Lactonization reactions through hydrolase-catalyzed peracid formation. Use of lipases for chemoenzymatic Baeyer-Villiger oxidations of cyclobutanones.

Daniel González-Martínez, María Rodríguez-Mata, Daniel Méndez-Sánchez, Vicente Gotor* and Vicente Gotor-Fernández*

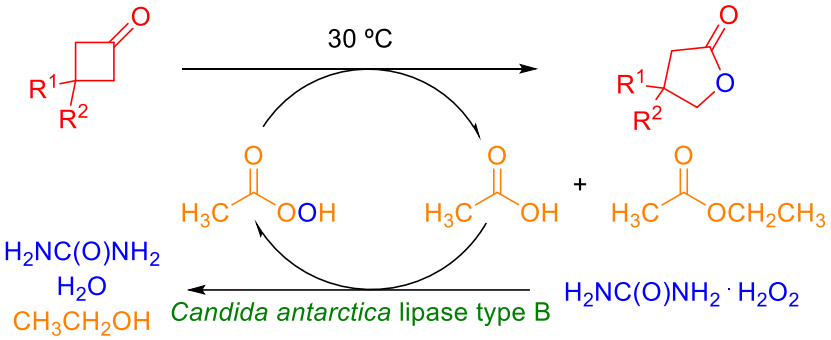
Departamento de Química Orgánica e Inorgánica, Instituto Universitario de Biotecnología de Asturias, Universidad de Oviedo. Avenida Julián Clavería 8, 33006, Oviedo, Spain.

Tel: +34-985103454

Fax: +34-985103456

E-mail: vicgotfer@uniovi.es

Graphical abstract:



Abstract: A *one-pot* chemoenzymatic method has been described for the synthesis of γ-butyrolactones starting from the corresponding ketones through a Baeyer-Villiger reaction. The approach is based on a lipase-catalyzed perhydrolysis for the formation of peracetic acid, which is the responsible for the ketone oxidation. Optimization studies have been performed in the oxidation of cyclobutanone, finding *Candida antarctica* lipase type B, ethyl acetate and urea-hydrogen peroxide complex as the best system. The relative ratio of these reagents has also been analyzed in depth. This synthetic approach has been successfully extended to a family of 3-substituted cyclobutanones in high substrate concentration, yielding the corresponding lactones with excellent isolated yields and purities, under mild reaction conditions and after a simple extraction protocol.

Keywords: Baeyer-Villiger reaction / *Candida antarctica* lipase type B / Cascade reactions / Cyclobutanones / Lactones

1. Introduction

Hydrolases are enzymes capable to naturally catalyze hydrolytic reactions for a vast number of organic compounds such as peptides, esters or amides.[1,2] Alternatively, and depending on the reaction conditions, they can also accelerate the reverse transformations leading to the corresponding esterification, aminolysis, ammonolysis, perhydrolysis, hydrazynolysis or thiolysis products, specially when working in non-aqueous media.[3,4] Within this class of enzymes, perhydrolases are able to efficiently catalyze perhydrolysis reactions for the formation of peracids,[5,6] but the unusual participation of lipases for global oxidative process has attracted the attention of different research groups in the last decade.[5,7,8] Thus, examples of lipase-mediated epoxidation,[9-14] Baeyer-Villiger reactions,[15-19] perhydrolysis of carboxylic acid and esters,[20] sequential Baeyer-Villiger reaction and ring-opening polymerization,[21] and also consecutive esterification and Baeyer-Villiger cascade reactions[22] have appeared in the literature, giving access to synthetically useful oxygenated heterocycles through clean and selective transformations under mild reaction conditions.

In this context, the synthesis of lactones is highly appealing because of their interesting properties as subunits for polymer industry, and their applications in medicinal chemistry, fragrance and food industry. Lipases provide useful possibilities for the synthesis of lactones by the proper combination of a peracid precursor, solvent and an oxidizing agent in mild reaction conditions,[7] avoiding the use and storage of peracids that are usually associated with explosion risks. This *in situ* formation of a peracid, commonly large aliphatic linear peracids or peracetic acid, provides an environmentally friendly alternative route to the desired oxygenated heterocyles.[23]

Examples described in the literature have been mainly focused on the oxidation of cyclopentanones and cyclohexanones.[15-19,24,25] Herein we have explored the possibility of using a cascade chemoenzymatic strategy for the production of γ-butyrolactones from cyclobutanones. With that purpose, different enzymes have been tested in order to find adequate oxidizing conditions, paying special attention to the oxygen source and the substrate concentration.

2. Experimental

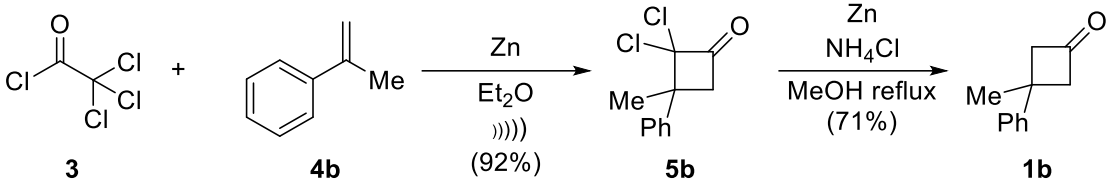
2.1. Material and methods

Candida antarctica lipase type B (CAL-B, Novozym-435, 7300 PLU/g) and *Rhizomucor miehei* lipase (RML, 150 IUN/g) were kindly gifted by Novo-Nordisk. *Pseudomonas cepacia* lipase supported on diatomite (PSL-SD, 23000 U/g), AK lipase from *Pseudomonas fluorescens* (AK, 23700 U/g) and *Candida rugosa* lipase (CRL, 1410 U/g) were acquired from Sigma-Aldrich. Other chemical reagents were used as purchased from Sigma-Aldrich, Acros or Fluka, without further additional purification. The only exceptions were phosphoryl chloride ($POCl_3$) that was used freshly distilled, and distilled Et_2O and THF, which were dried over sodium under inert atmosphere using benzophenone as indicator.

