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Lipase catalysed kinetic resolutions of 3-aryl alkanoic acids

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ABSTRACT

Hydrolase catalysed kinetic resolutions leading to a series of 3-aryl alkanoic acids (⩾94% ee) are described. Hydrolysis of the ethyl esters with a series of hydrolases was undertaken to identify biocatalysts that yield the corresponding acids with excellent enantiopurity in each case. Steric and electronic effects on the efficiency and enantioselectivity of the biocatalytic transformation were also explored.

1. Introduction

Lipases (triacylglycerol ester hydrolases, EC 3.1.1.3) are ubiquitous enzymes belonging to the family of serine hydrolases and are unequivocally, the most utilized enzymes in biocatalysis, providing one of the most advantageous and versatile biocatalytic methods in asymmetric synthesis.[1–11] Hydrolases are excellent biocatalysts, combining wide substrate specificity with high regio- and enantioselectivity enabling the resolution of organic substrates with efficient efficiency and selectivity.[12–14] Further advantages are that hydrolases do not require the use of labile co-factors, can be recycled, can be used in both free or immobilised form and are effective under mild, environmentally benign conditions and are biodegradable. These attributes make these catalysts especially attractive for the pharmaceutical and agrochemical industries, where the interest in enantiomerically pure and specifically functionalized compounds is growing continuously.[2,4–11]

Hydrolase catalysed kinetic bioresolution is widely used to provide highly enantioenriched chiral carboxylic acids, which are valuable synthetic intermediates for the preparation of a variety of compounds of biological interest. There have been many reports on the successful resolution of 2-aryl or 2-aryloxy-propionic acids; the former are non-steroidal anti-inflammatory drugs and the latter an important class of herbicides.[15–20] Successful hydrolase catalysed resolution of alkanoic acids, with remotely located methyl-branching has been reported,[21,22] however, the literature has revealed only limited success on the hydrolase mediated kinetic resolution of 3-aryl alkanoic acids. Enantiomerically pure 3-aryl alkanoic acids are used as chiral synthons in the asymmetric synthesis of antibacterial agents, such as (−)-malyngolide, a naturally occurring δ-lactone of algae origin,[23] curcumene and curcuphenol, biological important bisabolene sesquiterpenes[24] and in the synthesis of amino acids β-methyl phenylalanaine[25] and β-methyl tyrosine.[26] Within our own group, 3-aryl alkanoic acids are utilised in the synthesis of diazoketone derivatives, which in turn have been employed in Buchner cyclization reactions demonstrating excellent diastereoselectivity.[27,28] This key transformation is currently under investigation in the efficient asymmetric synthesis of the bicyclo[5.3.0]decane skeleton, characteristic of the aucane sesquiterpenoids.

Hydrolase catalysed non-aqueous enantioselective esterification of acids (±)-**1a**, (±)-**1b**, (±)-**1c** and (±)-**1d**, (Fig. 1) has previously been reported, however substrate acids (±)-**1a** and (±)-**1b** were esterified with a modest to slow rate resulting in very low *E* values (*E* <2) and no ester was observed under any conditions for acids (±)-**1c** and (±)-**1d**.[29] Traditional aqueous *Burkholderia cepacia* catalysed ester hydrolysis has been described for the resolution of 3-phenylbutanoic acid (±)-**1a** (*E* >50), however this work has not been expanded to include acid substrates (±)-**1b**, (±)-**1c** and (±)-**1d**, encompassing more sterically hindered substituents at the stereogenic centre.[30]

Herein, we wished to explore a wide range of hydrolases to establish if it was possible to generate the carboxylic acid (±)-**1a–i** in enantiopure form through kinetic bioresolution. Acids (±)-**1a–d**, were selected for investigation to determine the impact of steric effects at C3 on the efficiency of the kinetic resolution, while substrates (±)-**1e–i** were designed to explore both steric and electronic effects of substituents on the aromatic ring on the biotransformations. In contrast to the limited reported success in enantioselective esterification, this study focussed on enantioslective hydrolysis and indeed it was found that through an appropriate choice of biocatalyst and reaction conditions, each of the carboxylic acids could be obtained in highly enantioenriched form.

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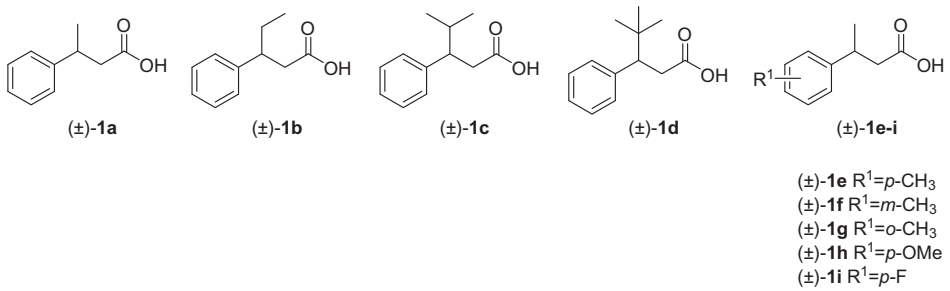


Figure 1.

2. Results and discussion

2.1. Synthesis of ethyl 3-aryl alkanoates

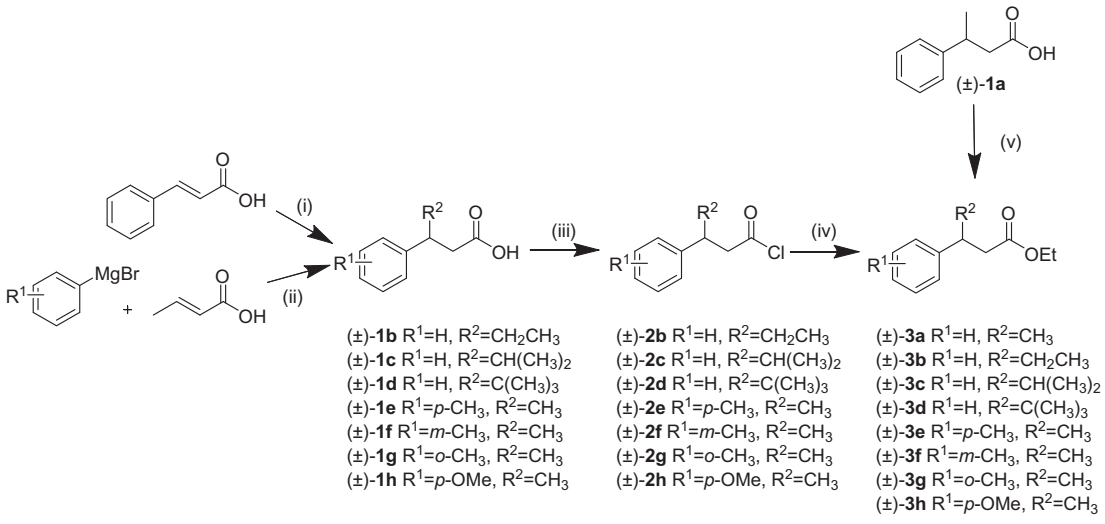
Racemic ester (±)-**3a** was obtained via a simple Fischer esterification reaction from commercial 3-phenylbutanoic acid (±)-**1a** (Scheme 1). The 3-aryl alkanoic esters (±)-**3b**–**h** were synthesized in a three step synthesis. Acids (±)-**1b**–**d** were synthesised by the conjugate addition of an alkyl Grignard to cinnamic acid, while acids (±)-**1e**–**h** were similarly prepared by the conjugate addition of the appropriate aryl Grignard to crotonic acid.[31] When the direct esterification of the crude carboxylic acid was attempted, it was found that it was simpler to obtain the ethyl esters in analytically pure form by first transforming the carboxylic acid (±)-**1b**–**h** isolated from Grignard additions directly to the analogous acid chloride, which was readily purified by vacuum distillation. Treatment of the pure acid chloride with ethanol in the presence of triethylamine led to an analytically pure ester (Scheme 1). An alternative route via a Wadsworth–Emmons reaction was employed in the synthesis of ethyl 3-(4-fluorophenyl)butanoate (±)-**3i** (Scheme 2).[32] Acids **1a**–**e** and **1h** have been previously reported in the literature in enantioenriched form and therefore the assignment of the absolute stereochemistry for each of these compounds was made by comparison of specific rotation data. Acids **1f**–**g** and **1i** have not been previously reported in enantiopure form and the absolute stereochemistry was determined in each case through crystallography studies.

With racemic samples of both the esters and acids in hand, chiral HPLC conditions were developed for each ester hydrolysis in which both enantiomers of the ester and acid could be seen on a single trace (Fig. 2). With a single injection, ready monitoring of both the efficiency and stereoselectivity of each of the hydrolase mediated transformations could be performed.

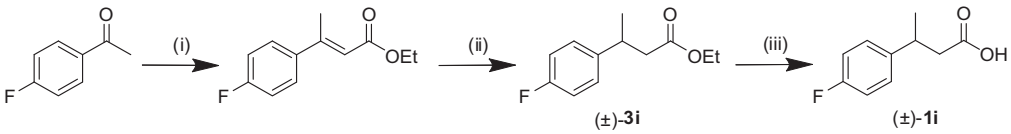
2.1.1. Hydrolase catalysed kinetic resolution of (±)-3-phenylbutanoic acid (±)-1a

In total, 21 lipases and 1 esterase were screened in resolving racemic 3-phenylbutanoic acid (±)-**1a**. All of the hydrolases investigated resulted in the hydrolysis of ethyl 3-phenylbutanoate (±)-**3a** to a certain extent and the screening results are summarised in Table 1. *Pseudomonas cepacia*, *Alcaligenes spp*. and *Pseudomonas fluorescens*, entries 6, 11 and 15, respectively, exhibited excellent enantioselection in the hydrolysis of substrate (±)-**3a**. *Burholderia cepacia* hydrolysis of the methyl ester of (±)-**1a** had previously been reported (E >50) providing access to the acid (*S*)-**1a** with 89% ee.[30] Herein, *Alcaligenes* spp. yielded the acid (*S*)-**1a** with excellent improved enantioselectivity of 97% ee (E >200) by hydrolysis of the corresponding ethyl ester (±)-**3a**. Unreacted (*R*)-**3a** was recovered in 98% ee providing access to both enantiomeric series in a single resolution.

From Table 1, it is evident that certain hydrolases preferentially hydrolysed the (*R*)-enantiomer of substrate (±)-**3a**, providing access to the complementary enantiomer (*R*)-**1a**. *Candida antarctica* lipase B hydrolysis of (±)-**3a** had previously been reported to yield (*R*)-**1a**, (E = 9),[33] while in this work, (Table 1, entry 16) it is clear that the (*R*) ester is selectively hydrolysed albeit with very low enantioselectivity. The less common pathway involving selective hydrolysis of the (*R*)-ester has been successfully extended in this



Scheme 1. Synthesis of ethyl 3-aryl alkanoate (±)-**3a**–**h**. Reagents: (i) R^2MgX, Et_2O, (±)-**1b**–**d**; (ii) Et_2O, (±)-**1e**–**h**; (iii) $SOCl_2$; (iv) Et_3N, EtOH, CH_2Cl_2; (v) EtOH, cat. H_2SO_4, (±)-**1a**.



Scheme 2. Synthesis of ethyl 3-(4-fluorophenyl)butanoate (±)-**3i** and ethyl 3-(4-fluorophenyl)butanoic acid (±)-**1i**. Reagents: (i) $(C_2H_5O)_2P(O)CH_2CO_2Et$, NaH, THF; (ii) H_2, Pd/C, EtOH; (iii) NaOH.[32]

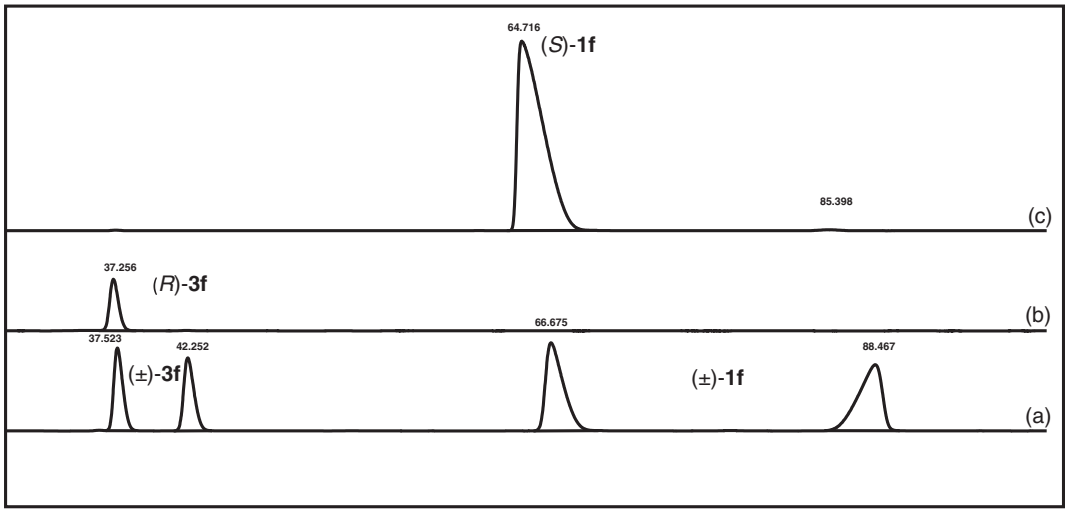
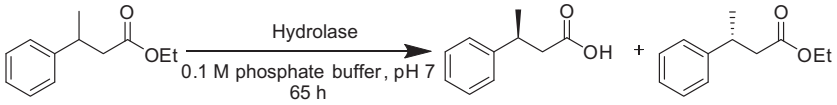


Figure 2. An overlay of HPLC traces of; (a) a racemic mixture of ethyl 3-(3-methylphenyl)butanoic acid (±)-**1f** and ethyl 3-(3-methylphenyl)butanoate (±)-**3f**; (b) enantiopure ethyl 3-(3-methylphenyl)butanoate (*R*)-**3f** and (c) enantiopure 3-(3-methylphenyl)butanoic acid (*S*)-**1f**. See Table 7 for chiral HPLC conditions.

