What to sacrifice? Fusions of cofactor regenerating enzymes with Baeyer-Villiger monooxygenases and alcohol dehydrogenases for self-sufficient redox biocatalysis

Ángela Mourelle-Insua a, Friso S. Aalbers b, Iván Lavandera a, Vicente Gotor-Fernández a, Marco W. Fraaije b, *

a Laboratorio de Química Bioorgánica, Departamento de Química Orgánica e Inorgánica, Universidad de Oviedo, Avenida Julián Clavería 8, 33006, Oviedo, Spain
b Molecular Enzymology Group, Groningen Biomolecular Sciences and Biotechnology Institute, University of Groningen, Nijenborgh 4, 9747, AG, Groningen, the Netherlands

A R T I C L E I N F O

Article history:
Received 13 November 2018
Received in revised form 1 February 2019
Accepted 5 February 2019
Available online 8 February 2019

Keywords:
Cofactor recycling
Enzyme fusion
Self-sufficient enzyme
Alcohol dehydrogenase
Baeyer-Villiger monooxygenase
Enantioselective

A B S T R A C T

A collection of fusion biocatalysts has been generated that can be used for self-sufficient oxygenations or ketone reductions. These biocatalysts were created by fusing a Baeyer-Villiger monooxygenase (cyclohexanone monooxygenase from Thermocrispum municipale: TmCHMO) or an alcohol dehydrogenase (alcohol dehydrogenase from Lactobacillus brevis: LbADH) with three different cofactor regeneration enzymes (formate dehydrogenase from Burkholderia stabilis: BsFDH; glucose dehydrogenase from Sulfolobus tokodaii: StGDH, and phosphite dehydrogenase from Pseudomonas stutzeri: PsPTDH). Their tolerance against various organic solvents, including a deep eutectic solvent, and their activity and selectivity with a variety of substrates have been studied. Excellent conversions and enantioselectivities were obtained, demonstrating that these engineered fusion enzymes can be used as biocatalysts for the synthesis of (chiral) valuable compounds.

© 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Biocatalysis can be used to synthesize chiral building blocks, such as monomers for polymer materials, and precursors for pharmaceuticals [1–4]. Enzymes are very suitable for catalyzing reactions with high enantioselectivity to obtain chiral products. For instance, alcohol dehydrogenases (ADHs, EC 1.1.1.X) – also known as carbonyl reductases or ketoreductases – depend on NAD(P)H to catalyze the asymmetric reduction of ketones to either (R)- or (S)-alcohols in excellent enantiomeric excess (ee) [5]. These enzymes, among others, have been applied for syntheses of pharmaceutical precursors [2,4]. Another group of redox enzymes that depend on NAD(P)H are the Baeyer-Villiger monooxygenases (BVOs) (EC 1.14.13.X). These FAD-containing enzymes can catalyze regio- and enantioselective transformations of ketones to esters or lactones, using dioxygen and NADPH. Interest in the application of BVOs has grown, in particular for the transformation of substituted cyclic ketones to chiral lactones, for branched polyesters [6–9]. Specifically, the recent discovery of robust BVOs, such as the thermostable cyclohexanone monooxygenase from Thermocrispum municipale (TmCHMO), has led to great interest for exploring these monooxygenases for industrial applications, as most of the previously reported BVOs were quite unstable [10].

Both ADHs and BVOs rely on the cofactor NAD(P)H for catalysis, which is too expensive to apply in stoichiometric amounts, and therefore should be regenerated. There are a number of different approaches to recycle NAD(P)H [5,11,12]. One approach is to apply another enzyme which can use the oxidized NAD(P)+ and a sacrificial cheap cosubstrate to regenerate the reduced nicotinamide cofactor: the so-called “coupled-enzyme” approach. Three commonly used coenzyme regenerating enzymes are formate dehydrogenase (FDH), glucose dehydrogenase (GDH), and phosphite dehydrogenase (PTDH), all using relatively cheap substrates [12]. Instead of producing and adding these enzymes separately, the recycling enzyme can also be covalently fused to the NADPH-dependent enzyme through enzyme engineering (Scheme 1). In

* Corresponding author.
E-mail address: m.w.fraaije@rug.nl (M.W. Fraaije).

https://doi.org/10.1016/j.tet.2019.02.015
0040-4020 © 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
this way, a bifunctional and self-sufficient fusion biocatalyst is produced enabling conversion using merely one biocatalyst. Moreover, some studies on enzyme fusions provided evidence that tethering of two enzymes can improve the productivity of a multi-enzyme system [13]. In 2008 Torres Pazmino et al. developed a platform for expressing BVMos fused to PTDH for efficient cofactor regeneration [14,15]. Later, a few other studies reported enzyme fusions with FDH [16], GDH [17], or PTDH [18–20], though no study yet has compared a single biocatalyst with different regenerating enzymes.