NMR spectra were recorded on Bruker AV-300 and Bruker DPX-300 spectrometers (300.13 MHz for ^1H and 75.5 MHz for ^{13}C). All chemical shifts (δ) are given in parts per million (ppm) and referenced to the residual solvent signal as internal standard. All coupling constants (*J*) are reported in Hz. Mass spectra (MS) were recorded using a MAT-95 Finigan spectrometer by positive electrospray ionization (ESI^+). High resolution mass spectra (HRMS) were obtained using a Bruker MicroQtof spectrometer by positive electrospray ionization (ESI^+). Gas chromatography (GC) analyses were performed on a Hewlett Packard 6890 Series chromatograph equipped with FID. All the data have been included in the

supporting information file. IR spectra were recorded as thin films on NaCl plates on a Perkin-Elmer Spectrum 100 FT-IR and are reported in frequency of absorption (cm^{-1}). Thin-layer chromatography (TLC) was conducted with Merck Silica Gel 60 F_{254} precoated plates and visualized using a UV lamp and/or potassium permanganate stain. Column chromatography was performed using Merck Silica Gel 60 (230-400 mesh).

*2.2. Typical procedure for the synthesis of 3-methyl-3-phenylcyclobutanone (**1b**)*



3 **4b** **5b** **1b**

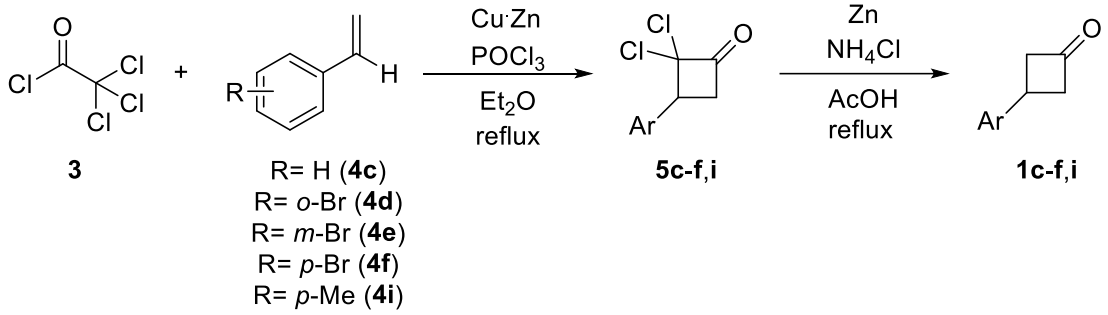
Scheme 1. Chemical synthesis of 3-methyl-3-phenylcyclobutanone (**1b**).

a) [2+2] cycloaddition reaction.[26] To a solution of α-methylstyrene (**4b**, 650 μL, 5.0 mmol) in dry Et_2O (50 mL), Zn (654 mg, 10.0 mmol) was added under inert atmosphere. The system was sonicated, while a solution of trichloroacetyl chloride (**3**, 837 μL, 7.5 mmol) in dry Et_2O (25 mL) was carefully added under inert atmosphere, maintaining the bath temperature between 15 and 20 ºC. Sonication was extended for an additional hour after the addition was completed, and after this time the reaction was stopped by filtration over celite. The reaction crude was washed with water (2 × 25 mL), an aqueous $NaHCO_3$ saturated solution (5 × 25 mL) and brine (25 mL). The organic phase was dried over Na_2SO_4, filtered and the solvent was evaporated under reduced pressure. The resulting crude was purified by column chromatography on silica gel (5% EtOAc/hexane), yielding the 2,2-dichloro-3-methyl-3-phenylcyclobutanone **5b** (92% yield).

b) Reduction with Zn. The 2,2-dichloro-3-methyl-3-phenylcyclobutanone (**5b**, 1.160 g, 5.06 mmol) was dissolved in MeOH (20 mL), and NH_4Cl was added until saturation. Then, Zn (1.987 g, 30.38 mmol) was added and the mixture stirred at 40 ºC for 6 h. After this time,

the reaction was filtered over celite and the solvent was evaporated under reduced pressure. The reaction crude was redissolved in Et_2O (100 mL) and washed with water (2 × 50 mL), an aqueous $NaHCO_3$ saturated solution (2 × 50 mL) and brine (50 mL). The organic phase was dried over Na_2SO_4, filtered and the solvent was evaporated under reduced pressure. The resulting crude was purified by column chromatography on silica gel (10% EtOAc/hexane), yielding the cyclobutanone **1b** (71% yield; 65% global yield for the two steps). Colourless oil; R_f (20% EtOAc/hexane): 0.68; IR (NaCl): ν 3059, 3026, 2958, 2921, 1785, 1602, 1496, 1445, 1381, 1080, 764 cm^{-1}; ^1H RMN ($CDCl_3$, 300.13 MHz): δ 1.62 (s, 3H, CH_3), δ 3.07-3.17 (m, 2H, C*H*H), δ 3.42-3.53 (m, 2H, CH*H*), δ 7.23-7.42 (m, 5H) ppm; ^{13}C RMN ($CDCl_3$, 75.5 MHz): δ 31.1 (CH_3), δ 34.0 (C), δ 59.3 ($2CH_2$), δ 125.7 (2CH), δ 126.3 (CH), δ 128.6 (2CH), δ 148.3 (C), δ 206.6 (CO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{11}H_{12}NaO$) $(M+Na)^+$: 183.0780, found: 183.0776.

*2.3. Typical procedure for the synthesis of 3-arylcyclobutanones **1c-f,i***[27,28]



Scheme 2. General synthesis of 3-arylcyclobutanones **1c**-**f**,**i**.

a) Preparation of the Cu-Zn complex. To a suspension of Zn (6.5 g, 99.4 mmol) in water (10 mL), a solution of $CuSO_4·5H_2O$ (760 mg, 4.76 mmol) in water (5 mL) was added in two times. After one minute, the solid was filtered and washed with water (2 × 5 mL), acetone (2 × 5 mL) and Et_2O (2 × 5 mL). The resulting grey-black solid was dried in a Kugelrohr apparatus at 100 ºC for 6 h, and stored under inert atmosphere.

b) [2+2] cycloaddition reaction. A suspension of the corresponding styrene **3c-f**,**i** (5.0 mmol) and Cu-Zn complex (1.31 g, 0.26 g/mmol styrene) in dry Et_2O (20 mL) was prepared under inert atmosphere. A mixture composed by trichloroacetyl chloride (**3**, 1.116 mL, 10.0 mmol) and freshly distilled phosphoryl chloride ($POCl_3$, 512 μL, 5.5 mmol) in dry Et_2O (11 mL) was slowly added under inert atmosphere at room temperature, and once the addition was finished, the mixture was refluxed for 24 h. After this time, the mixture was left to cool down until room temperature, and filtered over celite. A major part of the Et_2O was evaporated in the rotary evaporator, adding then hexane (100 mL). The mixture was vigorously stirred and then left unaltered, observing the formation of a precipitate. The supernatant was washed with an aqueous $NaHCO_3$ saturated solution (2 × 40 mL) and brine (40 mL). The organic phase was dried over Na_2SO_4, filtered and the solvent evaporated under reduced pressure, yielding the corresponding 2,2-dichloroketone **5c-f**,**i**.