Table 1
Hydrolase-mediated hydrolysis of (±)-ethyl 3-phenylbutanaoate (±)-**3a**



Entry	Enzyme	Temperature (°C)	ee[a] (%)		Conversion[b] (%)	*E* value[b]
			Ester **3a**	Acid **1a**		
1	*Candida cyclindracea* C1	30	11 (*S*)	58 (*R*)	16	4.2
2	*Candida cyclindracea* C2	Ambient	25 (*S*)	59 (*R*)	30	4.9
3	*Rhizopus oryzae*	30	—	—	<10[c]	—
4	*Achromobacter* spp.	30	11 (*R*)	90 (*S*)	11	21
5	*Alcaligenes* spp. 1	30	27 (*R*)	95 (*S*)	22	50
6	*Pseudomonas cepacia* P1	30	99 (*R*)	94 (*S*)	51	170
7	*Pseudomonas stutzeri*	Ambient	14 (*R*)	61 (*S*)	19	4.7
8	*Rhizopus* spp.	Ambient	—	—	<10[c]	—
9	*Rhizopus niveus*	Ambient	—	—	<10[c]	—
10	*Aspergillus niger*	Ambient	—	—	<10[c]	—
11	*Alcaligenes* spp. 2	Ambient	98 (*R*)	97 (*S*)	50	>200
12	*Pseudomonas cepacia* P2	Ambient	96 (*R*)	75 (*S*)	56	26
13	*Mucor javanicus*	Ambient	—	—	<10[c]	—
14	*Penicillium camembertii*	Ambient	—	—	<10[c]	—
15	*Pseudomonas fluorescens*	30	99 (*R*)	94 (*S*)	51	170
16	*Candida antarctica* lipase B	Ambient	13 (*S*)	0 (*R*)	51	1.4
17	*Mucor meihei*	Ambient	3 (*S*)	24 (*R*)	11	1.7
18	*Candida antarctica* lipase A	Ambient	10 (*R*)	68 (*S*)	13	5.8
19	*Candida antarctica* lipase B (immob)	Ambient	70 (*S*)	5 (*R*)	93	1.8
20	*Porcine pancrease* Type II	Ambient	15 (*R*)	93 (*S*)	14	31
21	*Porcine pancrease* Grade II	30	35 (*R*)	95 (*S*)	27	54
22	*Pig liver esterase*	Ambient	—	—	<10[c]	—

[a] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 95:5, flow rate 0.5 mL/min, 0 °C, λ = 209.8 nm].
[b] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3a** (ee_s) and product acid **1a** (ee_p).[34]
[c] Estimated by chiral HPLC.

study to include the hydrolases *Candida Cyclindracea* and *Mucor meihei*.[33]

To demonstrate the practical viability of this process, *Pseudomonas fluorescens* was selected as the most appropriate hydrolase for preparative scale use. The conversion and enantiopurity of the esters and acids were analysed utilising chiral HPLC and after 64 h, 50% conversion was achieved with 98% ee_{acid} and 99% ee_{ester} corresponding to an *E* value >200. Enantiopure samples of (*S*)-**1a** and (*R*)-**3a** were isolated by chromatography in 34% and 35% yield, respectively. Column chromatography proved more effective than acid-base extraction for recovery of the ester and acid in this instance.

In practise, while the use of *Candida antarctica* lipase B, *Candida Cyclindracea* and *Mucor meihei* all lead selectively to (*R*)-**1a**, access to the enantiopure (*R*)-**1a** is more effectively achieved via isolation of enantiopure (*R*)-**3a** using *Pseudomonas cepacia*, *Alcaligenes* spp. and *Pseudomonas fluorescens*, followed by saponification.

2.1.2. Hydrolase catalysed kinetic resolution of (±)-3-phenylpentanoic acid (±)-1b

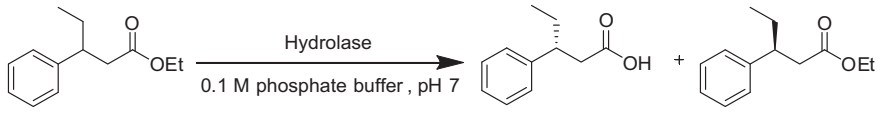
The enzymatic hydrolysis of (±)-ethyl 3-phenylpentanoate (±)-**3b** proved to be significantly less facile than with (±)-**3a**. Of the 16 hydrolases screened, many displayed no catalytic activity for the hydrolysis of the substrate ethyl 3-phenylpentanoate (±)-**3b**. Thus replacement of the methyl with the slightly larger ethyl moiety at the stereogenic centre C3 resulted in a very significant reduction of enzymatic activity. Just six of the hydrolases resulted in conversion as summarised in Table 2.

Significantly the biocatalysts which had yielded the most effective kinetic bioresolution with (±)-**3a** were ineffective for the enzymatic hydrolysis of (±)-**3b**. For the six biocatalysts which resulted in ester hydrolysis, the enantioselectivities were modest at best (Table 2). Interestingly with entries 2, 3 and 5, the poor enantioselectivity is associated with a lack of discrimination of the enantiomers by the biocatalyst with conversions ⩾78% in each case, while the same biocatalysts with (±)-**3a** gave very limited reaction. The immobilised *Candida antarctica* lipase B provided the best results in this instance ($E = 25$), this is in direct contrast to the limited reaction of (±)-**3a** with *Candida antarctica* lipase B (immob).

The direction of enantioselection in the hydrolysis of (±)-**3b** was consistent with that observed in the reactions of (±)-**3a** with *Candida antarctica* lipase B, *Candida antarctica* lipase B (immob) and *Pig liver esterase* providing the (*R*) acid selectively. Based on the initial promising results with *Candida antarctica* lipase B (immob), the reaction conditions for the hydrolysis were varied to determine if the outcome could be optimised.

Temperature control in hydrolase-catalysed resolutions has been explored due to its simplicity and reliability for enhancement of enantioselectivity, albeit at the expense of longer reaction times.[7,35,36] Thus *Candida antarctica* lipase B (immob) resolution of (±)-**3b**, was performed at 4 °C, (Table 2, entry 7) resulting in a decrease in conversion even with an extended incubation period.

Table 2
Hydrolase-mediated hydrolysis of (±)-ethyl 3-phenylpentanoate (±)-**3b**



(±)-**3b** (*R*)-**1b** (*S*)-**3b**

Entry	Enzyme[a]	Time (h)	Temperature (°C)	ee[b] (%)		Conversion[c] (%)	*E* value[c]
				Ester **3b**	Acid **1b**		
1	*Candida cyclindracea* C2	120	Ambient	—	—	<10[d]	—
2	*Candida antarctica* lipase B	65	Ambient	80 (*S*)	23 (*R*)	78	3.4
3	*Mucor meihei*	67	Ambient	—[e]	—[e]	100	—[e]
4	*Candida antarctica* lipase A	67	Ambient	5 (*R*)	44 (*S*)	10	2.7
5	*Pig liver esterase*	65	Ambient	87 (*S*)	15 (*R*)	85	3.1
6	*Candida antarctica*	65	Ambient	85 (*S*)	81 (*R*)	51	25
7	Lipase B (immob)	72	4	62 (*S*)	86 (*R*)	42	24

[a] The following hydrolases gave no conversion *Pseudomonas cepacia* P2, *Pseudomonas cepacia* P1, *Alcaligenes* spp. 2, *Pseudomonas fluorescens*, *Porcine Pancrease* Type II, *Pseudomonas stutzeri*, *Rhizopus niveus*, *Candida cyclindracea* C1, *Aspergillus niger* and *Mucor javanicus*.
[b] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 99:1, flow rate 0.5 mL/min, 0 °C, $\lambda = 209.8$ nm].
[c] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3b** (ee_s) and product acid **1b** (ee_p).[34]
[d] Estimated by chiral HPLC.
[e] Reaction went to 100% completion and no enantioselectivity observed.

Table 3
Investigation of co-solvent effect on *Candida antarctica* lipase B (immob) hydrolysis of (±)-ethyl 3-phenylpentanoate (±)-**3b**

Entry	Co-solvent	Time (h)	Temperature (°C)	ee[b] (%)		Conversion[c] (%)	*E* value[c]
				Ester (*S*)-**3b**	Acid (*R*)-**1b**		
1	DMSO	64	Ambient	93	81	53	31
2	Acetonitrile[a]	64	Ambient	28	93	23	36
3	Acetone[a]	64	Ambient	25	94	21	41
4	THF	64	Ambient	6	88	6	16
5	Dioxane	64	Ambient	72	92[d]	44	51
6	TBME[a]	64	Ambient	24	57	30	4.6

[a] HPLC grade.
[b] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 99:1, flow rate 0.5 mL/min, 0 °C, $\lambda = 209.8$ nm].
[c] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3b** (ee_s) and product acid **1b** (ee_p).[34]
[d] On one occasion, the enantiomeric excess isolated from dioxane of (*R*)-**1b** was 97% ee.

No significant increase in enantioselection was observed, therefore this approach was not pursued further.

The utilisation of organic co-solvents has been well established to increase the enantioselectivity of hydrolase catalysed resolution of an extensive range of compounds.[10,37,38] Screening reactions were therefore performed to assess the effect of a series of co-solvents (at 17% v/v) on the *Candida antarctica* lipase B (immob) resolution of (±)-**3b** (Table 3). The majority of co-solvents investigated resulted in a decrease in the rate of hydrolysis, but notably, with the exception of TBME, resulted in an equivalent or an improved enantiopurity of (*R*)-**1b**. The utilisation of acetone as an additive, (Table 3, entry 3) resulted in the recovery of (*R*)-**1b** with 94% ee and $E = 41$ while with dioxane (Table 3, entry 5) $E = 51$. Thus the hydrolase catalysed resolution can be effective as a route to enantioenriched (*R*)-**1b** provided the biocatalyst and reaction conditions are chosen carefully. The only prior report of hydrolase catalysed esterification of **1b** describes very low activity and enantioselectivity ($E < 2$).[29] Furthermore, acid (*S*)-**1b** has been resolved using amidase biocatalysis and again the enantiopurity was lower (88% ee).[39]

2.1.3. Hydrolase catalysed kinetic resolution of (±)-4-methyl-3-phenylpentanoic acid (±)-1c

Due to the decrease in biocatalytic activity on increasing the C3 substituent from methyl to ethyl it was anticipated that enzymatic hydrolysis to form (*S*)-**1c** and (*S*)-**1d** with the more sterically demanding *i*-propyl and *t*-butyl substituents would prove extremely challenging. Of the 19 hydrolases screened, many displayed no hydrolytic activity towards (±)-**3c** and hydrolysis failed to occur even at elevated temperature and extended reaction periods. Significantly, the hydrolases that were identified to hydrolyse (±)-**3b** were found to hydrolyse (±)-**3c** as depicted in Table 4, thus confirming that these biocatalysts can accommodate the increased steric demand in the C3 region of the enzyme pocket.

Interestingly the extent of reaction in entries 1, 2 and 4, Table 4, is decreased somewhat relatively to those seen with (±)-**3b** in Table 2, resulting in improved enantiopurities of the recovered acid (*S*)-**1c**. Thus discrimination between the phenyl and *i*-propyl groups in the active site of the enzymes is improved compared to that seen in (±)-**3b** where discrimination between the ethyl and phenyl substituents is quite poor. While the (*R*) and (*S*) labels in the acid (*S*)-**1c** are switched relative to acids (*R*)-**1a** and (*R*)-**1b** the sense of enantioselection is identical in hydrolysis of the ethyl and *i*-propyl esters (±)-**3b** and (±)-**3c** with the (*S*)-enantiomer isolated using enzymes *Candida antarctica* lipase B, *Mucor meihei* and *Candida antarctica* lipase B (immob). In this instance (*S*)-**1c** was obtained in 99% ee using *Candida antartica* lipase B; hence no further optimisation was required.