The aim of this work is to explore different recycling enzymes as fusion partner for two oxidoreductase enzymes (BVMO and ADH), and to compare their strengths and weaknesses for biocatalytic applications. We fused three different regenerating enzymes to a BVMO (TmCHMO, from Thermocrispum municipale) [10] and an (R)-selective alcohol dehydrogenase (LbADH, from Lactobacillus brevis) [21–23], to generate a panel of self-sufficient biocatalysts. The three recycling enzymes are: FDH from Burkholderia stabilis (BsFDH) [24], GDH from Sulfolobus tokodaii (SsGDH) [25], and an engineered PTDH from Pseudomonas stutzerii (PsPTDH) [26,27]. The fused enzymes were produced and purified, and applied for biotransformations. Both enzymes act on ketone substrates to form interesting products, though many of such organic substrates have low solubility in water. Therefore, the enzyme fusions were tested with a wide range of solvents. In particular, the tolerance of these biocatalysts to deep-eutectic solvents (DES) was evaluated, which at present has not been studied to a great extent.

2. Results and discussion
2.1. Cloning, expression and purification

The cloning approach was similar to that of previous fusion cloning work [14,15]. As linker region a variation of the short-linker from previous work was used, which was found to be optimal for fusions with BVMOs [15]. For ease of denoting, TmCHMO is named B (BVMO) while the LbADH is named A (ADH), see Table 1. The cofactor regeneration enzymes are also denoted in single letter codes: F for FDH, G for GDH and P for PTDH. After cloning of the six constructs (Table 1), the plasmids were used to transform competent E. coli NEB 10b cells. These cells were then used for recombinant expression and subsequent enzyme purification. Only one of the six fusion constructs had an inadequate level of soluble expression: G-A. Although it was used for some of the initial experiments, in later experiments this fusion enzyme was omitted. The other fusion enzymes could be produced in high quantities (>50 mg/L culture). After lysis of the cells and protein purification through affinity column chromatography, the enzyme fusions were used for further testing and biotransformations.

2.2. Reaction optimization

The first step was to establish optimal reaction conditions. The reactions were set up using cyclohexanone (5 mM) as model substrate for the TmCHMO constructs, and acetoephone (5 mM) for the LbADH constructs (see Supporting Information, Section 2.1). The optimal reaction conditions for each biocatalyst system were similar. All fusions were able to fully convert the substrate under mild reaction conditions: phosphate buffer 100 mM pH 8.5 for TmCHMO fusions, and phosphate buffer 100 mM pH 7.5 for LbADH constructs, at 30 °C in most cases. Previous studies have shown that PTDH is not inhibited by phosphate buffer [28]. The only exception was G-B that afforded a better selectivity towards the formation of caprolactone at 24 °C, since at 30 °C a significant amount of cyclohexanol was observed due to the undesired activity of SsGDH with cyclohexanone.

The biotransformations were monitored over time (Fig. 1). The reactions catalyzed by BsFDH and PsPTDH constructs were mostly completed after 16 h, while the SsGDH fusions needed 24 h to achieve full conversions. The conversion with the TmCHMO fusions resulted in a linear increase of product in time, whereas the LbADH fusions showed a higher initial rate up to 70% conversion, and then it decreased until full conversion. This was probably due to the relatively high K_M value for acetoephone (2.8 mM) of LbADH and/or product inhibition.