c) Reduction with Zn. The previous reaction crude containing the dichlorinated cyclobutanone **5c-f**,**i** (5.0 mmol) was dissolved in glacial acetic acid (20 mL) and Zn (1.34 g, 20.0 mmol) was added. The reaction was refluxed for 12 h, and after this time water (25 mL) was added. The solution was extracted with Et_2O (2 × 15 mL), the organic phases were combined and washed with an aqueous $NaHCO_3$ saturated solution (4 × 15 mL) and brine (2 × 15 mL). The resulting organic phase was dried over Na_2SO_4, filtered and the solvent was evaporated under reduced pressure. The reaction crude was purified by column chromatography on silica gel (10-20% EtOAc/hexane), yielding the cyclobutanones **1c-f**,**i** (12-50% isolated yield).

3-Phenylcyclobutanone (1c). 34% yield. Colourless oil; R_f (20% EtOAc/hexane): 0.45; IR (NaCl): ν 3062, 3029, 2975, 2923, 1785, 1603, 1496, 1380, 1104, 780 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 3.10-3.22 (m, 2H, C*H*H), 3.35-3.47 (m, 2H, CH*H*), 3.51-3.65 (m, 1H, CH), 7.13-7.31 (m, 5H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 28.5 (CH), 54.8 ($2CH_2$),

126.6 (2CH), 126.7 (CH), 128.8 (2CH), 143.7 (C), 206.8 (CO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_{10}NaO$) $(M+Na)^+$: 169.0624, found: 169.0632.

3-(2-Bromophenyl)cyclobutanone (1d). 31% yield. Yellow oil; R_f (20% EtOAc/hexane): 0.72; IR (NaCl): ν 3062, 2983, 2927, 1788, 1590, 1567, 1472, 1380, 1102, 1027, 755 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 3.16-3.29 (m, 2H, C*H*H), 3.46-3.59 (m, 2H, CH*H*), 3.87-4.02 (m, 1H, CH), 7.10-7.19 (m, 1H), 7.30-7.39 (m, 2H), 7.57-7.64 (m, 1H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 29.1 (CH), 53.2 ($2CH_2$), 124.9 (CBr), 126.6 (CH), 127.8 (CH), 128.4 (CH), 133.3 (CH), 141.7 (C), 206.0 (CO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_9BrNaO$) $(M_{79Br}+Na)^+$: 246.9729, found: 246.9703.

3-(3-Bromophenyl)cyclobutanone (1e). 32% yield. Pale yellow oil; R_f (30% EtOAc/hexane): 0.77; IR (NaCl): ν 3062, 2975, 2923, 1785, 1636, 1596, 1566, 1477, 1378, 1102, 1074, 780 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 3.18-3.30 (m, 2H, C*H*H), 3.45-3.58 (m, 2H, CH*H*), 3.61-3.74 (m, 1H, CH), 7.22-7.27 (m, 2H), 7.36-7.43 (m, 1H), 7.45-7.48 (m, 1H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 28.3 (CH), 54.7 ($2CH_2$), 122.9 (CBr), 125.3 (CH), 129.9 (2CH), 130.4 (CH), 146.0 (C), 205.7 (CO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_{10}BrO$) $(M_{79Br}+H)^+$: 224.9910, found: 224.9889.

3-(4-Bromophenyl)cyclobutanone (1f). 50% yield. Yellowish-orangish solid. Mp: 49-51 ºC; R_f (30% EtOAc/hexane): 0.59; IR (nujol): ν 3055, 2987, 1786, 1489, 1422, 1395, 1101, 1075, 1009, 821 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): 3.13-3.25 (m, 2H, C*H*H), 3.42-3.55 (m, 2H, CH*H*), 3.57-3.69 (m, 1H, CH), 7.13-7.19 (m, 2H), 7.42-7.48 (m, 2H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 28.2 (CH), 54.8 ($2CH_2$), 120.6 (CBr), 128.4 (2CH), 131.9 (2CH), 142.7 (C), 206.0 (CO) ppm; MS (ESI^+, *m/z*): 225 $(M_{79Br}+H)^+$; 227 $(M_{81Br}+H)^+$.

3-(4-Methylphenyl)cyclobutanone (1i). 12% yield. Yellowish oil; R_f (30% EtOAc/hexane): 0.79; IR (NaCl): ν 3023, 2974, 2922, 1785, 1608, 1516, 1450, 1417, 1379, 1167, 1109, 1020, 813 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 2.36 (s, 3H, CH_3), 3.17-3.29

(m, 2H, C*H*H), 3.42-3.55 (m, 2H, CH*H*), 3.59-3.71 (m, 1H, CH), 7.15-7.23 (m, 4H); ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 21.0 (CH_3), 28.1 (CH), 54.8 ($2CH_2$), 126.4 (2CH), 129.4 (2CH), 136.2 (*C*Me), 140.6 (C), 206.9 (CO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{22}H_{24}NaO_2$) $(2M+Na)^+$: 343.1669, found: 343.1654.

2.4. Synthesis of ethyl 3-oxocyclobutanecarboxylate (***1j***)

3-Oxocyclobutanecarboxylic acid (**6**, 200 mg, 1.75 mmol) was dissolved in dry THF (7 mL) and a drop of DMF was added under inert atmosphere. The solution was cooled down in an ice-bath, and oxalyl chloride (276 μL, 3.51 mmol) was added, stirring the mixture for 30 minutes. After this time, the reaction was left to warm to room temperature, the solvent evaporated under reduced pressure and the residue redissolved in ethanol (7 mL). The solution was stirred for 1 h at room temperature. Then the solvent was evaporated in the rotary evaporator and the reaction crude purified by column chromatography on silica gel (20-30% EtOAc/hexane), yielding the cyclobutanone **1j** as a pale yellow oil (82% isolated yield). R_f (20% EtOAc/hexane): 0.30; IR (NaCl): ν 2985, 2937, 1797, 1733, 1467, 1375, 1346, 1215, 1193, 1099, 1052, 858 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300.13 MHz): δ 1.25 (t, $^3J_{HH}$= 7.1, 3H, CH_3), 3.12-3.43 (m, 5H, $2CH_2$+CH), 4.17 (q, $^3J_{HH}$= 7.1, 2H, OC*H*$_2$) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 14.2 (CH_3), 27.4 (CH), 51.6 ($2CH_2$), 61.3 (OCH_2), 174.1 (COO), 203.9 (CO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_7H_{10}NaO_3$) $(M+Na)^+$: 165.0522, found: 165.0531.