Once again, the careful control of the reaction conditions and the selection of biocatalyst led to efficient bioresolution of (*S*)-**1c**, which is in contrast to the literature report which states that it was not possible to resolve this acid using hydrolase catalysis.[29]

A solvent screen involving dioxane, acetone and TBME was conducted for *Candida antarctica* lipase A and *Candida antarctica* lipase B resolution of (±)-**3c** to investigate the effect on enantiomeric excess, but resulted in a significant reduction in activity and therefore was no longer pursued.

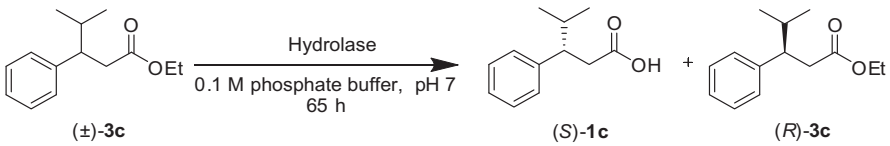
2.1.4. Hydrolase catalysed kinetic resolution of (±)-4,4-dimethyl-3-phenylpentanoic acid (±)-1d

The hydrolase catalysed resolution of ethyl 4,4-dimethyl-3-phenylpentanoate (±)-**3d** was achieved using the same biocatalysts, which catalysed the reaction of (±)-**3b** and (±)-**3c**, albeit at much lower extent of conversion, presumably due to the increased steric demand of the C3 substituent. However, the overall trends are very similar for (±)-**3b**, (±)-**3c** and (±)-**3d** with the optimum results being achieved with the immobilised or free *Candida antarctica* Lipase B, (Fig. 3). While the extent of the reaction at room temperature was extremely limited, increasing the temperature improved the conversion, for example see entries 2 and 6, Table 5. The direction of enantioselectivities is consistent with earlier observations for *Candida antarctica* lipase B (immob) and *Candida antarctica* lipase A. Interestingly the sense of enantioselection in the *Pig liver esterase* hydrolase, resulting in the selective hydrolysis of the (*R*)-enantiomer, is opposite to that seen in the hydrolysis of the corresponding ethyl derivative (±)-**3b**. Thus, in the ethyl derivative (±)-**3b**, *Candida antarctica* lipase A provided the (*S*)-enantiomer of the acid selectively while *Pig liver esterase* provides the (*R*)-enantiomer selectively, whereas the *t*-butyl derivative *Pig liver esterase* displays the same direction of enantioselection as *Candida antarctica* lipase A.

With both the free and immobilised *Candida antarctica* lipase B, while the extent of the hydrolyse is limited the enantioselectivity is excellent, with the acid (*S*)-**1d** isolated in enantiopure form. Increasing the temperature improved the conversion, thereby resulting in an increased enantiopurity of the unreacted ester (*R*)-**3d**.

It is evident that once the alkyl group at the C3 stereogenic centre increases in size greater than a methyl substituent, a large decrease in the efficiency of the hydrolysis and thereby the kinetic

Table 4
Hydrolase-mediated hydrolysis of (±)-ethyl 4-methyl-3-phenylpentanoate (±)-**3c**



(±)-**3c** (*S*)-**1c** (*R*)-**3c**

Entry	Enzyme[a]	ee[b] (%)		Conversion[c] (%)	*E* value[c]
		Ester **3c**	Acid **1c**		
1	*Candida antarctica* lipase B	12 (*R*)	99 (*S*)	11	>200
2	*Mucor meihei*	61 (*R*)	23 (*S*)	73	2.7
3	*Candida antarctica* lipase A	10 (*S*)	64 (*R*)	14	5
4	*Candida antarctica* lipase B (immob)	33 (*R*)	97 (*S*)	25	90
5	*Pig liver esterase*	—[d]	—[d]	100	—[d]

[a] The following hydrolases gave no conversion *Pseudomonas cepacia* P2, *Pseudomonas cepacia* P1, *Alcaligenes* spp. 1, *Penicillium camembertii*, *Pseudomonas fluorescens*, *Porcine Pancrease* Type II, *Candida cyclindracea* C2, *Rhizopus* spp., *Pseudomonas stutzeri*, *Rhizopus niveus*, *Candida cyclindracea* C1, *Aspergillus niger*, *Alcaligenes* spp. 2 and *Mucor javanicus*.
[b] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 98:2, flow rate 0.5 mL/min, 0 °C, $\lambda = 209.8$ nm].
[c] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3c** (ee_s) and product acid **1c** (ee_p).[34]
[d] Reaction went to 100% completion, no enantioselectivity observed.

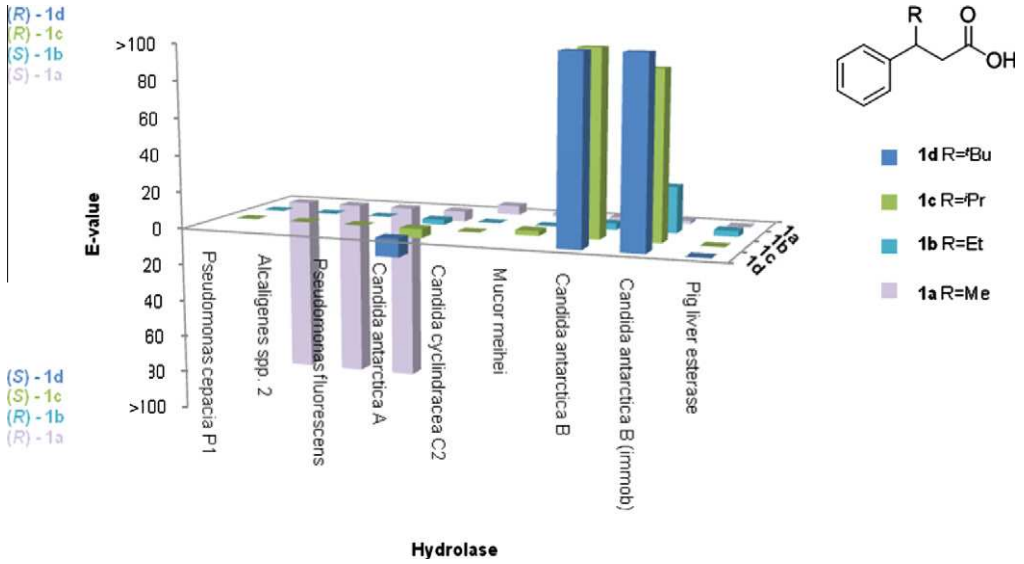
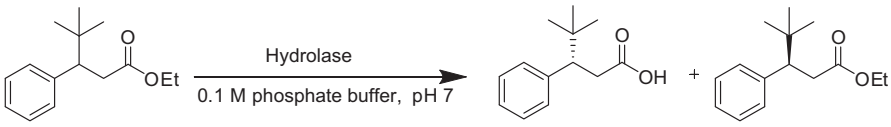


Figure 3. Graph of enantiomeric ratio (*E*) versus hydrolase; kinetic bioresolutions for **1a–d** performed under standard aqueous conditions.

Table 5
Hydrolase-mediated hydrolysis of (±)-ethyl 4,4-dimethyl-3-phenylpentanoate (±)-**3d** at variable temperature



(±)-**3d** (*S*)-**1d** (*R*)-**3d**

Entry	Enzyme[a]	Temperature °C	ee[e] (%)		Conversion[f] (%)	*E* value[f]
			Ester **3d**	Acid **1d**		
1	*Candida antarctica* lipase B	Ambient[b]	2 (*R*)	⩾99[h] (*S*)	2	>200
2		35–40 °C[c]	23 (*R*)	⩾99[h] (*S*)	19	>200
3	*Candida antarctica* lipase A	Ambient[b]	3 (*S*)	73 (*R*)	4	6.6
4		35–40 °C[d]	7 (*S*)	81 (*R*)	8	10
5	*Candida antarctica* lipase B (immob)	Ambient[b]	1 (*R*)	⩾99[h] (*S*)	1	>200
6		35–40 °C[c]	30 (*R*)	98 (*S*)	23	132
7	*Pig liver esterase*	Ambient[b]	32 (*S*)	34 (*R*)	48	2.7
8		35–40 °C[c]	—[g]	—[g]	100	—[g]

[a] The following hydrolases gave no conversion; *Pseudomonas cepacia* P1, *Rhizopus niveus*, *Pseudomonas fluorescens*, *Candida cyclindracea* C1, *Pseudomonas cepacia* P2 and *Porcine Pancrease* Type II.
[b] Time for ester hydrolysis was 66 h.
[c] Time for ester hydrolysis was 64.5 h at 35 °C temperature increased to 40 °C for the final 24 h.
[d] Time for ester hydrolysis was 72 h at 35 °C temperature increased to 40 °C for the final 24 h.
[e] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 96:4, flow rate 0.25 mL/min, 20 °C, λ = 209.8 nm].
[f] Conversion and the enantiomeric ratio *E* was calculated from enantiomeric excess of substrate ester **3d** (ee_s) and product acid **1d** (ee_p).[34]
[g] Reaction went to 100% completion, no enantioselectivity observed.
[h] When the second enantiomer was not observed, the enantiomeric excess can be stated as ⩾99% ee.

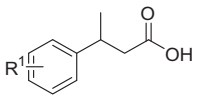
bioresolution with regards to the enantiopurity of the ester is observed. Despite the steric hindrance within the active site, 3-aryl alkanoic carboxylic acids **1a–d** can be obtained through optimisation of the reaction conditions with excellent enantioselectivity. Acid (*S*)-**1a** was obtained in 98% ee, through *Pseudomonas fluorescens* catalysed hydrolysis of (±)-**3a**, while acids (*R*)-**1b**, (*S*)-**1c** and (*S*)-**1d** were obtained in ⩾94% ee via immobilised or free *Candida antarctica* lipase B catalysed kinetic bioresolution (Fig. 3).

It is noteworthy that *Candida antarctica* lipase A provides a viable route to the complementary enantiomers (*S*)-**1b** and (*R*)-**1c–d** and overcomes the limitation of the modest enantiomeric excess of the esters achieved in the resolutions using the free and immobilised *Candida antarctica* lipase B. In addition, *Candida antarctica* lipase A has a unique ability to accept very bulky, highly sterically hindered substrates and this correlated with the observations herein whereby the enantiopurity of the acid obtained via *Candida antartica* lipase A catalysed resolution improved as the size of the alkyl substituent at C3 increased, the highest enantiopurity obtained being of (*R*)-**1d** at 81% ee (Table 5, entry 4).[40,41]

2.1.5. Hydrolase catalysed kinetic resolution of substituted phenyl butanoic acids (±)-1e–i

A series of substituted phenyl butanoic acids were selected to study the impact of the substituents on the aryl ring on the efficiency of the kinetic bioresolution process. The substrates selected were *ortho*-, *meta*- and *para*-tolylbutanoic acid and *para*-methoxy, *para*-fluoro-phenyl butanoic acids in order to study the electronic effect in addition to the impact of the position of substitution (Fig. 4).

The results of the enzymatic screens are summarised in Tables 6-10. In each case, effective kinetic bioresolution was achieved with *Pseudomonas cepacia* P1, *Pseudomonas cepacia* P2 and



R^1 = *o*, *m*, *p*-Me
R^1 = *p*-OMe
R^1 = *p*-F

Figure 4.

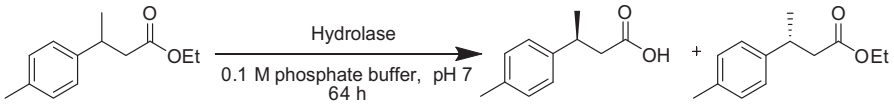
Pseudomonas fluorescens resulting in the successful hydrolysis of the *S* enantiomer with very similar outcomes to those seen with 3-phenylbutanoic acid (*S*)-**1a**, thus indicating that the aryl substituent had little impact on the enzymatic hydrolysis.

In all cases highly enantioenriched samples of the (3*S*)-acids and the (3*R*)-esters are readily obtained using the *Pseudomonas* biocatalysts, see Figure 5. 3-(4-Methylphenyl)butanoic acid (±)-**1e** had previously been resolved utilising *Pseudomonas cepacia* immobilized on ceramic particles to yield (*S*)-**1e** in 99% ee.[24] The results obtained utilising the free hydrolase (Table 6, entry 1) correlate strongly. The only significant effect of the substituent seen in this series of substituted phenyl butanoic acids was with the *para*-F substrate (±)-**3i** where the conversion is increased relative to the other substrates resulting in a slight decrease in enantiopurity of the recovered acids. The use of the *Candida cyclindracea* biocatalyst with the substituted substrates was also explored; while *Candida cyclindracea* had resulted in some hydrolysis with the parent compound (±)-**3a**, very little conversion was seen with the substituted derivatives (Fig. 5).