Assuming that the TmCHMO and LbADH enzymes had roughly the same catalytic properties (activity and K_M) for the three different fusions, the only difference concerning the kinetic performance of the fusion enzymes is due to the recycling enzyme. The amount of sacrificial substrate (10 mM glucose, 50 mM sodium formate or 20 mM sodium phosphite) was decided based on the reported K_M values of each enzyme, ensuring maximal activity (V_max) throughout the whole reaction. The k_cat values for the three recycling enzymes PTDH, FDH and GDH with NADP+ are, respectively: 6.5 s⁻¹ (at 25 °C) [15], 4.75 s⁻¹ (at 30 °C) [24], and -3.8 s⁻¹ (at 35 °C, derived from reported activity and temperature optimum) [25]. This was in agreement with the time course of the biotransformations (Fig. 1): PTDH fusions were the fastest, while FDH fusions were the second. From this initial experiment it was clear that GDH constructs had the weakest performance. The respective biotransformations were the slowest, maybe due to the fact that the reaction with G-B worked better at 24 °C while the SsGDH has a relatively high temperature optimum. Furthermore, G-A showed also a poor expression.

2.3. Enzymatic preparations

The need for NADPH is a cost factor when considering the
utilization of biocatalysts at larger scale. In this context, Torres Pazmino et al. published interesting results using cell-free extract preparations of different self-sufficient BVMOs without external addition of the nicotinamide cofactor [14]. This approach was also tested for our fusions (Table 2, entries 1, 4, 7, 10, 13 and 16), but resulted in good results only for G-B and P-B fusions. F-B and LbADH fusions had a significantly lower activity. Apart from that, and still in order to make the process economically feasible, each biotransformation using the purified enzyme was set up adding just 0.5 mM NADPH (Table 2, entries 3, 6, 9, 15 and 18). High conversions and excellent ee values were found, though the reactions with LbADH (entries 15 and 18) could not reach full conversion. Although the $K_M$ value for NADPH is 40$\mu$M for the native LbADH, possibly the $K_M$ of the respective fusion enzymes is a bit higher, as was observed for other PTDH-BVMO fusions [14]. This could slow down the reaction, in particular in combination with the aforementioned slower reaction rates after 70% conversion, due to the high $K_M$ for acetoephone (Fig. 1).

### 2.4. Cosolvent screening

At this point, the model reaction for each fusion was fully studied. However, in order to perform reactions with high substrate concentrations, the low water solubility of many ketone substrates must be addressed. One of the common strategies is the employment of an organic cosolvent. For this reason, the enzyme fusions were first tested with a wide range of organic solvents (1% v/v, Fig. 2), including tert-butyl methyl ether (MTBE), methanol (MeOH), ethanol (EtOH), 1,4-dioxane and acetonitrile (MeCN). First of all, it must be pointed out that not a single cosolvent affected the selectivity of LbADH fusion enzymes (data not shown), thus providing the enantiopure (R)-alcohol. MTBE and acetonitrile revealed to be the best cosolvents for all enzyme fusions, as they led to high conversions (>90%) in all cases. Methanol and ethanol showed very good results with most of the constructs, with the exception of P-B using MeOH and G-A using EtOH; in these cases the conversion values dropped down to 51% and 69%, respectively. Finally, 1,4-dioxane caused a huge drop of activity (90% decrease) with G-B and F-B fusions, and a 40% decrease for G-A.

These results are surprising, as it seems that particular combinations of enzymes can be sensitive to a cosolvent, even though other combinations containing one of those enzymes are tolerant. For instance, with 1,4-dioxane and F-B, it is not simply that TmCHMO was intolerant, since P-B did give full conversion. The same was true for BsFDH, as F-A was able to afford 90% conversion. Based on those two results, one would expect F-B to give high conversion as well, yet it was only 10%. In other words, it was observed that particular combinations of enzymes can be more tolerant to organic solvents than other combinations with the same enzyme. It could be that certain enzymes can transmit tolerance for