*2.5. Synthesis of benzyl 3-oxocyclobutanecarboxylate (****1k****).*

3-Oxocyclobutanecarboxylic acid (**6**, 200 mg, 1.75 mmol) was dissolved in dry THF (7 mL), and a drop of DMF was added under inert atmosphere. The solution was cooled down in an ice-bath, and oxalyl chloride (276 μL, 3.51 mmol) was added, stirring the mixture for 30 minutes. After this time, the reaction was left to warm to room temperature and benzyl alcohol (544 μL, 5.26 mmol) was added. The solution was stirred overnight at room

temperature. Then the solvent was evaporated in the rotary evaporator and the reaction crude purified by column chromatography on silica gel (20% EtOAc/hexane), yielding the cyclobutanone **1k** as a pale yellow oil (76% isolated yield). R_f (30% EtOAc/hexane): 0.56; IR (NaCl): ν 3034, 2926, 2854, 1792, 1732, 1498, 1456, 1380, 1347, 1186, 1100, 1051, 752 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 3.20-3.50 (m, 5H, $2CH_2$+CH), 5.19 (s, 2H, CH_2Ph), 7.33-7.39 (m, 5H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 27.5 (CH), 51.7 ($2CH_2$), 67.2 (OCH_2), 128.4 (2CH), 128.6 (CH), 128.7 (2CH), 135.5 (C), 173.9 (COO), 203.6 (CO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{12}H_{12}NaO_3$) $(M+Na)^+$: 227.0679, found: 227.0660

*2.6. General procedure for the synthesis of lactones **2b-l** with m-chloroperbenzoic acid (MCPBA).*

To a solution of the corresponding 3-arylcyclobutanone **1b-l** (0.25 mmol) in CH_2Cl_2 (1.0 mL), MCPBA (88 mg, 0.50 mmol) was added and the mixture was stirred for 20 h. The mixture was washed with an aqueous $NaHCO_3$ saturated solution (6 x 5 mL), the organic phase dried over Na_2SO_4, filtered and the solvent evaporated under reduced pressure. The reaction crude was purified by column chromatography on silica gel (10-30% EtOAc/hexane), yielding the lactones **2b-l** (44-99% isolated yield: 93% for **2b**; 83% for **2c**; 72% for **2d**; 99% for **2e**; 85% for **2f**; 86% for **2g**; 88% for **2h**; 44% for **2i**; 77% for **2j**; 75% for **2k**; 96% for **2l**). These standards were used for the development of GC analysis methods prior to carry out the chemoenzymatic reactions.

*2.7. General procedure for the chemoenzymatic synthesis of lactones **2a-l** using CAL-B, UHP and EtOAc.*

Over a solution of the corresponding cyclobutanone **1a-l** (0.25 mmol) in EtOAc (379 μL, 30.0 mmol), complex urea-hydrogen peroxide (UHP, 35 mg, 0.38 mmol) and CAL-B (12.5 mg) were added. The suspension was shaken for 20 h at 30 ºC and 250 rpm, then an

aliquot was analyzed by GC. The reaction was left shaken until complete conversion was reached, then water was added (2 mL) and the enzyme filtered off. The solution was extracted with EtOAc (3 × 5 mL) and the organic phases combined and washed with water (2 × 5 mL) and brine (5 mL). The resulting organic phase was dried over Na_2SO_4, filtered and the solvent was evaporated under reduced pressure to obtain the corresponding lactones **2a-l** (51-99% isolated yield). For fluorinated lactone **2k** a column chromatography on silica gel (30% EtOAc/hexane) was necessary, as the reaction did not lead to complete conversion.

4-Methyl-4-phenyldihydrofuran-2(3*H*)-one (2b). 93% yield; White solid; Mp: 49-51 ºC; R_f (30% EtOAc/hexane): 0.43; IR (nujol): ν 3024, 2969, 2930, 2904, 1773, 1601, 1497, 1305, 1173, 1094, 1020, 767 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 1.54 (s, 3H, CH_3), 2.68 (dd, $^2J_{HH}$= 16.8, $^4J_{HH}$= 0.4, 1H, C*H*H), 2.93 (dd, $^2J_{HH}$= 16.8, $^4J_{HH}$= 0.6, 1H, CH*H*), 4.39-4.47 (m, 2H, OCH_2), 7.18-7.23 (m, 2H), 7.27-7.33 (m, 1H), 7.36-7.42 (m, 2H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 28.1 (CH_3), 42.1 (CH_2), 44.2 (C), 78.5 (OCH_2), 125.2 (2CH), 127.3 (CH), 129.1 (2CH), 144.4 (C), 176.2 (CO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{11}H_{12}NaO_2$) $(M+Na)^+$: 199.0730, found: 199.0781.

4-Phenyldihydrofuran-2(3*H*)-one (2c). 83% yield; White solid; Mp: 46-47 ºC; R_f (20% EtOAc/hexane): 0.20; IR (nujol): ν 3064, 3032, 2973, 2904, 1763, 1601, 1456, 1355, 1163, 1010, 761 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 2.67 (dd, $^2J_{HH}$= 17.5, $^3J_{HH}$= 9.1, 1H, C*H*H), 2.92 (dd, $^2J_{HH}$= 17.5, $^3J_{HH}$= 8.3, 1H, CH*H*), 3.73-3.85 (m, 1H, CH), 4.26 (dd, $^2J_{HH}$= 9.0, $^3J_{HH}$= 8.1, 1H, OC*H*H), 4.66 (dd, $^2J_{HH}$= 9.0, $^3J_{HH}$= 8.3, 1H, OCH*H*), 7.21-7.40 (m, 5H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 35.8 (CH_2), 41.2 (CH), 74.1 (OCH_2), 126.8 (2CH), 127.8 (CH), 129.2 (2CH), 139.5 (C), 176.5 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_{10}NaO_2$) $(M+Na)^+$: 185.0573, found: 185.0592.

