first indication about the real environmental impact. Nevertheless, the dominance of (co-)solvents points out in which direction future improvements are necessary. First, the product concentration needs to be increased dramatically. Fed-batch strategies adding the reagents over time appear particularly suitable to obtain high concentrations. Possibly, this will require higher concentrations of the cosolvent (acetonitrile or environmentally more acceptable alternatives) to reduce the water consumption. In this way, the reaction system will also meet the requirements formulated by Huisman and co-workers for the biocatalytic synthesis of APIs. Isopropanol also contributed significantly to the E-factor (21 kg × kg⁻¹ corresponding to 8% of the overall E-factor). Considering that the isopropanol’s main function was to shift the equilibrium of the ADH-catalysed reduction reaction, smarter, irreversible regeneration systems for the reduced nicotinamide cofactor or switching to enzyme-coupled regeneration approaches appear attractive to reduce this contribution.

### Conclusion

Overall, we have established a biocatalytic access to complementary chiral phenylethanols from simple ethylbenzene derivatives by combining the peroxxygenase-catalysed thorough oxidation of alkyl benzenes to the corresponding ketones, followed by stereoselective alcohol dehydrogenase-catalysed synthesis of enantiomerically enriched alcohols. Further steps will comprise broadening the substrate scope (e.g. to heteroaromatic starting materials) and increasing the substrate loading in order to turn this approach into an economically and ecologically interesting methodology for the synthesis of fine chemicals and APIs.

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**Table 3. Results from the one-pot two-step conversion of ethylbenzene derivatives 1a-j to the corresponding phenylethanols 3a-j.**

| Starting material | ADH-A [mM] | ee [%] | LiADH | Alcohol 3 [mM] | ee [%] |
|------------------|------------|--------|-------|----------------|--------|
| 1a               | 36.2 ± 2.6 | > 99 (S)| 40.1 ± 1.0 | > 99 (R) |
| 1b               | 38.6 ± 3.2 | > 99 (S)| 36.7 ± 3.3 | > 99 (R) |
| 1c               | 23.9 ± 11.5| 98 (S) | 34.0 ± 8.5 | > 99 (R) |
| 1d               | 36.7 ± 0.6 | > 99 (S)| 38.2 ± 0.8 | > 99 (R) |
| 1e               | 33.5 ± 6.7 | > 99 (S)| 30.9 ± 1.2 | > 99 (R) |
| 1f               | 37.9 ± 0.8 | > 99 (R)| 37.6 ± 1.7 | > 99 (R) |
| 1g               | 24.6 ± 4.8 | > 99 (S)| 13.1 ± 1.9 | > 99 (R) |
| 1h               | 27.1 ± 1.3 | > 99 (S)| 35.8 ± 5.4 | 91 (R)  |
| 1i               | 5.2 ± 0.1  | > 99 (R)| 5.4 ± 0.3  | > 99 (R) |
| 1j               | 47.7 ± 4.9 | 92 (S) | 51.7 ± 0.9 | > 99 (R) |

Reaction conditions: [substrate] = 50 mM, [AaeUPO] = 2 μM, buffer: 50 mM KPi pH 7 containing 10% v/v of acetonitrile, 25 °C, H₂O₂ dosing rate: 20 mM h⁻¹, reaction time: 6 h. For the second step the reaction mixture was supplemented with [NAD(P)H] = 0.1 mM, [MgCl₂] = 2 mM, 10% v/v 2-propanol, ADH-A (100 μL cell-free extract), and incubated overnight. Experiments were performed as triplicates.
Experimental Section

Enzyme preparation: Recombinant expression and purification of the evolved unspecific peroxygenase mutant from *A. aegerita* in *P. pastoris* was performed following a previously described procedure.[11]

Acetophenone derivatives production: In a 20 mL glass vial the reaction mixture (6.5 mL total volume) contained 2 μM *rAaeUPO*, 30 mM substrate, and 10% v/v CH₃CN in 50 mM KPi buffer pH 7.0. The reaction started by addition of H₂O₂, which was supplied with a continuous flow rate of 20 mM/h and run at room temperature (about 20°C), 600 rpm, 6 h.

**Acetophenone reduction:** In a 1.5 mL GC glass vial the reaction mixture (700 μL total volume) contained 2 mM MgCl₂, 0.1 mM NAD(P)H, 50 μL cell-free extract or 20 mg lyophilised cells of LkADH or ADH-A, 10% v/v 2-propanol and 15 mM acetophenone in 50 mM KPi buffer pH 7.0. The reaction was run at 30°C, 600 rpm, overnight.

**One-pot one-step system:** In a 1.5 mL GC glass vial the reaction mixture (700 μL total volume) contained 2 μM *rAaeUPO*, 50 mM ethylbenzene, 2 mM MgCl₂, 0.1 mM NAD(P)H, 10% v/v 2-propanol, 50 μL of ADH-A or LkADH cell-free extract in 50 mM KPi buffer pH 7.0. The reaction was started by addition of H₂O₂, which was supplied with a continuous flow rate 10 mM/h with 10 h, and run at 30°C, 600 rpm, 24 h.

**One-pot two-step system:** In a 20 mL glass vial the reaction mixture (6.5 mL total volume) contained 2 μM *rAaeUPO*, 50 mM substrates, 10% v/v CH₃CN in 50 mM KPi buffer pH 7.0. The reaction was started by addition of H₂O₂, which was supplied with a continuous flow rate of 20 mM/h and run at room temperature (about 20°C), 600 rpm. After 6 h, 365 μL of the reaction mixture was taken into a 1.5 mL glass vial, then 2 mM MgCl₂, 0.1 mM NAD(P)H, 10% v/v 2-propanol, 100 μL of ADH-A or LkADH cell-free extract was added and run at 30°C, 600 rpm, overnight.

Thermomixers were used for controlling temperature and shaking. For each sampling over time, 100 μL of reaction mixture was extracted with 500 μL ethyl acetate containing 5 mM n-octanol as internal standard. The extraction was then dried by MgSO₄ and analysed by achiral and chiral gas chromatography. Details of gas chromatography and temperature profiles are shown in the Supporting Information.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords: alcohol dehydrogenases · asymmetric reduction · biocatalytic cascades · oxyfunctionalisation · peroxygenases

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