---

**Table 2**

Biotransformations mediated by self-sufficient TmCHMOs and LbADHs using different enzymatic preparations and different amounts of cofactor.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Fusion</th>
<th>Protein preparation</th>
<th>[NADPH] (mM)</th>
<th>Conv. (%)</th>
<th>ee (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>G-B</td>
<td>Cell-free extract</td>
<td>1</td>
<td>92</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>G-B</td>
<td>Purified</td>
<td>0.5</td>
<td>96</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>G-B</td>
<td>Purified</td>
<td>0.5</td>
<td>96</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>F-B</td>
<td>Cell-free extract</td>
<td>—</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>F-B</td>
<td>Purified</td>
<td>1</td>
<td>&gt;99</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>F-B</td>
<td>Purified</td>
<td>0.5</td>
<td>99</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>P-B</td>
<td>Cell-free extract</td>
<td>—</td>
<td>&gt;99</td>
<td>—</td>
</tr>
<tr>
<td>8</td>
<td>P-B</td>
<td>Purified</td>
<td>1</td>
<td>&gt;99</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>P-B</td>
<td>Purified</td>
<td>0.5</td>
<td>96</td>
<td>—</td>
</tr>
<tr>
<td>10</td>
<td>G-A</td>
<td>Cell-free extract</td>
<td>—</td>
<td>13</td>
<td>81 (R)</td>
</tr>
<tr>
<td>11</td>
<td>G-A</td>
<td>Purified</td>
<td>0.5</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12</td>
<td>G-A</td>
<td>Purified</td>
<td>0.5</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>13</td>
<td>F-A</td>
<td>Cell-free extract</td>
<td>—</td>
<td>68</td>
<td>96 (R)</td>
</tr>
<tr>
<td>14</td>
<td>F-A</td>
<td>Purified</td>
<td>1</td>
<td>&gt;99</td>
<td>&gt;99 (R)</td>
</tr>
<tr>
<td>15</td>
<td>F-A</td>
<td>Purified</td>
<td>0.5</td>
<td>74</td>
<td>&gt;99 (R)</td>
</tr>
<tr>
<td>16</td>
<td>P-A</td>
<td>Cell-free extract</td>
<td>—</td>
<td>42</td>
<td>&gt;99 (R)</td>
</tr>
<tr>
<td>17</td>
<td>P-A</td>
<td>Purified</td>
<td>1</td>
<td>&gt;99</td>
<td>&gt;99 (R)</td>
</tr>
<tr>
<td>18</td>
<td>P-A</td>
<td>Purified</td>
<td>0.5</td>
<td>86</td>
<td>&gt;99 (R)</td>
</tr>
</tbody>
</table>

*Cell-free extract preparations were prepared as described in the Experimental Section.

b Measured by GC analysis.

c Caprolactone is not an optically active molecule so no ee value is associated to TmCHMO constructs results. For the reactions with the purified enzyme, 2 [$\mu$M] of TmCHMO fusion or 0.2 mg/mL (approx. 2.5 [$\mu$M]) of LbADH fusion were used.

---

![Figure 1](image.png)

Fig. 1. Monitoring of the conversions in the self-sufficient TmCHMO and LbADH-catalyzed enzymatic biotransformations.
a particular cosolvent when fused to its partner enzyme, e.g., PTDH in P-B for 1,4-dioxane.

Taking all these data into account, we decided to test the fusions behavior in a biphasic system using larger amounts of MTBE, as it was the best cosolvent among the tested ones (see Supporting information, Section 2.2). The TmCHMO fusions were able to catalyze the Baeyer-Villiger oxidation of cyclohexanone with full conversion using up to 10% v/v of MTBE. An amount of 15% v/v of MTBE led to a drop in the formation, Section 2.2). The FDH was the best cosolvent among the tested ones (see Supporting information, Section 2.2). The Biotransformation of model substrates using different organic cosolvents (1% v/v).

Deep eutectic solvents (DES) represent a promising new generation of environmentally-friendly solvents [29]. We evaluated the use of DES as cosolvents for the biotransformations catalyzed by the engineered fusion biocatalysts. Concentrations of 10%–30% v/v of DES derived from choline chloride and glycerol (ChCl:Gly 1:2 mol/mol) were employed (see Supporting information, Section 2.3). G-B and F-B appeared as the most robust enzymes as they could achieve full conversion to caprolactone using up to 20% v/v of MTBE, while P-A showed a small drop of activity at 20% v/v of MTBE. Overall, it was clear that for this cosolvent BsFDH was the most tolerant NADPH-regenerating enzyme.