4-(2-Bromophenyl)dihydrofuran-2(3*H*)-one (2d). 72% yield; White solid; Mp: 56-57 ºC; R_f (20% EtOAc/hexane): 0.41; IR (nujol): ν 3064, 2990, 2914, 1779, 1568, 1473, 1440, 1372, 1168, 1023, 753 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): 2.67 (dd, $^2J_{HH}$= 17.6, $^3J_{HH}$= 6.7,

1H, C*H*H), 2.97 (dd, $^{2}J_{HH}$= 17.6, $^{3}J_{HH}$= 8.6, 1H, CH*H*), 4.17-4.24 (m, 2H, CH+OC*H*H), 4.71 (dd, $^{2}J_{HH}$= 9.0, $^{3}J_{HH}$= 7.2, 1H, OCH*H*), 7.17 (ddd, $^{3}J_{HH}$= 8.0, $^{3}J_{HH}$= 7.1, $^{4}J_{HH}$= 1.9 ,1H), 7.26-7.35 (m, 2H), 7.61 (dd, $^{3}J_{HH}$= 8.0, $^{4}J_{HH}$= 1.3, 1H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 34.9 (CH_2), 40.3 (CH), 73.0 (OCH_2), 124.5 (CBr), 126.8 (CH), 128.4 (CH), 129.3 (CH), 133.6 (CH), 140.0 (C), 176.2 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_9BrNaO_2$) $(M_{79Br}+Na)^+$: 262.9678, found: 262.9670.

4-(3-Bromophenyl)dihydrofuran-2(3*H*)-one (2e). 99% yield; Yellowish oil; R_f (30% EtOAc/hexane): 0.50; IR (NaCl): ν 3058, 2971, 2913, 1781, 1597, 1568, 1479, 1266, 1169, 1024, 737 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300.13 MHz): 2.64 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.8, 1H, C*H*H), 2.93 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.7, 1H, CH*H*), 3.70-3.82 (m, 1H, CH), 4.25 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.6, 1H, OCH*H*), 4.66 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.8, 1H, OC*H*H), 7.16 (dt, $^{3}J_{HH}$= 7.7, $^{4}J_{HH}$= 1.2,1H), 7.25 (t, $^{3}J_{HH}$= 7.8, 1H), 7.38 (t, $^{4}J_{HH}$= 1.8, 1H), 7.42 (ddd, $^{3}J_{HH}$= 7.8, $^{4}J_{HH}$= 1.8, $^{4}J_{HH}$= 1.2, 1H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 35.6 (CH_2), 40.8 (CH), 73.7 (OCH_2), 123.3 (CBr), 125.4 (CH), 130.1 (CH), 130.9 (CH), 131.0 (CH), 141.9 (C), 175.9 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_9BrNaO_2$) $(M_{79Br}+Na)^+$: 262.9678, found: 262.9657.

4-(4-Bromophenyl)dihydrofuran-2(3*H*)-one (2f). 85% yield; White solid; Mp: 72-74 ºC; R_f (30% EtOAc/hexane): 0.31; IR (nujol): ν 3016, 2930, 2901, 1767, 1589, 1487, 1424, 1221, 1158, 1016, 826 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300.13 MHz): δ 2.62 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.8, 1H, C*H*H), 2.93 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.7, 1H, CH*H*), 3.68-3.83 (m, 1H, CH), 4.23 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.6, 1H, OC*H*H), 4.65 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.8, 1H, OCH*H*), 7.08-7.14 (m, 2H), 7.46-7.52 (m, 2H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 35.7 (CH_2), 40.7 (CH), 73.8 (OCH_2), 121.7 (CBr), 128.5 (2CH), 132.4 (2CH), 138.6 (C), 176.0 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_9BrNaO_2$) $(M_{79Br}+Na)^+$: 262.9678, found: 262.9673.

4-(4-Chlorophenyl)dihydrofuran-2(3*H*)-one (2g). 86% yield; Pale yellow solid; Mp: 54-56 ºC; R_f (30% EtOAc/hexane): 0.41; IR (nujol): ν 3055, 2987, 2914, 1782, 1496, 1423,

1170, 1094, 1025, 828 $cm^{-1;}$ ^{1}H NMR ($CDCl_3$, 300.13 MHz): δ 2.61 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.9, 1H, C*H*H), 2.92 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.7, 1H, CH*H*), 3.70-3.82 (m, 1H, CH), 4.23 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.7, 1H, OC*H*H), 4.65 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.8, 1H, OCH*H*), 7.13-7.19 (m, 2H), 7.30-7.36 (m, 2H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 35.7 (CH_2), 40.6 (CH), 73.9 (OCH_2), 128.2 (2CH), 129.4 (2CH), 133.6 (CCl), 138.1 (C), 176.1 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_9ClNaO_2$) $(M+Na)^+$: 219.0183, found: 219.0156.

4-(4-Fluorophenyl)dihydrofuran-2(3*H*)-one (2h). 88% yield; White solid; Mp: 65-67 ºC; R_f (30% EtOAc/hexane): 0.38; IR (nujol): ν 3068, 2914, 1777, 1602, 1514, 1433, 1219, 1165, 1013, 843 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300.13 MHz): δ 2.62 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.9, 1H, C*H*H), 2.92 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.7, 1H, CH*H*), 3.71-3.84 (m, 1H, CH), 4.23 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.7, 1H, OC*H*H), 4.65 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.8, 1H, OCH*H*), 7.00-7.09 (m, 2H), 7.16-7.24 (m, 2H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 35.9 (CH_2), 40.6 (CH), 74.1 (OCH_2), 116.2 (d, $^{2}J_{CF}$= 21.5, 2CH), 128.4 (d, $^{3}J_{CF}$= 8.0, 2CH), 135.3 (d, $^{4}J_{CF}$= 2.9, C), 162.2 (d, $^{1}J_{CF}$= 246.6, CF), 176.2 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{10}H_9FNaO_2$) $(M+Na)^+$: 203.0479, found: 203.0474.

4-(4-Methylphenyl)dihydrofuran-2(3*H*)-one (2i). 44% yield; White solid; Mp: 40-42 ºC; IR (nujol): ν 2978, 2948, 2916, 1761, 1608, 1519, 1484, 1455, 1427, 1350, 1214, 1158, 1008, 827 cm^{-1}; R_f (30% EtOAc/hexane): 0.54; ^{1}H NMR ($CDCl_3$, 300.13 MHz): δ 2.34 (s, 3H, CH_3), 2.65 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 9.2, 1H, C*H*H), 2.90 (dd, $^{2}J_{HH}$= 17.5, $^{3}J_{HH}$= 8.6, 1H, CH*H*), 3.69-3.82 (m, 1H, CH), 4.24 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 8.0, 1H, OC*H*H), 4.65 (dd, $^{2}J_{HH}$= 9.1, $^{3}J_{HH}$= 7.9, 1H, OCH*H*), 7.10-7.20 (m, 4H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 21.1 (CH_3), 35.9 (CH_2), 40.9 (CH), 74.3 (OCH_2), 126.7 (2CH), 129.9 (2CH), 136.4 (CMe), 137.6 (C), 176.6 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{11}H_{12}NaO_2$) $(M+Na)^+$: 199.0730, found: 199.0728.