The use of *Candida antarctica* Lipase B (immob) with the parent substrate (±)-**1a** provided access to the opposite enantiomeric series (Table 1, entry 19), albeit with a very high extent of reaction. In general similar reaction patterns were seen with the substituted substrates resulting in recovery of the (*S*)-esters **3e**–**f** and **3h** and the (*R*)-acids **1e**–**f** and **1h**. Notably, with the *p*-Me substrate (±)-**3e** the extent of reaction was less, resulting in a decrease in the enantiopurity of the recovered ester (*S*)-**3e**, while with the *para*-F substrate both enantiomers are completely indiscriminately hydrolysed. The sense of enantioselection in *Candida antarctica* lipase B (immob) resolution of the *o*-Me substrate (±)-**3g** was the same as that seen with the *Pseudomonas* biocatalysts. This biocatalyst was the one that was able to accommodate the increased steric demand at the C3 position. The switch in enantioselection must be due to combined steric effects of the *ortho*-Me and 3-Me substituents, possibly via conformational changes, (Fig. 6).

As summarised in Table 11, nine of the hydrolyses were scaled up to synthetic batches leading to isolations of acids **1a**–**i** and esters **3a**–**i** in excellent enantiopurity in most cases. It is noteworthy that

Table 6
Hydrolase-mediated hydrolysis of (±)-ethyl 3-(4-methylphenyl)butanoate (±)-**3e**

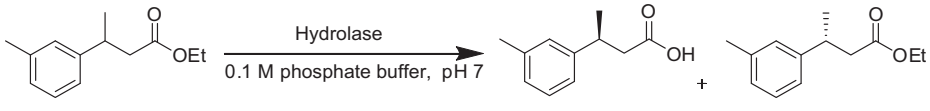


(±)-**3e** (*S*)-**1e** (*R*)-**3e**

Entry	Enzyme	Temperature (°C)	ee[a] (%)		Conversion[b] (%)	*E* value[b]
			Ester **3e**	Acid **1e**		
1	*Pseudomonas cepacia* P1	30	98 (*R*)	99 (*S*)	50	>200
2	*Pseudomonas cepacia* P2	30	99 (*R*)	96 (*S*)	51	>200
3	*Pseudomonas fluorescens*	30	⩾99[d] (*R*)	95 (*S*)	51	>200
4	*Candida cyclindracea*	30	—[c]	—[c]	0	—[c]
5	*Candida antarctica* lipase A	30	5 (*R*)	68 (*S*)	7	5.5
6	*Candida antarctica* lipase B (immob)	30	6 (*S*)	5 (*R*)	55	1.2

[a] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 99.5:0.5, flow rate 0.5 mL/min, 0 °C, λ = 211 nm].
[b] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3e** (ee_s) and product acid **1e** (ee_p).[34]
[c] Reaction failed to proceed; no enantioselectivity observed.
[d] When the second enantiomer was not observed, the enantiomeric excess could be stated as ⩾99% ee.

Table 7
Hydrolase-mediated hydrolysis of (±)-ethyl 3-(3-methylphenyl)butanoate (±)-**3f**

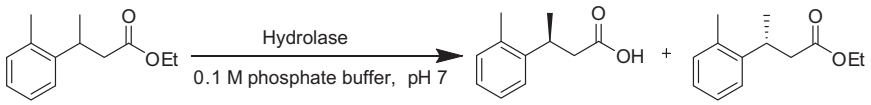


(±)-**3f** (*S*)-**1f** (*R*)-**3f**

Entry	Enzyme	Temperature (°C)	ee[a,b] (%)		Conversion[c] (%)	*E* value[c]
			Ester **3f**	Acid **1f**		
1	*Pseudomonas cepacia* P1	30	88 (*R*)	96 (*S*)	48	143
2	*Pseudomonas cepacia* P2	30	⩾99[e] (*R*)	76 (*S*)	57	52
3	*Pseudomonas fluorescens*	30	96 (*R*)	97 (*S*)	50	>200
4	*Candida cyclindracea*	30	—[d]	—[d]	0	—[d]
5	*Candida antarctica* Lipase B (immob)	30	⩾99[e] (*S*)	7 (*R*)	93	4.7

[a] Time for ester hydrolysis was 65 h with the exception of *Candida cyclindracea* catalysed hydrolysis which was 64 h.
[b] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 98:2, flow rate 0.25 mL/min, 0 °C, λ = 209.8 nm].
[c] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3f** (ee_s) and product acid **1f** (ee_p).[34]
[d] Reaction failed to proceed, no enantioselectivity observed.
[e] When the second enantiomer was not observed, the enantiomeric excess could be stated as ⩾99% ee.

Table 8
Hydrolase-mediated hydrolysis of (±)-ethyl 3-(2-methylphenyl)butanoate (±)-**3g**

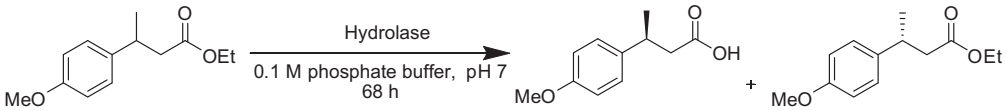


(±)-**3g** (*S*)-**1g** (*R*)-**3g**

Entry	Enzyme source	Temperature (°C)	ee[a,b] (%)		Conversion[c] (%)	E value[c]
			Ester **3g**	Acid **1g**		
1	*Pseudomonas cepacia* P1	30	⩾99[e] (*R*)	99 (*S*)	50	>200
2	*Pseudomonas cepacia* P2	30	⩾99[e] (*R*)	80 (*S*)	56	65
3	*Pseudomonas fluorescens*	30	⩾99[e] (*R*)	⩾99[e] (*S*)	50	>200
4	*Candida cyclindracea*	30	—[d]	—[d]	0	—[d]
5	*Candida antarctica* Lipase B (immob)	30	90 (*R*)	46 (*S*)	66	7.7

[a] Time for ester hydrolysis was 67 h with the exception of *Pseudomonas fluorescens* catalysed hydrolysis which was 64 h.
[b] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 94:6, flow rate 0.25 mL/min, 0 °C, λ = 209.8 nm].
[c] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3g** (ee_s) and product acid **1g** (ee_p).[34]
[d] Reaction failed to proceed, no enantioselectivity observed.
[e] When the second enantiomer was not observed, the enantiomeric excess could be stated as ⩾99% ee.

Table 9
Hydrolase-mediated hydrolysis of (±)-ethyl 3-(4-methoxyphenyl)butanoate (±)-**3h**

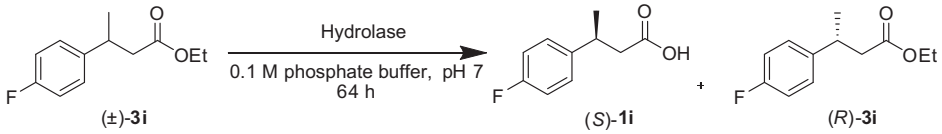


(±)-**3h** (*S*)-**1h** (*R*)-**3h**

Entry	Enzyme	Temperature (°C)	ee[a] (%)		Conversion[b] (%)	*E* value[b]
			Ester **3h**	Acid **1h**		
1	*Pseudomonas cepacia* P1	30	98 (*R*)	86 (*S*)	53	60
2	*Pseudomonas cepacia* P2	30	99 (*R*)	88 (*S*)	53	81
3	*Pseudomonas fluorescens*	30	⩾99[d] (*R*)	97 (*S*)	51	>200
4	*Candida Antarctica* Lipase A	30	4 (*R*)	48 (*S*)	8	3
5	*Candida cyclindracea*	30	—	—	<10[c]	—
6	*Candida antarctica* Lipase B (immob)	30	66 (*S*)	7 (*R*)	90	1.9

[a] Determined by chiral HPLC analysis [Daicel Chiralcel OJ-H, hexane/*i*-PrOH (3% trifluoroacetic acid) = 82:18, flow rate 0.25 mL/min, 0 °C, λ = 216.9 nm].
[b] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3h** (ee_s) and product acid **1h** (ee_p).[34]
[c] Estimated by chiral HPLC.
[d] When the second enantiomer was not observed, the enantiomeric excess could be stated as ⩾99% ee.

Table 10
Hydrolase-mediated hydrolysis of (±)-ethyl 3-(4-fluorophenyl)butanoate (±)-**3i**



(±)-**3i** (*S*)-**1i** (*R*)-**3i**

Entry	Enzyme	Temperature (°C)	ee[a] (%)		Conversion[b] (%)	*E* value[b]
			Ester **3i**	Acid **1i**		
1	*Pseudomonas cepacia* P1	30	⩾99[d] (*R*)	84 (*S*)	54	59
2	*Pseudomonas cepacia* P2	30	⩾99[d] (*R*)	69 (*S*)	84	27
3	*Pseudomonas fluorescens*	30	⩾99[d] (*R*)	94 (*S*)	62	170
4	*Candida cyclindracea*	30	3 (*S*)	25 (*R*)	11	1.7
5	*Candida antarctica* Lipase B (immob)	30	—[c]	—[c]	100	—[c]

[a] Determined by chiral HPLC analysis [Daicel Chiralcel AS-H column, Step gradient: 0 °C, λ = 256 nm, hexane/*i*-PrOH (3% trifluoroacetic acid), 0–30 min; 99.7:0.3, flow rate 1 mL/min. 31 min; 94:6, flow rate 0.25 mL/min].
[b] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3i** (ee_s) and product acid **1i** (ee_p).[34]
[c] Reaction went to 100% completion, no enantioselectivity observed.
[d] When the second enantiomer is not observed enantiomeric excess is stated as ⩾99% ee.

on scale-up, the efficiencies and selectivities mirrored quite closely the outcomes seen in the analytical scale reactions summarised in Tables 1–10. Notably with the *para*-F series, acid (*S*)-**1i** was recovered in excellent enantiopurity in contrast to the small scale reaction (Table 10, entry 3). With the 3-aryl butanoic acids, the products of the biocatalysis were readily isolated by extraction with ethyl acetate followed by chromatographic separation of the acids and esters. With the bulkier 3-alkyl substituents, chromatography

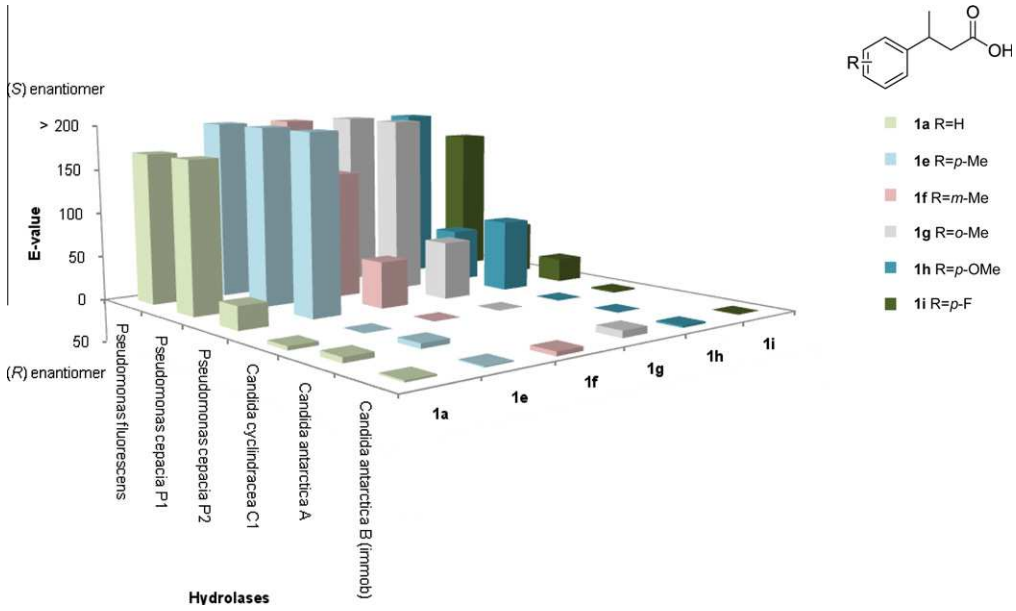


Figure 5. Graph of enantiomeric ratio (*E*) versus hydrolase—kinetic bioresolutions for **1a** and **1e–i** performed under standard aqueous conditions.

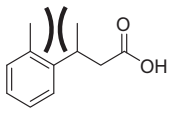


Figure 6.

was less effective. In practice the ester was recovered first by heptane extraction of the biotransformation mixture, then subsequent acidification and extraction with ethyl acetate provided the acids (*R*)-**1b** and (*S*)-**1c–d**. Each of the products were characterised by ^{1}H NMR and chiral HPLC.

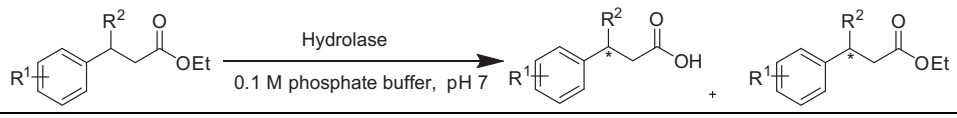
3. Conclusion

Herein a series of 3-aryl alkanoic acids (±)-**1a–i** were successfully resolved with enantiopurity ⩾94% ee via hydrolase catalysed kinetic hydrolysis of the corresponding ethyl esters. It was apparent upon resolving acids (±)-**1a–d** that a large reduction in reaction rate and enantioselectivity was observed once the moiety at the C3 stereogenic centre increased in size greater than a methyl. Despite this, the highest obtained enantiopurities of the hydrolase catalysed bioresolutions of 3-aryl alkanoic acids (±)-**1a–d** are reported through optimisation of reaction conditions and a viable route to both enantiomers has been identified. Furthermore, substituents on the phenyl ring, acids (±)-**1e–i** were determined to have limited effect on the excellent enantioselectivities attainable indicating that these hydrolases can tolerate increased steric demand in the aryl group more readily than in the 3-alkyl group. Significantly, nine of these experiments were conducted on a synthetic scale leading to the isolation of acids **1a–i** and esters **3a–i** with excellent enantiopurity being achieved in most cases.