Keeping in mind previous studies on ketone reductions with ADHs [23], some acetophenone derivatives were chosen as alternative substrates for the LbADH fusions (substrates 7–12a, Table 3). The lengthening of chain R2 from a methyl group (acetophenone, 10a; Table 3, entries 16 and 17) to an ethyl group (propiophenone, 11a; Table 3, entries 22 and 23) as substrates, a dramatic loss of activity was observed. At this point, we decided to evaluate the influence of the aromatic pattern substitution at different positions. For this purpose, we studied various chlorine-substituted acetophenone derivatives (10–12a). BsFDH fusion behaved reasonably well with p-chloroacetophenone (10a; Table 3, entry 24) and m-chloroacetophenone (11a; Table 3, entry 26) as substrates. On the contrary, although P-PTDH construct maintained excellent selectivity, it afforded low conversions for the same substrates (Table 3, entries 25 and 27). Finally, the biotransformation of o-chloroacetophenone (12a) catalyzed by the BsFDH fusion was set up leading to low conversions (Table 3, entry 28).

2.5. Substrate screening

In order to check the synthetic versatility of the engineered fusion biocatalysts, other substrates were tested (see Fig. 3). TmCHMO constructs were employed to catalyze the Baeyer-Villiger oxidation of substrates differing on the ring substitution and the ring size (substrates 2-4a, Table 3). In this manner, 4-methylcyclohexanone (2a) was converted into (S)-4-methyl-

Fig. 2. Biotransformation of model substrates using different organic cosolvents (1% v/v).
At this point, we aimed to show the applicability of the enzyme fusions by scaling-up some selected biotransformations. Before that, the effect of the substrate concentration and the amount of biocatalyst were studied (Supporting information, Section2.6) in order to identify the best conditions for each preparation. Once optimized, several semi-preparative biotransformations were set up using the best conditions for each fusion without observing the formation of any by-product. Hence, for P-B 25 mg of cyclohexanone (10 mM) were transformed into caprolactone at pH 8.5 with full conversion but in moderate isolated yield (51%) after purification by extraction and centrifugation of the combined organic phases. Suspecting that part of the caprolactone had been hydrolyzed, the biotransformation was set up using a phosphate buffer pH 7.5. In this case, it was possible to obtain the caprolactone in high isolated yield (90%). Afterwards, the same Baeyer-Villiger oxidation were performed using F-B and G-B. Again, full conversions and high isolated yields (89% and 80%, respectively) were attained for caprolactone after an extraction protocol. The LbADH constructs were also tested in semi-preparative biotransformations. However, F-A revealed worse results than those obtained at small scale. Using 15 mg of acetophenone (20 mM), it was transformed into (R)-1-phenylethanol in 65% conversion. After
separation of the remaining ketone, the desired enantiopure alcohol was obtained in 51% isolated yield. On the other hand, the result obtained in the same bioreduction catalyzed by P-A was as good as that obtained at small scale, and the corresponding alcohol was produced in full conversion, with excellent enantioselectivity and high isolated yield (85%).

3. Conclusions

In this study we have developed and investigated three NADPH-regenerating fusion partners with two different enzyme systems: a BVMO and an ADH. With the exception of one fusion construct (SrGDH with LbADH), all fusion enzymes resulted in good soluble expression as well as fully functional as self-sufficient biocatalysts. The fusion biocatalysts displayed tolerance to various organic cosolvents, including DES. From the different fusion partners, FDH was the most tolerant to organic solvents, fully converting cyclohexanone for the BVMO fusion at 15% v/v MTBE, and acetonophene for the ADH fusion even at 40% v/v MTBE. We also demonstrate that the fusion enzymes can be used as enantioselective biocatalysts for a large variety of reactions by retaining almost all catalytic characteristics of the native non-fused enzymes. We demonstrated the applicability of three different NADPH regenerating fusions for these two enzyme systems, which broadens the choice of regenerating enzymes for future applications of these systems.

4. Experimental section

4.1. General materials and methods

Oligonucleotide primers were ordered from Sigma-Aldrich (Merck KGaA, Darmstadt, Germany). T4 ligase and restriction enzyme BsaI were ordered from New England Biolabs. The PfuUltra Hotstart PCR master mix was purchased from Agilent Technologies. Escherichia coli NEB® Stable (New England Biolabs) chemically competent cells were used as host for cloning of the recombinant plasmids, and as host for protein expression.

All acetophenones, cyclohexanones, cyclopentanone, cyclohexanone and thioanisole were purchased from Sigma-Aldrich-Fluka. NADPH as enzyme cofactor and all the other chemical reagents were obtained with the highest quality available from Sigma-Aldrich-Fluka (Steinheim, Germany).