Ethyl 5-oxotetrahydrofuran-3-carboxylate (2j). 77% yield; Yellowish liquid; R_f (40% EtOAc/hexane): 0.30; IR (NaCl): ν 2986, 2941, 1783, 1733, 1477, 1375, 1348, 1198, 1176, 1024, 845 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 1.25 (t, $^3J_{HH}$= 7.1, 3H, CH_3), 2.70 (dd, $^2J_{HH}$= 17.9, $^3J_{HH}$= 9.6, 1H, C*H*H), 2.83 (dd, $^2J_{HH}$= 17.9, $^3J_{HH}$= 7.2, 1H, CH*H*), 3.36-3.47 (m, 1H, CH), 4.17 (q, $^3J_{HH}$= 7.1, 2H, OC*H*$_2$$CH_3$), 4.37-4.52 (m, 2H, OCH_2) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 14.1 (CH_3), 30.9 (CH_2), 40.0 (CH), 61.9 (O*C*H_2CH_3), 69.1 (OCH_2), 171.2 (*C*O_2Et), 175.3 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_7H_{10}NaO_4$) $(M+Na)^+$: 181.0471, found: 181.0477.

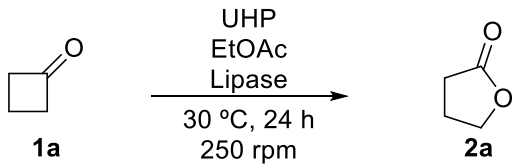
Benzyl 5-oxotetrahydrofuran-3-carboxylate (2k). 75% yield; White gummy solid; R_f (30% EtOAc/hexane): 0.33; IR (NaCl): ν 3066, 3034, 2959, 1779, 1736, 1636, 1498, 1456, 1383, 1350, 1175, 1013, 754 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 2.74 (dd, $^2J_{HH}$= 17.9, $^3J_{HH}$= 9.6, 1H, C*H*H), 2.88 (dd, $^2J_{HH}$= 17.9, $^3J_{HH}$= 7.3, 1H, CH*H*), 3.44-3.56 (m, 1H, CH), 4.42-4.56 (m, 2H, OCH_2), 5.20 (s, 2H, CH_2Ph), 7.33-7.44 (m, 5H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 30.9 (CH_2), 40.1 (CH), 67.7 (CH_2Ph), 69.0 (OCH_2), 128.5 (2CH), 128.8 (3CH), 135.0 (C), 171.0 (*C*O_2Bn), 175.1 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{12}H_{12}NaO_4$) $(M+Na)^+$: 243.0628, found: 243.0671.

4-(Benzyloxy)dihydrofuran-2(3*H*)-one (2l). 96% yield; White gummy solid; R_f (40% EtOAc/hexane): 0.30; IR (NaCl): ν 3066, 3034, 2923, 1779, 1603, 1455, 1401, 1374, 1333, 1166, 1086, 1050, 993, 886, 747 cm^{-1}; ^1H NMR ($CDCl_3$, 300.13 MHz): δ 2.58-2.73 (m, 2H), 4.34-4.41 (m, 3H, CH+OCH_2), 4.49-4.57 (m, 2H, OCH_2Ph), 7.27-7.40 (m, 5H) ppm; ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 35.0 (CH_2), 71.2 (OCH_2Ph), 73.2 (OCH_2), 73.9 (CH), 127.8 (2CH), 128.2 (CH), 128.7 (2CH), 137.0 (C), 175.6 (COO) ppm; HRMS (ESI^+, *m/z*): calculated for ($C_{11}H_{12}NaO_3$) $(M+Na)^+$: 215.0679, found: 215.0726.

3. Results and discussion

To start with, a screening of biocatalysts for the oxidation of cyclobutanone (**1a**) was performed, considering a representative set of lipases such as CAL-B, RML, AK, PSL-SD and CRL. Searching for a simple catalytic cascade system, ethyl acetate (EtOAc) was selected as both solvent and peracetic acid precursor, using the stable and safe urea-hydrogen peroxide (UHP) complex as oxidizing agent. Initially, the reactions were carried out with 1 equivalent of UHP complex and a 0.66 M concentration of **1a** in EtOAc at 30 ºC (Table 1).

Table 1. Baeyer-Villiger reaction of cyclobutanone (**1a**) using 1 equivalent of UHP, different lipases (50 mg enzyme/mmol **1a**) in EtOAc (0.66 M of **1a**) after 24 h at 30 ºC and 250 rpm.



Entry	Lipase	Conversion (%)[a]
1	----	3
2	CAL-B	77
3	RML	32
4	AK	34
5	PSL-SD	46
6	CRL	42

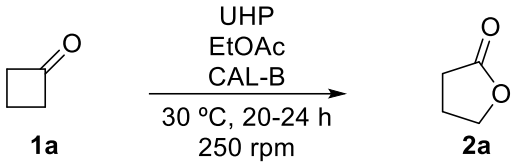
[a] Calculated by GC analyses of the reaction crudes.

In all cases conversions into the lactone **2a** were much higher (>30%, entries 2-6) compared to that in absence of enzyme, which just proceeded in 3% conversion (entry 1). Moreover, **2a** was found to be the unique final product, not detecting any other side reactions. Remarkably, the use of an aqueous 30% H_2O_2 solution[29,30] led to the formation of various by-products and poor reproducibility. CAL-B came out as the most efficient catalyst,[31]

reaching a 77% conversion after 24 h (entry 2), while RML, AK, PSL-SD and CRL did not overcome a 46% yield (entries 3-6).

In order to obtain complete conversions, different reaction parameters were studied such as the amount of UHP or the substrate concentration, maintaining CAL-B as biocatalyst (Table 2).[28] Thus, the amount of UHP was varied between 1.0 and 2.0 equivalents, **1a** being used in a really high concentration if compared to other classes of enzymes (0.5-1.0 M). Regarding previous results (entry 1), doubling the amount of UHP led to a complete conversion in the same reaction time (entry 2). It must be noticed that 24 h were necessary to reach complete conversion, as a 91% conversion was achieved after 20 h (entry 3). Satisfactorily, 1.5 equivalents of the oxidizing agent allowed the formation of **2a** quantitatively after 20 h (entry 4), which suggests a deactivation of the enzyme during the timeframe at higher UHP concentration. This reaction was performed with both 0.25 mmol and 0.5 mmol of **1a** observing identical results. Unfortunately a decrease of UHP to only 1 equivalent at both lower (0.5 M, entry 5) or very high substrate concentration (0.8 and 1.0 M, entries 7 and 8), led to modest 64-75% conversion values after 20 h (entries 5-8). Finally, a 1.0 M substrate concentration was studied. Hence, after examining the influence of UHP ratio (1-2 equivalents, entries 8-11), it was observed that an almost complete conversion could only be achieved using 2 equivalents of the oxidizing agent (entry 11).