4. Experimental

All solvents were distilled prior to use as follows: dichloromethane was distilled from phosphorus pentoxide and ethyl acetate

Table 11
Synthetic scales of hydrolase-mediated hydrolysis of (±)-**3a–i**



Entry	Ester substrate			Enzyme	ee[a] (%)		Conversion[b] (%)	*E* value[b]
		R^1	R^2		Ester	Acid		
1	**3a**	H	CH_3	*Pseudomonas fluorescens*	99 (*R*)-**3a**	98 (*S*)-**1a**	50	>200
2	**3b**	H	CH_2CH_3	*Candida antarctica* lipase B (immob)[c]	65 (*S*)-**3b**	90 (*R*)-**1b**	42	37
3	**3c**	H	$CH(CH_3)_2$	*Candida antarctica* lipase B (immob)	26 (*R*)-**3c**	98 (*S*)-**1c**	21	127
4	**3d**	H	$C(CH_3)_3$	*Candida antarctica* lipase B (immob)	12 (*R*)-**3d**	99 (*S*)-**1d**	11	>200
5	**3e**	*p*-CH_3	CH_3	*Pseudomonas cepacia* P1	97 (*R*)-**3e**	⩾99[d] (*S*)-**1e**	49	>200
6	**3f**	*m*-CH_3	CH_3	*Pseudomonas fluorescens*	94 (*R*)-**3f**	⩾99[d] (*S*)-**1f**	49	>200
7	**3g**	*o*-CH_3	CH_3	*Pseudomonas fluorescens*	98 (*R*)-**3g**	⩾99[d] (*S*)-**1g**	50	>200
8	**3h**	*p*-OCH_3	CH_3	*Pseudomonas fluorescens*	99 (*R*)-**3h**	97 (*S*)-**1h**	51	>200
9	**3i**	*p*-F	CH_3	*Pseudomonas fluorescens*	⩾99[d] (*R*)-**3i**	97 (*S*)-**3i**	51	>200

[a] For chiral HPLC conditions see details on relevant Tables 1–10.
[b] Conversion and the enantiomeric ratio *E* was calculated from the enantiomeric excess of substrate ester **3a–i** (ee_s) and product acid **1a–i** (ee_p).[34]
[c] 17% v/v dioxane co-solvent was added, see Section 4 for further information.
[d] When the second enantiomer was not observed, the enantiomeric excess could be stated as ⩾99% ee.

was distilled from potassium carbonate. Ethanol was distilled from magnesium in the presence of iodine and stored over 3 Å molecular sieves. Hexane was distilled prior to use. Tetrahydrofuran was distilled from sodium and benzophenone. Molecular sieves were activated by heating at 150 °C overnight. Organic phases were dried using anhydrous magnesium sulphate. Infrared spectra were recorded as thin films on sodium chloride plates for oils or as potassium bromide (KBr) discs for solids on a Perkin–Elmer Paragon 1000 FT-IR spectrometer.

^{1}H (300 MHz) and ^{13}C (75.5 MHz) NMR spectra were recorded on a Bruker Avance 300 MHz NMR spectrometer. ^{1}H (400 MHz) NMR spectra were recorded on a Bruker Avance 400 MHz NMR spectrometer. All spectra were recorded at room temperature (~20 °C) in deuterated chloroform ($CDCl_3$) unless otherwise stated using tetramethylsilane (TMS) as an internal standard. Chemical shifts (δ_H & δ_C) are reported in parts per million (ppm) relative to TMS and coupling constants are expressed in Hertz (Hz).

Low resolution mass spectra were recorded on a Waters Quattro Micro triple quadrupole spectrometer in electrospray ionization (ESI) mode using 50% water/acetonitrile containing 0.1% formic acid as eluant; samples were made up in acetonitrile. High resolution mass spectra (HRMS) were recorded on a Waters LCT premier Time of Flight spectrometer in electrospray ionization (ESI) mode using 50% water/acetonitrile containing 0.1% formic acid as eluant; samples were made up in acetonitrile.

Elemental analysis was performed by the Microanalysis Laboratory, National University of Ireland, Cork, using Perkin–Elmer 240 and Exeter Analytical CE440 elemental analysers. Melting points were carried out on a uni-melt Thomas Hoover Capillary melting point apparatus and are uncorrected. Wet flash chromatography was performed using Kieselgel Silica Gel 60, 0.040–0.063 mm (Merck). Thin layer chromatography (TLC) was carried out on precoated silica gel plates (Merck 60 PF_{254}). Visualisation was achieved by UV (254 nm) light detection and bromocresol green staining.

Optical rotations were measured on a Perkin–Elmer 141 polarimeter at 589 nm in a 10 cm cell; concentrations (c) are expressed in g/100 mL. $[\alpha]_D^{20}$ is the specific rotation of a compound and is expressed in units of 10^{-1} deg cm^2 g^{-1}. The hydrolases used for these biotransformations were obtained from Almac Sciences. All reagents are analytical grade and purchased from Sigma Aldrich chemical company. All enzymatic reactions were performed on a VWR Incubating Mini Shaker 4450. The enantiomeric purity of acids **1a–h** and esters **3a–h** were determined by chiral HPLC analysis on a Chiralcel OJ-H column (5 × 250 mm); the enantiomeric purity of acid **1i** and ester **3i** were determined on a Chiralcel AS-H column (5 × 250 mm) purchased from Daicel Chemical Industries, Japan. Mobile phase, flow rate, detection wavelength and temperature are stated in the appropriate Table 1–10. HPLC analysis was performed on a Waters alliance 2690 separations module with a PDA detector. All solvents employed were of HPLC grade. Bulb to bulb distillations were carried out on an Aldrich Kugelrohr apparatus and the oven temperature is given as the boiling point of the substrate. (±)-3-(*p*-Fluorophenyl)butanoic acid (±)-**1i** and (±)-ethyl 3-(*p*-fluorophenyl)butanoate (±)-**3i** were prepared according to the procedure described by Speranza.[32]

4.1. Synthesis of carboxylic acids

4.1.1. (±)-3-Phenylpentanoic acid (±)-1b[28,31,42]

Ethyl magnesium bromide was freshly prepared from magnesium (2.85 g, 117 mmol) and iodine (catalytic amount) in diethyl ether (30 mL) and ethyl bromide (8.7 mL, 117 mmol) in diethyl ether (30 mL) at 0 °C under nitrogen and the mixture was stirred for 0.5 h at 0 °C. Cinnamic acid (5.00 g, 33.75 mmol) was added portionwise while stirring at 0 °C, then the reaction mixture was heated at reflux for 3 h. The reaction mixture was subsequently cooled to room temperature and carefully poured onto aqueous hydrochloric acid (10%, ~100 mL) and ice (~65 g). The layers were separated and the aqueous layer was washed with diethyl ether (3 × 50 mL). The combined organic layer was washed with hydrochloric acid (10%, 50 mL), water (50 mL), brine (50 mL), dried, filtered and concentrated under reduced pressure to give the crude acid (±)-**1b** (5.54 g, 92%) as an orange oil which was used without further purification. ν_{max}/cm^{-1} (film) 2965 (OH), 1708 (CO), 1603, 1495, 1454; δ_H (400 MHz) 0.79 [3H, t, J 7.4, C(5)H_3], 1.46–1.83 [2H, m, C(4)H_2], 2.60 [1H, dd, A of ABX, J_{AB} 15.6, J_{AX} 7.9, one of C(2)H_2], 2.68 [1H, dd, B of ABX, J_{AB} 15.6, J_{BX} 7.1, one of C(2)H_2], 2.89–3.08 [1H, m, X of ABX, C(3)H], 7.09–7.38 (5H, m, ArH).

4.2. Preparation of the analytically pure acid by basic hydrolysis of the corresponding acid chloride

Aqueous potassium hydroxide (20%, 35 ml) was added to a sample of 3-phenylpentanoyl chloride (±)-**2b** (0.5 g, 2.6 mmol) under nitrogen. The reaction mixture was heated at reflux and stirred at reflux overnight. The reaction mixture was then cooled to room temperature and acidified to pH 1 with aqueous hydrochloric acid (10%), which resulted in a white precipitate. The suspension was then extracted with dichloromethane (3 × 50 ml), and the combined organic layers where washed with brine (100 ml), dried, filtered and concentrated under reduced pressure to give the acid (±)-**1b** (0.428 g, 92%) as a cream solid, mp 59–62 °C (Lit.,[31] 60–61 °C) and with spectroscopic characteristics identical to those described above.

4.2.1. (±)-4-Methyl-3-phenylpentanoic acid (±)-1c[28,42]

This was prepared following the procedure described for (±)-**1b** from isopropyl magnesium bromide [freshly prepared from magnesium (2.70 g, 111 mmol) and iodine (catalytic amount) in diethyl ether (30 mL), and isopropyl bromide (11.25 mL, 120 mmol) in diethyl ether (30 mL)] and cinnamic acid (5.00 g, 33.75 mmol) to give the crude acid (±)-**1c** (5.38 g, 83%) as an orange oil, which was used without further purification. ν_{max}/cm^{-1} (film) 2963 (OH), 1709 (CO), 1602, 1495, 1454; δ_H (400 MHz) 0.74, 0.92 [2 × 3H, 2 × d, J 6.7, J 6.7, C(4)HCH_3, C(5)H_3], 1.79–1.91 [1H, m, C(4)H], 2.60 [1H, dd, A of ABX, J_{AB} 15.5, J_{AX} 9.5, one of C(2)H_2], 2.72–2.92 [2H, m, BX of ABX, one of C(2)H_2, C(3)H], 7.10–7.28 (5H, m, ArH).

4.3. Preparation of the analytically pure acid by basic hydrolysis of the corresponding acid chloride

This was prepared following the procedure described for (±)-**1b**, from aqueous potassium hydroxide (20%, 50 mL) and 4-methyl-3-phenylpentanoyl chloride (±)-**2c** (1.00 g, 4.75 mmol) to give the acid (±)-**1c** (900 mg, 99%) as a cream, white solid, mp 48–50 °C (Lit.,[28] 46–48 °C) and with spectroscopic characteristics identical to those described above.

4.3.1. (±)-4,4-Dimethyl-3-phenylpentanoic acid (±)-1d[28,31]

This was prepared following the procedure described for (±)-**1b**, from *t*-butyl magnesium chloride (2 M in diethyl ether, 106 mL, 212 mmol) and cinnamic acid (7.85 g, 52.98 mmol) to give the crude acid (±)-**1d** (8.63 g, 79%) as a yellow solid, which was used without further purification. ν_{max}/cm^{-1} (KBr) 2955 (OH), 1726 (CO), 1638, 1453; δ_H (400 MHz) 0.87 [9H, s, C(CH_3)$_3$], 2.73 [1H, dd, A of ABX, J_{AB} 15.8, J_{AX} 10.8, one of C(2)H_2], 2.81 [1H, dd, B of ABX, J_{AB} 15.8, J_{BX} 4.5, one of C(2)H_2], 2.93 [1H, dd, X of ABX, J_{AX} 10.8, J_{BX} 4.5, C(3)H], 7.07–7.33 (5H, m, ArH).

4.4. Preparation of the analytically pure acid by basic hydrolysis of the corresponding acid chloride

This was prepared following the procedure described for (±)-**1b**, from aqueous potassium hydroxide (20%, 8 mL) and 4,4-dimethyl-3-phenylpentanoyl chloride (±)-**2d** (214 mg, 0.95 mmol) to give the acid (±)-**1d** (153 mg, 78%) as a white solid, mp 108–110 °C (Lit.,[28] 114–116 °C) and with spectroscopic characteristics identical to those described above.

4.4.1. (±)-3-(4-Methylphenyl)butanoic acid (±)-1e[42]

This was prepared from *p*-tolyl magnesium bromide [freshly prepared from magnesium (10 g, 411 mmol) and iodine (catalytic amount) in diethyl ether (80 mL), and 4-bromotoluene (51.6 mL, 419 mmol) in diethyl ether (60 mL)] and crotonic acid (12.00 g, 139 mmol). The reaction mixture, containing product (±)-**1e** and the Wurtz coupling product, was acidified to pH 2 and the aqueous layer washed with diethyl ether (2 × 100 mL). The combined diethyl ether extracts were washed with sodium hydroxide (20%, 2 × 100 mL) and the aqueous layer was acidified to pH 1 with conc. hydrochloric acid and extracted with diethyl ether (3 × 100 mL). The organic layer was dried, filtered and concentrated under reduced pressure to give the crude acid (±)-**1e** as a viscous yellow oil (21.19 g, 86%) which was used without further purification. υ_{max}/cm^{-1} (film) 2926 (OH), 1704 (CO), 1515, 1455, 1416; δ_H (300 MHz) 1.30 [3H, d, *J* 7.0, C(4)H_3], 2.31 [3H, s, C(4′)CH_3], 2.55 [1H, dd, A of ABX, J_{AB} 15.5, J_{AX} 8.2, one of C(2)H_2], 2.65 [1H, dd, B of ABX, J_{AB} 15.5, J_{BX} 6.9, one of C(2)H_2], 3.18–3.30 [1H, m, X of ABX, C(3)H], 7.11 (4H, s, ArH).