NMR spectra were recorded on a Bruker AV300 MHz spectrometer (Bruker Co., Faellanden, Switzerland). All chemical shifts (δ) are given in parts per million (ppm) and referenced to the residual solvent signal as internal standard.

Gas chromatography (GC) and high performance liquid chromatography (HPLC) analyses were performed for conversion and enantiomeric excess measurements. GC analyses were performed on an Agilent HP6820 GC chromatograph equipped with a FID detector. HPLC analyses were carried out on a Hewlett Packard 1100 chromatograph equipped with a UV detector. HPLC analyses were performed on a Merck Silica Gel 60 (230–400 mesh).

4.2. Cloning and purification

Cloning of fusion constructs: Three fusion constructs with the lbadh gene were cloned into a pBAD vector through the Golden Gate method. The pBAD vector contains a region coding for an N-terminal His-tag (6xHis) upstream from the first BsaI restriction site, an AraC promoter, and an ampicillin-resistance gene (bla). Primers were designed to have a non-overlapping region coding for the BsaI restriction site (GGTCTCNNNNN), such that the vector and PCR product have a four base-pair overlap after digestion with BsaI. These primers were used for PCR to amplify the lbadh gene (accession: Q84EX5) from an in-house plasmid, fhd (accession: EU825923.1) and gdh (accession: Q96ZY7) synthetic codon-optimized genes were ordered from Gensect (NJ, USA), and pdth x12 mutant was also cloned from an in-house plasmid. Primers were designed such that the lbadh would be the second gene of the fusion; at the C-terminal side of the fusion enzyme. In addition to the BsaI sites, an additional ‘linker’ region was added to the reverse primers of the first gene and the forward primer of the second gene of a construct. These introduced ‘linker’ regions together code for a short peptide linker (SGSAAG), after ligation of the PCR products.

The fusion constructs were produced by incubating together: two PCR products (lbadh gene and either fhd, gdh or pdth), pBAD vector containing BsaI sites, BsaI restriction enzyme, T4 ligase, ligation buffer, and sterile miliQ water (total volume of 20 μL). The incubation temperature alternated between 16 °C (for 5 min) and 37 °C (for 10 min) for 30 cycles, then was set to 55 °C for 10 min, and finally to 80 °C for 20 min to inactivate the enzymes. To transform host cells with the fusion constructs, 3 μL of the Golden Gate reaction was added to chemically competent E. coli cells, and a heat shock was applied at 42 °C for 30 s. After overnight growth on a llysogeny broth (LB) agar plate with ampicillin, colonies were picked, grown in liquid LB with appropriate antibiotic, and the plasmids were isolated and sent for sequencing (GATC, Germany) to confirm correct ligation of the genes. For the three constructs with TmCHMO, traditional restriction-digestion cloning was used.

All enzymes were expressed using NEB 10-β Escherichia coli cells. The freshly-prepared strains were cultivated in TB medium supplemented with 50 μg/mL ampicillin at 37 °C. Protein expression was induced by adding l-arabinose (0.02% w/v) when A600 reached 0.5. G-B and F-B were incubated overnight at 30 °C, P-A and P-B were incubated at 24 °C for 48 h and G-A and F-A were incubated at 17 °C for 72 h. After this time, the cells were harvested by centrifugation.

The cells were resuspended in 20 mM phosphate buffer pH 7.5 (TmCHMO fusions were implemented with FAD) and lysed in an iced bath by ultrasonication (cycles of 20s on/20s off for 7 min). After centrifugation, the supernatant was used either for protein purification using Ni-Sepharose material or as cell-free extract preparations for biotransformations.

For lyophilization purposes, the cells obtained after expression were resuspended in the minimum amount of 20 mM phosphate buffer pH 7.5 and lyophilized using an Alpha 2–4 DLplus freeze dryer (Martin Christ Gefriertrocknungsanlagen GmbH, Germany).