Table 2. Baeyer-Villiger reaction of cyclobutanone (**1a**) using UHP complex and CAL-B (50 mg/mmol **1a**) in EtOAc at 30 ºC and 250 rpm.



Entry	Time (h)	UHP (eq)	[1a] (M)	Conversion (%)[a]
1	24	1.0	0.66	77
2	24	2.0	0.66	>99
3	20	2.0	0.66	91
4	20	1.5	0.66	>99
5	20	1.0	0.5	64
6	20	1.0	0.66	71
7	20	1.0	0.8	74
8	20	1.0	1.0	75
9	20	1.2	1.0	79
10	20	1.5	1.0	83
11	20	2.0	1.0	96

[a] Calculated by GC analyses of the reaction crudes. Lactone **2a** was the only product detected.

With these results in hand, the strategy was extended to a broad panel of 3-substituted cyclobutanones, some of them commercially available and other synthesized through conventional chemical protocols (see experimental section). For this study, prochiral cyclobutanones, such as the 3,3-disubstituted **1b**, 3-aryl-substituted **1c**-**h**, ketoesters **1i**-**j** and the alkoxy substituted **1l**, were considered. Prior to the performance of the chemoenzymatic studies, lactones **2b**-**l** were synthesized by reaction of the corresponding cyclobutanone **1b**-**l** with *m*-chloroperbenzoic acid in dichloromethane, developing adequate GC methods for the

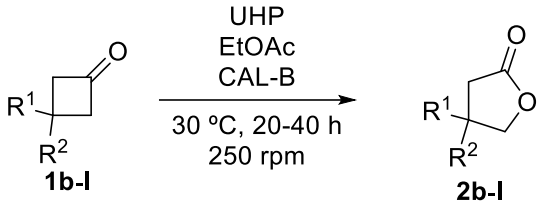
analysis of the lipase-mediated oxidations of **1b-l** (see experimental section and supporting information). Table 3 shows the results achieved for the Baeyer-Villiger reaction of 3-substituted cyclobutanones **1b-l** using CAL-B, UHP complex and EtOAc. Control experiments in the absence of the enzyme led in all cases to poor conversions (lower than 22%), the highest value being obtained with the brominated derivative **1d**. This observation demonstrates the efficiency of the chemoenzymatic system here employed. Lower conversion values (< 5%) were reached with ketoesters **1j-k**, and in the presence of unsubstituted phenyl derivatives **1b-c**.

Remarkably, after 20 h conversions were equal or higher than 90% in all cases except for the fluorinated derivative in the *para*-position of the phenyl ring **1h** (entry 7). A periodic time course analysis was performed in order to reach complete conversions, which facilitates the purification of the final products, avoiding column chromatography separations. Thus, high to excellent isolated yields were achieved for the final γ-butyrolactones after a simple and effective extraction protocol following the enzyme filtration, which is in contrast with traditional oxidative processes using metal complexes or inorganic salts. It is also worthy to mention that ketoesters **1j** and **1k** (entries 9 and 10) led to the lactones without formation of any undesired hydrolytic products in spite of using a hydrolase in the transformation.

Complete conversions were found for seven out of the eleven tested substrates after 20 h, requiring 30 h for the 3-phenyl-cyclobutanones **1b-c** and 40 h for the 3-(benzyloxy)cyclobutanone (**1l**). Nevertheless, the oxidation of the 3-(4-fluorophenyl)cyclobutanone (**1h**) did not proceed to complete conversion after prolonged time periods. The chemoenzymatic global oxidative approach was extremely effective for ketones presenting substitutions in the phenyl ring such as alkyl rests (methyl, **1i**) or halogen atoms (bromine or chlorine, **1d-g**) in different positions (*orto*, *meta* or *para*), but also when alkyl carboxylates (**1j**,**k**) and the benzyloxy rest (**1l**) were considered. All the final products were racemic, probing that the enzyme is only responsible for the perhydrolysis reaction leading to

the formation of non chiral peracetic acid, which is in turn the responsible for the non enantioselective oxidation.[8] The scalability of the process was probed at a 250 mg-scale using 3-(4-methylphenyl)cyclobutanone (**1i**) as substrate. Gratifyingly, it was quantitatively transformed after 20 h.

Table 3. Baeyer-Villiger reaction of 3-substituted cyclobutanones **1b-l** using 1.5 equivalents of UHP and CAL-B (50 mg/mmol **1b-l**) in EtOAc (0.66 M) at 30 ºC and 250 rpm.



Entry	Substrate	R^1	R^2	t (h)	Conversion (%)[a]	Yield (%)[c]
1	**1b**	Me	Ph	30	>99 (94)[b]	93
2	**1c**	H	Ph	30	>99 (94)[b]	99
3	**1d**	H	2-Br-C_6H_4	20	>99	98
4	**1e**	H	3-Br-C_6H_4	20	>99	97
5	**1f**	H	4-Br-C_6H_4	20	>99	99
6	**1g**	H	4-Cl-C_6H_4	20	>99	87
7	**1h**	H	4-F-C_6H_4	20	78	51
8	**1i**	H	4-Me-C_6H_4	20	>99	97
9	**1j**	H	COOEt	20	>99	84
10	**1k**	H	COOBn	20	>99	96
11	**1l**	H	OBn	40	>99 (90)[b]	94

[a] Calculated by GC analyses of the reaction crudes.
[b] Conversion values after 20 h appear in parentheses.
[c] Isolated yields after purification by extraction of the final products, once complete conversions were detected by GC. For **1h** none significant improvements in the conversion value were observed over the time, so **2h** was purified by column chromatography on silica gel.