4.5. Preparation of the analytically pure acid by basic hydrolysis of the corresponding acid chloride

This was prepared following the procedure described for (±)-**1b**, from aqueous potassium hydroxide (20%, 8 mL) and 3-(4-methylphenyl)butanoyl acid chloride (±)-**2e** (200 mg, 1.02 mmol) to give the acid (±)-**1e** (152 mg, 83%) as a white solid, mp 91–92 °C (Lit.,[43] 87–88 °C) and with spectroscopic characteristics identical to those described above.

4.5.1. (±)-3-(3-Methylphenyl)butanoic acid (±)-1f[44]

This was prepared following the procedure described for (±)-**1e** from 3-tolyl magnesium bromide [freshly prepared from magnesium (4.24 g, 174 mmol) and iodine (catalytic amount) in diethyl ether (40 mL), and 3-bromotoluene (21 mL, 173 mmol) in diethyl ether (40 mL)] and crotonic acid (5.00 g, 58 mmol) to give the crude acid (±)-**1f** (8.55 g, 83%) as an orange oil, which was used without further purification. υ_{max}/cm^{-1} (film) 2971 (OH), 1718 (CO), 1608, 1490, 1455; δ_H (300 MHz) 1.30 [3H, d, *J* 7.0, C(4)H_3], 2.33 [3H, s, C(3′)CH_3], 2.55 [1H, dd, A of ABX, J_{AB} 15.5, J_{AX} 8.4, one of C(2)H_2], 2.66 [1H, dd, B of ABX, J_{AB} 15.5, J_{BX} 6.7, one of C(2)H_2], 3.14–3.31 [1H, m, X of ABX, C(3)H], 6.91–7.22 (4H, m, ArH).

4.6. Preparation of the analytically pure acid by basic hydrolysis of the corresponding acid chloride

This was prepared following the procedure described for (±)-**1b**, from aqueous potassium hydroxide (20%, 150 mL) and 3-(3-methylphenyl)butanoyl chloride (±)-**2f** (4.59 g, 23.36 mmol) to give acid (±)-**1f** (2.87 g, 69%) as a clear oil and with spectroscopic characteristics identical to those described above.

4.6.1. (±)-3-(2-Methylphenyl)butanoic acid (±)-1g[45]

This was prepared following the procedure described for (±)-**1e** from 2-tolyl magnesium bromide [freshly prepared from magnesium (4.22 g, 174 mmol) and iodine (catalytic amount) in diethyl ether (40 mL), and 2-bromotoluene (21 mL, 175 mmol) in diethyl ether (40 mL)] and crotonic acid (5.00 g, 58 mmol) to give the crude acid (±)-**1g** (8.21 g, 79%) as an orange oil, which was used without further purification. υ_{max}/cm^{-1} (film) 2973 (OH), 1712 (CO), 1605, 1492, 1460; δ_H (400 MHz) 1.27 [3H, d, *J* 6.9, C(4)H_3], 2.36 [3H, s, C(2′)CH_3], 2.55 [1H, dd, A of ABX, J_{AB} 15.7, J_{AX} 8.6, one of C(2)H_2], 2.67 [1H, dd, B of ABX, J_{AB} 15.6, J_{BX} 6.3, one of C(2)H_2], 3.45–3.58 [1H, m, X of ABX, C(3)H], 7.06–7.27 (4H, m, ArH).

4.7. Preparation of the analytically pure acid by basic hydrolysis of the corresponding acid chloride

This was prepared following the procedure described for (±)-**1b**, from aqueous potassium hydroxide (20%, 100 mL) and 3-(2-methylphenyl)butanoyl chloride (±)-**2g** (3.10 g, 15.75 mmol) to give the acid (±)-**1g** (2.20 g, 78%) as a yellow solid, mp 46–48 °C (Lit.,[45] 46–47 °C) and with spectroscopic characteristics identical to those described above.

4.7.1. (±)-2-(4-Methoxyphenyl)butanoic acid (±)-1h[46,47]

This was prepared following the procedure described for (±)-**1e** from *p*-methoxyphenyl magnesium bromide [freshly prepared from magnesium (10.22 g, 420 mmol) and iodine (catalytic amount) in diethyl ether (80 mL), and 4-bromoanisole (52 mL, 415 mmol) in diethyl ether (100 mL)] and crotonic acid (12.00 g, 139 mmol) to give the crude acid (±)-**1h** (19.17 g, 71%) as a yellow oil, which was used without further purification. υ_{max}/cm^{-1} (film) 2963 (OH), 1711 (CO), 1611, 1511, 1458; δ_H (400 MHz) 1.29 [3H, d, *J* 7.0, C(4)H_3], 2.54 [1H, dd, A of ABX, J_{AB} 15.4, J_{AX} 8.1, one of C(2)H_2], 2.62 [1H, dd, B of ABX, J_{AB} 15.4, J_{BX} 7.0, one of C(2)H_2], 3.17–3.29 [1H, m, X of ABX, C(3)H], 3.77 (3H, s, OCH_3), 6.79–6.88 [2H, m, C(3′)H, C(5′)H], 7.11–7.16 [2H, m, C(2′)H, C(6′)H].

4.8. Preparation of the analytically pure acid by basic hydrolysis of the corresponding acid chloride

This was prepared following the procedure described for (±)-**1b**, from aqueous potassium hydroxide (20%, 8 mL) and 3-(4-methoxyphenyl)butanoyl chloride (±)-**2h** (200 mg, 0.94 mmol) to give the acid (±)-**1h** (114 mg, 62%) as a cream solid, mp 66–68 °C (Lit.,[46] 67–69 °C) and with spectroscopic characteristics identical to those described above.

4.9. Synthesis of acid chlorides

The acid chlorides were generally prepared from the crude acids. The yield given below is the yield of acid chloride over two steps calculated from the unsaturated precursor for the acid.

4.9.1. (±)-3-Phenylpentanoyl chloride (±)-2b[28]

3-Phenylpentanoic acid (±)-**1b** (5.01 g, 28.13 mmol) in thionyl chloride (16 mL, 225 mmol) was heated at reflux for 3 h while stirring under nitrogen. Excess thionyl chloride was evaporated under reduced pressure to give the acid chloride (±)-**2b** as a brown oil. Purification by vacuum distillation gave the acid chloride (±)-**2b** (2.07 g, 31%) as a bright yellow oil; bp 72–76 °C at 0.09 mmHg (Lit.,[28] 113–115 °C at 0.5 mmHg); υ_{max}/cm^{-1} (film) 1799 (CO), 1604, 1495, 1454; δ_H (400 MHz) 0.80 [3H, t, *J* 7.4, C(5)H_3], 1.58–1.80 [2H, m, C(4)H_2], 3.04–3.23 [3H, m, C(2)H_2, C(3)H], 7.16–7.34 (5H, m, ArH).

4.9.2. (±)-4-Methyl-3-phenylpentanoyl chloride (±)-2c[28]

This was prepared following the procedure described for (±)-**2b**, from crude 4-methyl-3-phenylpentanoic acid (±)-**1c** (5.28 g,

27.46 mmol) and thionyl chloride (16 mL, 220 mmol) to give the crude acid chloride (±)-**2c** as a brown oil. Purification by distillation gave the acid chloride (±)-**2c** (2.54 g, 36%) as a clear oil; bp 78–80 °C at 0.15 mmHg (Lit.,[28] 90–94 °C at 0.08 mmHg); ν_{max}/cm^{-1} (film) 1799 (CO), 1602, 1495, 1454; δ_H (400 MHz) 0.76, 0.97 [2 × CH_3, 2 × d, *J* 6.7, *J* 6.7, C(4)HCH_3, C(5)H_3], 1.82–1.94 [1H, m, C(4)H], 2.92–2.98 [1H, m, X of ABX, C(3)H], 3.18 [1H, dd, A of ABX, J_{AB} 16.4, J_{AX} 9.7, one of C(2)H_2], 3.34 [1H, dd, B of ABX, J_{AB} 16.4, J_{AX} 5.2, one of C(2)H_2], 7.09–7.35 (5H, m, ArH).

4.9.3. (±)-4,4-Dimethyl-3-phenylpentanoyl chloride (±)-2d[28]

This was prepared following the procedure described for (±)-**2b**, from crude 4,4-dimethyl-3-phenylpentanoic acid (±)-**1d** (8.63 g 42 mmol) and thionyl chloride (24 mL, 335 mmol) to give the crude acid chloride (±)-**2d** as a brown oil. Purification by distillation gave the acid chloride (±)-**2d** (5.04 g, 54%) as a bright yellow solid, bp 84–86 °C at 0.12 mmHg (Lit.,[28] 123–125 °C at 0.1 mmHg); ν_{max}/cm^{-1} (KBr) 1793 (CO), 1601, 1494, 1453; δ_H (400 MHz) 0.91 [9H, s, C(CH_3)$_3$], 3.04 [1H, dd, X of ABX, *J* 8.9, 6.1, C(3)H], 3.26–3.39 [2H, m, C(2)H_2], 7.14–7.31 (5H, m, ArH).

4.9.4. (±)-3-(4-Methylphenyl)butanoyl chloride (±)-2e[48]

This was prepared following the procedure described for (±)-**2b**, from crude 3-(4-methylphenyl)butanoic acid (±)-**1e** (21.19 g, 119 mmol) and thionyl chloride (86 mL, 1190 mmol) to give the crude acid chloride (±)-**2e** as a black oil. Purification by distillation gave the acid chloride (±)-**2e** (12.09 g, 44%) as a dark orange oil, bp 66–68 °C at 0.2 mmHg (Lit.,[48] 127 °C at 0.20 mmHg); ν_{max}/cm^{-1} (film) 1800 (CO), 1649, 1516, 1455; δ_H (300 MHz) 1.32 [3H, d, *J* 7.0, C(4)H_3], 2.32 [3H, s, C(4′)CH_3], 3.07 [1H, dd, A of ABX, J_{AB} 16.4, J_{AX} 7.9, one of C(2)H_2], 3.17 [1H, dd, B of ABX, J_{AB} 16.4, J_{BX} 6.4, one of C(2)H_2], 3.27–3.38 [1H, m, X of ABX, C(3)H], 7.04–7.21 (4H, m, ArH).

4.9.5. (±)-3-(3-Methylphenyl)butanoyl chloride (±)-2f

This was prepared following the procedure described for (±)-**2b**, from crude 3-(3-methylphenyl)butanoic acid (±)-**1f** (8.55 g, 47.97 mmol) and thionyl chloride (28 mL, 384 mmol) to give the crude acid chloride (±)-**2f** as a black oil. Purification by distillation gave the acid chloride (±)-**2f** (4.59 g, 40%) as a bright yellow oil, bp 77–80 °C at 0.2 mmHg; ν_{max}/cm^{-1} (film) 1800 (CO), 1608, 1491, 1456; δ_H (300 MHz) 1.32 [3H, d, *J* 6.9, C(4)H_3], 2.33 [3H, s, C(3′)CH_3], 3.06 [1H, dd, A of ABX, J_{AB} 16.5, J_{AX} 8.0, one of C(2)H_2], 3.17 [1H, dd, B of ABX, J_{AB} 16.5, J_{BX} 6.5, one of C(2)H_2], 3.25–3.36 [1H, m, X of ABX, C(3)H], 6.98–7.05 [3H, m, C(4′)H, C(5′)H, C(6′)H, ArH], 7.17–7.22 [1H, m, C(2′)H, ArH].

4.9.6. (±)-3-(2-Methylphenyl)butanoyl chloride (±)-2g

This was prepared following the procedure described for (±)-**2b**, from crude 3-(2-methylphenyl)butanoic acid (±)-**1g** (8.21 g, 46 mmol) and thionyl chloride (27 mL, 368 mmol) to give the crude acid chloride (±)-**2g** as a black oil. Purification by distillation gave the acid chloride (±)-**2g** (4.68 g, 41%) as a bright yellow oil, bp 64–66 °C at 0.09 mmHg; ν_{max}/cm^{-1} (film) 1801 (CO), 1605, 1492, 1459; δ_H (400 MHz) 1.27 [3H, d, *J* 7.0, C(4)H_3], 2.35 [3H, s, C(2′)CH_3], 3.03 [1H, dd, A of ABX, J_{AB} 16.6, J_{AX} 8.2, one of C(2)H_2], 3.16 [1H, dd, B of ABX, J_{AB} 16.6, J_{BX} 6.3, one of C(2)H_2], 3.54–3.63 [1H, m, X of ABX, C(3)H], 7.07–7.28 (4H, m, ArH).