4.3. Conversion of cyclohexanone and derivatives, cyclopentanone, cyclobutanone and thioanisole using self-sufficient TmCHMOs

Purified self-sufficient TmCHMOs (2 μM or 4 μM) were employed for biotransformation of cyclohexanone (5–25 mM), 4-methylcyclohexanone (5 mM), cyclopentanone (5 mM), cyclobutanone (5 mM) and thioanisole (5 mM) at 30 °C (F-B and P-B) or 24 °C (G-B) and 250 rpm. All reactions contained 1 or 0.5 mmol NADPH, the co-substrate (10 mM glucose for G-B, 50 mM sodium formate for F-B and 20 mM sodium phosphate for P-B) and 100 mM phosphate buffer pH 8.5. Additionally, G-B fusion needs the external addition of magnesium chloride (1 mM). In some cases, a cosolvent (1% v/v 1,4-dioxane, 1% v/v acetonitrile, 1% v/v ethanol, 1% v/v methanol, 1–50% v/v tert-butyl methyl ether) or CHCl3/Cly (1:2 mol/mol) was added. In any case, the final volume of the reaction was adjusted up to 0.5 mL in a 2 mL eppendorf tube.

For cell-free extract biotransformations, 5 mM cyclohexanone
was used as substrate and the reaction was implemented with the corresponding co-substrate (10 mM glucose for G-B, 50 mM sodium formate for F-B and 20 mM sodium phosphate for P-B) and 1 mM of MgCl₂·6H₂O when G-B was employed. Cell-free extract prepa-
rations were used at 8 mg/mL concentration and the final volume was adjusted with 100 mM phosphate buffer pH 8.5 up to a 0.5 mL in a 2 mL eppendorf tube. The reactions were incubated at 30 °C (F-B and P-B) or 24 °C (G-B) and 250 rpm for 24 h.

When using lyophilized preparations (10 mg), cyclohexanone (5 mM) was used as substrate and reactions were implemented with NADPH (1 mM), the corresponding co-substrate (10 mM glucose for G-B, 50 mM sodium formate for F-B and 20 mM sodium phosphate for P-B) and 1 mM of MgCl₂·6H₂O. The final volume was adjusted to 0.5 mL with 100 mM phosphate buffer pH 8.5 in a 2 mL eppendorf tube and the reactions were incubated at 30 °C (F-B and P-B) or 24 °C (G-B) and 250 rpm for 24 h. After incubation, all reactions were extracted with ethyl acetate (2 × 0.2 mL) and the organic layers were combined and dried over anhydrous Na₂SO₄. The results were analyzed using GC and/or HPLC.

4.4. Preparative biotransformation of cyclohexanone into caprolactone using TmCHMO fusions

G-B (2 μM) was employed to convert 30 mg of cyclohexanone (5 mM) into caprolactone. The reaction media was composed of 100 mM phosphate buffer pH 8.5 implemented with NADPH (1 mM), glucose (10 mM) and MgCl₂·6H₂O (1 mM). The reaction was set up in a 150 mL Falcon tube and incubated at 24 °C and 250 rpm for 24 h. After this time, the mixture was extracted with ethyl acetate (3 × 20 mL), the organic layers separated by centrifugation (5 min, 4900 rpm), combined and finally dried over anhydrous Na₂SO₄. Conversion was determined by GC. Caprolactone was obtained in 80% isolated yield (>99% conv.).

F-B (4 μM) was used to convert 30 mg of cyclohexanone (15 mM) into caprolactone in 100 mM phosphate buffer pH 8.5 in a 50 mL Falcon tube. The reaction was implemented with NADPH (1 mM) and sodium formate (50 mM) and incubated at 30 °C for 24 h. Afterwards, the mixture was extracted with ethyl acetate (3 × 20 mL), the organic layers separated by centrifugation (5 min, 4900 rpm), combined and finally dried over anhydrous Na₂SO₄. Conversion was determined by GC. Caprolactone was obtained in 89% isolated yield (>99% conv.).

P-B (2 μM) was employed to convert 30 mg of cyclohexanone (10 mM) into caprolactone. The reaction media (100 mM phosphate buffer pH 8.5) was added. The final volume was adjusted up to 0.5 mL with 100 mM phosphate buffer pH 7.5 in a 1.5 mL eppendorf tube and the reactions were incubated at 30 °C and 250 rpm for 24 h. After incubation, all reactions were extracted with ethyl acetate (2 × 0.2 mL) and the organic layers were combined and dried over anhydrous Na₂SO₄. The results were analyzed using GC and/or HPLC.