4. Conclusions

The development of cascade reactions is a challenging task for organic chemists since they simplify the overall process, allowing the participation of unstable intermediates and improving the yields of the final products. Herein, we have described a chemoenzymatic strategy for the synthesis of γ-butyrolactones starting from the corresponding cyclobutanones. This Baeyer-Villiger reaction is based on two sequential steps carried out in *one-pot*. Firstly, a lipase-catalyzed perhydrolysis of ethyl acetate allows the formation of peracetic acid, which smoothly performs the oxidation of the ketones into the lactones in a non-enzymatic fashion. Cyclobutanone was selected for simplicity and commercial availability as model substrate, finding *Candida antarctica* lipase type B as the most efficient enzyme to carry out this transformation, while the stable UHP complex has served as a mild oxidative agent. The influence of the substrate concentration and the amount of UHP has also been studied in depth. Satisfyingly, 1.5 equivalents of UHP allowed the preparation of γ-butyrolactones in good to excellent yields after a simple extraction protocol, from a previously acquired or synthetized representative number of cyclobutanones in a 0.66 M concentration. Finally, the reaction has been satisfactorily scaled-up, demonstrating the efficiency of this chemoenzymatic cascade approach.

5. Acknowledgments

We thank Novozymes for the generous gift of *Rhizomucor miehei* lipase (RML) and *Candida antarctica* lipase type B (CAL-B). Financial support from the Spanish Ministerio de Ciencia e Innovación (MICINN-12-CTQ2011-24237), Principado de Asturias (SV-PA-13-ECOEMP-42) and the University of Oviedo (UNOV-13-EMERG-01) are also gratefully acknowledged.

6. References

[1] K. Faber, Biotransformation in Organic Chemistry. A Textbook, sixth ed., Springer-Verlag, Heildeberg, 2011.

[2] U. T. Bornscheuer, R. J. Kazlauskas, Hydrolases in Organic Synthesis: Regio- and Stereoselective Biotansformations, second ed., Wiley-VCH, Weinheim, 2006.

[3] G. Carrea, S. Riva, Organic Synthesis with Enzymes in Non-Aqueous Media, Wiley-VCH, Weinheim, 2008.

[4] V. Gotor, I. Alfonso, E. García-Urdiales (Eds.), Asymmetric Organic Synthesis with Enzymes, Wiley-VCH, Weinheim 2008.

[5] C. Carboni-Oerlrmans, P. Domínguez de María, B. Tuin, G. Bargeman, A. van der Meer, R. van Gemert, J. Biotecnol.126 (2006) 140-151.

[6] G. Chávez, J.-A. Rasmussen, M. Janssen, G. Mamo, R. Hatti-Kaul, R. A. Sheldon, Top. Catal. 57 (2014), 349-355.

[7] D. Gamenara, G. A. Seoane, P. Saenz-Méndez, P. Domínguez de María (Eds), Redox Biocatalysis: Fundamentals and Applications, John Wiley & Sons, Inc. Hoboken, 2013, pp 433-452.

[8] E. Busto, V. Gotor-Fernández, V. Gotor, Chem. Soc. Rev. 39 (2010) 4504-4523.

[9] F. A. Corrêa, F. K. Sutili, L. S. M. Miranda, S. G. F. Leite, R. O. M. A. Souza, I. C. R. Leal, J. Mol. Catal. B: Enzym. 81 (2012) 7-11.

[10] J. M. R. da Silva, M. G. Nascimiento, Process Biochem. 47 (2012) 517-522.

[11] D. Méndez-Sánchez, N. Ríos-Lombardía, V. Gotor, V. Gotor-Fernández, Tetrahedron 70 (2014) 1144-1148.

[12] D. Hurem, T. Dudding, RSC Adv. 4 (2014) 15552-15557.

[13] C. Aouf, E. Durand, J. Lecomte, M.-C. Figueroa-Espinoza, E. Dubreucq, H. Fulcrand, P. Villeneuve, Green Chem. 16 (2014) 1740-1752.

[14] A. F. Zanette, I. Zampakidi, G. T. Sotiroudis, M. Zompanioti, I. C. R. Leal, R. O. M. A. de Souza, L. Cardozo-Filho, A. Xenakis, J. Mol. Catal. B: Enzym. 107 (2014) 89-94.

[15] M. Y. Ríos, E. Salazar, H. F. Olivo, Green Chem. 9 (2007) 459-462.

[16] M. Y. Ríos, E. Salazar, H. F. Olivo, J. Mol. Catal. B: Enzym. 54 (2008) 61-66.

[17] A. J. Kotlewska, F. van Rantwijk, R. A. Sheldon, I. W. C. E. Sheldon, Green Chem. 13 (2011) 2154.

[18] G. Chávez, R. Hatti-Kaul, R. A. Sheldon, G. Mamo, J. Mol. Catal. B: Enzym. 89 (2013) 67-72.

[19] A. Drozdz, A. Chrobok, S. Baj, K. Szymańska, J. Mrowiec-Białoń, A. B. Jarzębski, Applied. Catal. A: Gen. 467 (2013) 163-170.

[20] D. Yin, V. M. Purpero, R. Fujii, Q. Jing, R. J. Kazlauskas, Chem. Eur. J. 19 (2013) 3037-3046.

[21] J. Zhong, F. Xu, J. Wang, Y. Li, X. Lin, Q. Wu, RSC Adv. 4 (2014) 8533-8540.

[22] C. Orellana-Coca, J. M. Billakanti, B. Mattiasson, R. Hatti-Kaul, J. Mol. Catal. B: Enzym. 44 (2007) 133-137.

[23] G.-J. ten Brink, I. W. C. E. Arends, R. A. Sheldon, Chem. Rev. 104 (2004), 4105-4123.

[24] S. C. Lemoult, P. F. Richardson, S. M. Roberts, J. Chem. Soc. Perkin Trans 1, (1995) 89-91.

[25] B. K. Pchelka, M. Gelo-Pujic, E. Guibé-Jampel, J. Chem. Soc. Perkin Trans 1, (1998) 2625-2628.

[26] G. Mehta, H. S. P. Rao, Synth. Commun. 15 (1985), 991-1000.

[27] F. Coehlo, M. B. M. de Azevedo, R. Boschiero, P. Resende, Synth. Commun. 27 (1997) 2455-2465.

[28] B. M. Trost, J. Xie, J. Am. Chem. Soc. 130 (2008) 6231-6242.

[29] For the application of hydrogen peroxide in non enzymatic Baeyer-Villiger reactions see: M. Uyanik, K. Ishihara, ACS Catal. 3 (2013) 513-520.

[30] For a recent paper related to improvements in CAL-B stability towards hydrogen peroxide using immobilization techniques: K. Hernández, R. Fernández-Lafuente, Process. Biochem. 46 (2011) 873-878.

[31] V. Gotor-Fernández, E. Busto, V. Gotor, Adv. Synth. Catal. 348 (2006) 797-812.