4.9.7. (±)-3-(4-Methoxyphenyl)butanoyl chloride (±)-2h[46]

This was prepared following the procedure described for (±)-**2b**, from crude 3-(4-methoxyphenyl)butanoic acid (±)-**1h** (19.17 g, 99 mmol), thionyl chloride (57 mL, 790 mmol) to give the crude acid chloride (±)-**2h** as a black oil. Purification by distillation gave the acid chloride (±)-**2h** (8.69 g, 29%) as a orange brown oil, bp 102–110 °C at 0.35 mmHg (Lit.,[46] 100 °C at 0.5 mmHg); ν_{max}/cm^{-1} (film) 1790 (CO), 1614, 1515, 1463; δ_H (400 MHz) 1.32 [3H, d, *J* 7.0, C(4)H_3], 3.07 [1H, dd, A of ABX, J_{AB} 16.4, J_{AX} 7.8, one of C(2)H_2], 3.15 [1H, dd, B of ABX, J_{AB} 16.4, J_{BX} 6.8, one of C(2)H_2], 3.27–3.36 [1H, m, X of ABX, C(3)H], 3.78 (3H, s, OCH_3), 6.84–6.87 [2H, m, C(3′)H, C(5′)H], 7.11–7.15 [2H, m, C(2′)H, C(6′)H].

4.10. Synthesis of ethyl esters

4.10.1. (±)-Ethyl 3-phenylbutanoate (±)-3a[49]

Sulfuric acid (1.0 mL, 18.76 mmol) was added to a solution of 3-phenylbutanoic acid (±)-**1a** (998 mg, 6.08 mmol) in absolute ethanol (20 mL) and refluxed overnight. Excess ethanol was evaporated under reduced pressure. The crude product was dissolved in dichloromethane (45 mL) and washed with water (2 × 45 mL), sat. $NaHCO_3$ (2 × 45 mL), brine (50 mL), dried, filtered and concentrated under reduced pressure to give the crude ester (±)-**3a** (972 mg) as a clear oil. Purification by chromatography on silica gel using hexane/ethyl acetate 60/40 as eluant gave the pure ester (±)-**3a** (909 mg, 78%) as a clear oil; ν_{max}/cm^{-1} (film) 2969 (CH), 1733 (CO), 1604, 1495, 1454 (Ar), 1174 (C–O); δ_H (400 MHz) 1.17 (3H, t, *J* 7.1, OCH_2CH_3), 1.30 [3H, d, *J* 7.0, C(4)H_3], 2.53 [1H, dd, A of ABX, J_{AB} 15.0, J_{AX} 8.2, one of C(2)H_2], 2.61 [1H, dd, B of ABX, J_{AB} 15.0, J_{BX} 7.0, one of C(2)H_2], 3.23–3.32 [1H, sym. m, X of ABX, C(3)H], 4.08 (2H, q, *J* 7.1, O$CH_2$$CH_3$), 7.17–7.34 (5H, m, ArH).

4.10.2. (±)-Ethyl 3-phenylpentanoate (±)-3b[50]

3-Phenylpentanoyl chloride (±)-**2b** (1.96 g, 9.96 mmol) in dichloromethane (10 mL) was added dropwise to a solution of triethylamine (1.7 mL, 11.9 mmol), dichloromethane (10 mL) and distilled ethanol (1.45 mL, 24.9 mmol), at 0 °C. The reaction mixture was stirred at room temperature overnight. The crude product was dissolved in dichloromethane (30 mL) and washed with water (2 × 50 mL), HCl (10%, 2 × 50 mL), brine (100 mL) dried, filtered and concentrated under reduced pressure to give the crude ester (±)-**3b** (1.64 g) as a deep orange oil. Purification by chromatography on silica gel using hexane/ether 97:3 as eluant gave the pure ester (±)-**3b** (1.49 g, 72%) as a clear oil; ν_{max}/cm^{-1} (film) 2967 (CH), 1735 (CO), 1603, 1493, 1454 (Ar), 1167 (C–O); δ_H (400 MHz) 0.79 [3H, t, *J* 7.4, C(5)H_3], 1.13 (3H, t, *J* 7.1, OCH_2CH_3), 1.55–1.76 [2H, m, C(4)H_2], 2.55 [1H, dd, A of ABX, J_{AB} 15.0, J_{AX} 8.2, one of C(2)H_2], 2.63 [1H, dd, B of ABX, J_{AB} 15.0, J_{BX} 7.1, one of C(2)H_2], 2.96–3.04 [1H, m, X of ABX, C(3)H], 4.02 (2H, q, *J* 7.1, O$CH_2$$CH_3$), 7.17–7.30 (5H, m, ArH).

4.10.3. (±)-Ethyl 4-methyl-3-phenylpentanoate (±)-3c[51]

This was prepared following the procedure described for (±)-**3b**, from 4-methyl-3-phenylpentanoyl chloride (±)-**2c** (2.43 g, 11.52 mmol), triethylamine (1.9 mL, 13.82 mmol), dichloromethane (10 mL) and distilled ethanol (1.7 mL, 28.79 mmol) to yield the crude ester (±)-**3c** (2.02 g) as a yellow orange oil. Purification by chromatography on silica gel using hexane/ether 97:3 as eluant gave the pure ester (±)-**3c** (1.6 g, 63%) as a clear oil. ν_{max}/cm^{-1} (film) 2961 (CH), 1736 (CO), 1602, 1494, 1453 (Ar), 1162 (C–O); δ_H (400 MHz) 0.75, 0.95 [2 × 3H, 2 × d, *J* 6.7, *J* 6.7, C(4)HCH_3, C(5)H_3], 1.05 (3H, t, *J* 7.1, OCH_2CH_3) 1.79–1.91 [1H, sym m, C(4)H], 2.58 [1H, dd, A of ABX, J_{AB} 14.9, J_{AX} 9.9, one of C(2)H_2], 2.77 [1H, dd, B of ABX, J_{AB} 14.9, J_{BX} 5.6, one of C(2)H_2], 2.85–2.91 [1H, m, X of ABX, C(3)H], 3.95 (2H, q, *J* 7.1, O$CH_2$$CH_3$), 7.14–7.28 (5H, m, ArH).

4.10.4. (±)-Ethyl 4,4-dimethyl-3-phenylpentanoate (±)-3d[52]

This was prepared following the procedure described for (±)-**3b**, from 4,4-dimethyl-3-phenylpentanoyl chloride (±)-**2d** (5.04 g, 22.4 mmol), triethylamine (3.8 mL, 26.9 mmol), dichloromethane (30 mL) and distilled ethanol (3.3 mL, 56.1 mmol) to yield the crude ester (±)-**3d** (3.81 g) as a bright yellow oil. Purification by

chromatography on silica gel using hexane/ether 97:3 as eluant gave the pure ester (±)-**3d** (2.94 g, 56%) as a pale yellow oil. υ_{max}/cm^{-1} (film) 2965 (CH), 1737 (CO), 1602, 1454 (Ar), 1152 (C–O); δ_H (400 MHz) 0.89 [9H, s, C(CH$_3$)$_3$], 0.99 (3H, t, *J* 7.1 OCH$_2$C*H*$_3$) 2.71 [1H, dd, A of ABX, J_{AB} 15.2, J_{AX} 10.9, one of C(2)H$_2$], 2.79 [1H, dd, B of ABX, J_{AB} 15.2, J_{BX} 5.0, one of C(2)H$_2$], 2.98 [1H, dd, X of ABX, J_{AX} 10.9, J_{BX} 5.0, C(3)H], 3.85–3.97 (2H, m, OC*H*$_2$CH$_3$), 7.13–7.26 (5H, m, ArH).

4.10.5. (±)-Ethyl 3-(4-methylphenyl)butanoate (±)-3e[24]

This was prepared following the procedure described for (±)-**3b**, from 3-(4-methylphenyl)butanoyl chloride (±)-**2e** (12.09 g, 61.47 mmol), triethylamine (10.28 mL, 73.76 mmol), dichloromethane (25 mL) and distilled ethanol (8.9 mL, 153.7 mmol) to yield the crude ester (±)-**3e** (9.41 g) as a deep orange oil. Purification by chromatography on silica gel using hexane/ether 97/3 as eluant gave the pure ester (±)-**3e** (7.84 g, 62%) as a clear oil. υ_{max}/cm^{-1} (film) 2967 (CH), 1732 (CO), 1516, 1456 (Ar), 1166 (C–O); δ_H (400 MHz) 1.19 (3H, t, *J* 7.1, OCH$_2$C*H*$_3$), 1.28 [3H, d, *J* 7.0, C(4)H$_3$], 2.32 [3H, s, C(4′)CH$_3$], 2.51 [1H, dd, A of ABX, J_{AB} 15.0, J_{AX} 8.2, one of C(2)H$_2$], 2.59 [1H, dd, B of ABX, J_{AB} 15.0, J_{BX} 7.0, one of C(2)H$_2$], 3.20–3.29 [1H, m, X of ABX, C(3)H], 4.07 (2H, q, *J* 7.2, OC*H*$_2$CH$_3$), 7.11 (4H, s, ArH).

4.10.6. (±)-Ethyl 3-(3-methylphenyl)butanoate (±)-3f

This was prepared following the procedure described for (±)-**3b**, from 3-(3-methylphenyl)butanoyl chloride (±)-**2f** (7.32 g, 37.2 mmol), triethylamine (6.2 mL, 44.64 mmol), dichloromethane (30 mL) and distilled ethanol (5.4 mL, 92.99 mmol) to yield the crude ester (±)-**3f** (6.53 g) as a dark brown oil. Purification by chromatography on silica gel using hexane/ether 97/3 as eluant gave the pure ester (±)-**3f** (5.16 g, 67%) as a clear oil. (Found C, 75.13; H 8.77. $C_{13}H_{18}O_2$ requires C, 75.69; H, 8.80); υ_{max}/cm^{-1} (film) 2968 (CH), 1733 (CO), 1608, 1461 (Ar), 1177 (C–O); δ_H (400 MHz) 1.18 (3H, t, *J* 7.1, OCH$_2$C*H*$_3$), 1.28 [3H, d, *J* 7.0, C(4)H$_3$], 2.32 [3H, s, C(3′)CH$_3$], 2.51 [1H, dd, A of ABX, J_{AB} 15.0, J_{AX} 8.3, one of C(2)H$_2$], 2.59 [1H, dd, B of ABX, J_{AB} 15.0, J_{BX} 6.9, one of C(2)H$_2$], 3.19–3.28 [1H, m, X of ABX, C(3)H], 4.07 (2H, q, *J* 7.1, OC*H*$_2$CH$_3$), 6.97–7.05 [3H, m, C(4′)H, C(5′)H, C(6′)H, ArH], 7.13–7.19 [1H, m, C(2′)H, ArH]. δ_C (75.5 MHz) 14.2, 21.5, 21.8 [3 × CH$_3$, C(4)H$_3$, OCH$_2$*C*H$_3$, C(3′)CH$_3$], 36.5 [CH, C(3)H], 43.0 [CH$_2$, C(2)H$_2$], 60.3 [CH$_2$, O*C*H$_2$CH$_3$], 123.7, 127.1, 127.6, 128.4 (4 × CH, aromatic CH), 138.0, 145.8 (2 × C, aromatic C), 172.5 [C, C(1)]. HRMS (ES+): Exact mass calculated for $C_{13}H_{18}O_2$ [M+H]$^+$ 207.1385. Found 207.1390; *m*/*z* (ES+) 207.1 {[($C_{13}H_{18}O_2$)+H]$^+$, 57%}, 202.1 (100%), 161.1 {[($C_{11}H_{13}O$)−C_2H_5O]$^-$, 60%}, 151.0 (23%), 141.0 (7%).