4.5. General procedures for conversion of acetophenone and derivatives using self-sufficient LbADHs

Purified self-sufficient LbADHs (0.2 mg/mL or 4 mg/mL) were employed for biotransformation of acetophenone (5–25 mM) and derivatives (5 mM) at 30 °C and 250 rpm. All reactions contained 1 or 0.5 mM NADPH, the co-substrate (10 mM glucose for G-A, 50 mM sodium formate for F-A and 20 mM sodium phosphate for P-A), MgCl₂·6H₂O (1 mM) and 100 mM phosphate buffer pH 7.5. In some cases, a cosolvent (1% v/v 1,4-dioxiane, 1% v/v acetonitrite, 1% v/v ethanol, 1% v/v methanol, 1–50% v/v tert-butyl methyl ether), ChCl:Gly (1:2 mol/mol) or ChCl:Glu (1:5:1 mol/mol) was added. In any case, the final volume of the reaction was adjusted up to 0.5 mL in a 1.5 mL eppendorf tube.

For cell-free extract biotransformations, 5 mM acetophenone was used as substrate and the reaction was implemented with the corresponding co-substrate (10 mM glucose for G-A, 50 mM sodium formate for F-A and 20 mM sodium phosphate for P-A) and MgCl₂·6H₂O (1 mM). Cell-free extract preparations were used at 8 mg/mL concentration and the final volume was adjusted with 100 mM phosphate buffer pH 7.5 up to a 0.5 mL in a 1.5 mL eppendorf tube. The reactions were incubated at 30 °C and 250 rpm for 24 h.

When using lyophilized preparations (10 mg), acetophenone (5 mM) was used as substrate and reactions were implemented with NADPH (1 mM), the corresponding co-substrate (10 mM glucose for G-A, 50 mM sodium formate for F-A and 20 mM sodium phosphate for P-A) and MgCl₂·6H₂O (1 mM). The final volume was adjusted up to 0.5 mL with 100 mM phosphate buffer pH 7.5 in a 1.5 mL eppendorf tube and the reactions were incubated at 30 °C and 250 rpm for 24 h.

After incubation, all reactions were extracted with ethyl acetate (2 × 0.2 mL) and the organic layers were combined and dried over anhydrous Na₂SO₄. The results were analyzed using GC and/or HPLC.

4.6. Preparative biotransformation of acetophenone into (R)-1-phenylethanol using LbADH fusions

F-A (0.4 mg/mL) was used to convert 30 mg of acetophenone (20 mM) into (R)-1-phenylethanol. The reaction media contained NADPH (1 mM), sodium formate (50 mM), MgCl₂·6H₂O (1 mM) and 100 mM phosphate buffer pH 7.5. This mixture was incubated at 30 °C for 24 h and, afterwards, it was extracted with ethyl acetate (3 × 20 mL), the organic layers separated by centrifugation (5 min, 4900 rpm), combined and finally dried over anhydrous Na₂SO₄. Conversion and enantiomeric excess were determined by GC. (R)-1-phenylethanol was obtained in 51% isolated yield (65% conv.) after purification by column chromatography (Hex: EtOAc 3:1).

P-A (0.2 mg/mL) was employed to convert 30 mg of acetophenone (10 mM) into (R)-1-phenylethanol. The reaction media (100 mM phosphate buffer pH 8.5) was implemented with NADPH (1 mM), sodium phosphate (20 mM) and MgCl₂·6H₂O (1 mM) and the reaction was incubated at 30 °C for 24 h. After this time, the mixture was extracted with ethyl acetate (3 × 20 mL), the organic layers separated by centrifugation (5 min, 4900 rpm), combined and finally dried over anhydrous Na₂SO₄. Conversion was determined by GC. LbADH was obtained in 85% isolated yield (>99% conv.).

Acknowledgements

The research for this work has received funding from the European Union (EU) project ROBOX (grant agreement n°635734) under EU’s Horizon 2020 Program Research and Innovation actions H2020-LEIT BIO-2014-1. The views and opinions expressed in this article are only those of the authors and do not necessarily reflect those of the European Union Research Agency. The European Union is not liable for any use that may be made of the information contained herein. Financial support from the Spanish Ministry of Economy and Competitiveness (MEC, Projects CTQ2013-44153-P and CTQ2016-75752-R) is gratefully acknowledged. A.M.-I thanks MEC for a predoctoral fellowship inside the FPI program.
Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tet.2019.02.015.

References