4.10.7. (±)-Ethyl 3-(2-methylphenyl)butanoate (±)-3g

This was prepared following the procedure described for (±)-**3b**, from 3-(2-methylphenyl)butanoyl chloride (±)-**2g** (4.68 g, 23.79 mmol), triethylamine (4 mL, 28.54 mmol), dichloromethane (20 mL) and distilled ethanol (3.5 mL, 59.46 mmol) to yield the crude ester (±)-**3g** (2.85 g) as a yellow oil. Purification by chromatography on silica gel using hexane/ether 97:3 as eluant gave the ester (±)-**3g** (2.5 g, 67%) as a clear oil. Further purification by distillation gave the ester (±)-**3g** (2.14 g, 44%) as a clear oil, bp 96 °C at 0.06 mmHg; (Found C, 75.43; H 8.67. $C_{13}H_{18}O_2$ requires C, 75.69; H, 8.80%); υ_{max}/cm^{-1} (film) 2975 (CH), 1733 (CO), 1605, 1492, 1462 (Ar), 1175 (CO); δ_H (400 MHz) 1.17 (3H, t, *J*7.1, OCH$_2$C*H*$_3$), 1.25 [3H, d, *J* 6.9, C(4)H$_3$], 2.37 [3H, s, C(2′)CH$_3$], 2.52 [1H, dd, A of ABX, J_{AB} 15.2, J_{AX} 8.5, one of C(2)H$_2$], 2.61 [1H, dd, B of ABX, J_{AB} 15.2, J_{BX} 6.6, one of C(2)H$_2$], 3.46–3.61 [1H, m, X of ABX, C(3)H], 4.07 (2H, q, *J* 7.1, OC*H*$_2$CH$_3$), 7.07–7.19 (4H, m, ArH). δ_C (75.5 MHz) 14.2, 19.5, 21.3 [3 × CH$_3$, C(4)H$_3$, OCH$_2$*C*H$_3$, C(2′)CH$_3$], 31.5 [CH, C(3)H], 42.2 [CH$_2$, C(2)H$_2$], 60.3 [CH$_2$, O*C*H$_2$CH$_3$], 125.1, 126.1, 126.3, 130.4 (4 × CH, aromatic CH), 135.3, 143.9 (2 × C, aromatic C), 172.6 [C, C(1)]. HRMS (ES+): Exact mass calculated for $C_{13}H_{18}O_2$ [M+H]$^+$ 207.1385. Found 207.1393; *m*/*z* (ES+) 207.1 {[($C_{13}H_{18}O_2$)+H]$^+$, 71%}, 202.1 (100%), 161.1 {[($C_{11}H_{13}O$)−C_2H_5O]$^-$, 48%}, 151.0 (68%), 141.0 (24%).

4.10.8. (±)-Ethyl 3-(4-methoxyphenyl)butanoate (±)-3h[53]

This was prepared following the procedure described for (±)-**3b**, from 3-(4-methoxyphenyl)butanoyl chloride (±)-**2h** (8.49 g, 39.9 mmol), triethylamine (6.7 mL, 47.88 mmol), dichloromethane (50 mL) and distilled ethanol (5.8 mL, 99.75 mmol) to yield the crude ester (±)-**3h** (6.68 g) as an orange oil. Purification by chromatography on silica gel using hexane/ethyl acetate as eluant (gradient elution 0–10% ethyl acetate) gave the ester (±)-**3h** (5.32 g, 56%) as a clear oil. υ_{max}/cm^{-1} (film) 2966 (CH), 1732 (CO), 1613, 1513, 1461 (Ar), 1174 (CO); δ_H (400 MHz) 1.18 (3H, t, *J* 7.1, OCH$_2$C*H*$_3$), 1.27 [3H, d, *J* 7.0, C(4)H$_3$], 2.5 [1H, dd, A of ABX, J_{AB} 14.9, J_{AX} 8.0, one of C(2)H$_2$], 2.57 [1H, dd, B of ABX, J_{AB} 15.0, J_{BX} 7.2, one of C(2)H$_2$], 3.17–3.29 [1H, m, X of ABX, C(3)H], 3.77 (3H, s, OCH$_3$), 4.07 (2H, q, *J* 7.1, OC*H*$_2$CH$_3$), 6.81–6.85 [2H, m, C(3′)H, C(5′)H], 7.12–7.16 [2H, m, C(2′)H, C(6′)H].

4.11. Enzyme screening

4.11.1. General procedure for the hydrolase catalysed kinetic resolution of the 3-aryl alkanoic ethyl esters (±)-3a–i (analytical scale)

A spatula tip of enzyme (~5-10 mg) was added to the substrate (±)-**3a–i** (~50 mg) in 0.1 M phosphate buffer, pH 7 (4.5 mL). Co-solvents (17% v/v) were added as indicated in Table 3. The reaction vessel was shaken at 700–750 rpm and incubated at the appropriate temperature for the required length of time. The aqueous layer was extracted with diethyl ether (3 × 5 mL) and the combined organic extracts were filtered through Celite and concentrated under reduced pressure. The sample was analysed by ^{1}H NMR spectroscopy, reconcentrated and dissolved in a mixture of hexane/*iso*-propyl alcohol (HPLC grade) and enantioselectivity determined by chiral HPLC. The results of the screen are summarised in the appropriate Tables 1–10.

4.11.1.1. Preparative scale hydrolysis of (±)-ethyl 3-phenylbutanoate (±)-3a. *Pseudomonas fluorescens* (108 mg) was added to ethyl 3-phenylbutanoate (±)-**3a** (510 mg, 2.65 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL) and this was shaken at 750 rpm for 64 h at 30 °C. The solution was filtered through a pad of Celite and the hydrolase washed with water (2 × 20 mL) and ethyl acetate (10 × 10 mL). The layers were separated and the aqueous layer was extracted with ethyl acetate (2 × 30 mL) and then acidified with 10% HCl solution and extracted with a further (3 × 30 mL) ethyl acetate. The combined organic layers were washed with brine (1 × 100 mL) dried, filtered and concentrated under reduced pressure to produce a clear oil (395 mg). Conversion estimated at 50%.[34] Purification by column chromatography using hexane/ethyl acetate as eluant (gradient elution 10–40% ethyl acetate) gave ester (*R*)-**3a** (178 mg, 35%) as a clear oil $[\alpha]_D^{20} = -27.55$ (*c* 1.1, CHCl$_3$), 99% ee, lit[54] $[\alpha]_D^{25} = +19.0$ (*c* 1.1, CHCl$_3$), (*S*)-isomer, 90% ee and acid (*S*)-**1a** (147 mg, 34%) as a clear oil $[\alpha]_D^{20} = +27.9$ (*c* 1.0, EtOH), 98% ee, lit[55] $[\alpha]_D^{25} = +24.5$ (*c* 1.0, EtOH), 97% ee. ^{1}H NMR spectra were identical to the racemic materials previously prepared.

4.11.1.2. Preparative scale hydrolysis of (±)-ethyl 3-phenylpentanoate (±)-3b. *Candida antarctica* lipase B (immob) (410 mg) was added to ethyl 3-phenylpentanoate (±)-**3b** (408 mg, 1.98 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL) and dioxane (17% v/v, 4 mL). The reaction mixture was shaken at 750 rpm for 62 h at 30 °C, the solution was filtered through a pad of Celite and the hydrolase washed with water (2 × 20 mL) and heptane (10 × 10 mL). The

layers were separated and the aqueous layer was extracted with heptane (3 × 30 mL). The combined organic layers were washed with brine (1 × 100 mL), dried, filtered and concentrated under reduced pressure to produce the ester (*S*)-**3b** (79.2 mg, 19%) as a light yellow oil. $[\alpha]_D^{20} = +9.45$ (*c* 0.55, $CHCl_3$), 65% ee, lit[56] $[\alpha]_D^{26} = -18.3$ (*c* 1.1, $CHCl_3$), (*R*)-isomer, 97% ee. The aqueous layer was acidified with 10% HCl solution and extracted with (3 × 30 mL) ethyl acetate. The combined organic layers were washed with brine (1 × 100 mL), dried, filtered and concentrated under reduced pressure to produce the acid (*R*)-**1b** (77.6 mg, 22%) as a yellow oil. $[\alpha]_D^{20} = -33.7$ (*c* 1.37, C_6H_6), 90% ee, lit[39] $[\alpha]_D^{25} = +42.3$ (*c* 8.0, C_6H_6), (*S*)-isomer, 83% ee. Conversion estimated at 42%.[34] ^{1}H NMR spectra were identical to the racemic materials previously prepared.

4.11.1.3. Preparative scale hydrolysis of (±)-ethyl 4-methyl-3-phenylpentanoate (±)-3c. This was prepared following the procedure described for (±)-**3b** from *Candida antarctica* lipase B (immob) (426 mg) and ethyl 4-methyl-3-phenylpentanoate (±)-**3c** (428 mg, 1.94 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL). The reaction mixture was shaken at 750 rpm for 63 h at 30 °C to produce the ester (*R*)-**3c** (107 mg, 25%) as a clear oil $[\alpha]_D^{20} = +7.05$ (*c* 1.0, $CHCl_3$), 26% ee, lit[56] $[\alpha]_D^{26} = -25.4$ (*c* 1.0, $CHCl_3$), (*S*)-isomer, 98% ee and the acid (*S*)-**1c** (88 mg, 24%) as a clear oil $[\alpha]_D^{20} = -24.35$ (*c* 0.655, $CHCl_3$), 98% ee, lit[57] $[\alpha]_D^{23} = +28.1$ (*c* 1.855, $CHCl_3$), (*R*)-isomer, 96% ee. Conversion estimated at 21%.[34] ^{1}H NMR spectra were identical to the racemic materials previously prepared.

4.11.1.4. Preparative scale hydrolysis of (±)-ethyl 4,4-dimethyl-3-phenylpentanoate (±)-3d. This was prepared following the procedure described for (±)-**3b** from *Candida antarctica* lipase B (immob) (200 mg) and ethyl 4,4-dimethyl-3-phenylpentanoate (±)-**3d** (200 mg, 0.85 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL). The reaction mixture was shaken at 750 rpm for ~65 h at 35 °C and at 40 °C for the final 24 h to produce the ester (*R*)-**3d** (79 mg, 39%) as a clear oil. $[\alpha]_D^{20} = +8.0$ (*c* 1.0, $CHCl_3$), 12% ee and the acid (*S*)-**1d** (23 mg, 13%) as a yellow oil which solidified overnight $[\alpha]_D^{20} = -10.5$ (*c* 0.114, $CHCl_3$), 99% ee, lit[58] $[\alpha]_D^{20} = -20.4$ (*c* 2.2, $CHCl_3$), 91% ee. Conversion estimated at 11%.[34] ^{1}H NMR spectra were identical to the racemic materials previously prepared.

4.11.1.5. Preparative scale hydrolysis of (±)-ethyl 3-(4-methylphenyl)butanoate (±)-3e. This was prepared following the procedure described for (±)-**1a** from *Pseudomonas cepacia* P1 (95 mg) and ethyl 3-(4-methylphenyl)butanoate (±)-**3e** (446 mg, 2.26 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL). The reaction mixture was shaken at 750 rpm for 62 h at 30 °C to produce a yellow oil (361 mg). Conversion estimated at 49%.[34] Purification by column chromatography using hexane/ethyl acetate as eluant (gradient elution 10–40% ethyl acetate) gave ester (*R*)-**3e** (145 mg, 31%) as a clear oil $[\alpha]_D^{20} = -28.7$ (*c* 3.5, $CHCl_3$), 97% ee, lit[24] $[\alpha]_D^{25} = -26.2$ (*c* 3.5, $CHCl_3$), 92% ee and acid (*S*)-**1e** (163 mg, 40%) as a yellow oil which solidified overnight $[\alpha]_D^{20} = +31.8$ (*c* 1.0, $CHCl_3$), ⩾99% ee, lit[24] $[\alpha]_D^{25} = +34.2$ (*c* 1.0, $CHCl_3$), 99% ee. ^{1}H NMR spectra were identical to the racemic materials previously prepared.

4.11.1.6. Preparative scale hydrolysis of ethyl 3-(3-methylphenyl)butanoate (±)-3f. This was prepared following the procedure described for (±)-**3a** from *Pseudomonas fluorescens* (94 mg) and ethyl 3-(3-methylphenyl)butanoate (±)-**3f** (471 mg, 2.28 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL). The reaction mixture was shaken at 750 rpm for 62 h at 30 °C to produce a yellow oil (232 mg). Conversion estimated at 49%.[34] Purification by column chromatography using hexane/ethyl acetate as eluant (gradient elution 10–40% ethyl acetate) gave ester (*R*)-**3f** (105 mg, 22%) as a yellow oil $[\alpha]_D^{20} = -24.4$ (*c* 1.0, $CHCl_3$), 94% ee and acid (*S*)-**1f** (107 mg, 26%) as a clear oil $[\alpha]_D^{20} = +32.3$ (*c* 0.622, $CHCl_3$), ⩾99% ee. ^{1}H NMR spectra were identical to the racemic materials previously prepared.

4.11.1.7. Preparative scale hydrolysis of ethyl 3-(2-methylphenyl)butanoate (±)-3g. This was prepared following the procedure described for (±)-**1a** from *Pseudomonas fluorescens* (74 mg) and ethyl 3-(2-methylphenyl)butanoate (±)-**3g** (371 mg, 1.80 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL). The reaction mixture was shaken at 750 rpm for 66 h at 30 °C to produce a yellow oil (268 mg). Conversion estimated at 50%.[34] Purification by column chromatography using hexane/ethyl acetate as eluant (gradient elution 10–40% ethyl acetate) gave ester (*R*)-**3g** (100 mg, 27%) as a clear oil $[\alpha]_D^{20} = -11.0$ (*c* 1.0, $CHCl_3$), 98% ee and acid (*S*)-**1g** (90 mg, 28%) as a yellow oil $[\alpha]_D^{20} = +24.2$ (*c* 1.38, $CHCl_3$), ⩾99% ee. ^{1}H NMR spectra were identical to the racemic materials previously prepared.

4.11.1.8. Preparative scale hydrolysis of (±)-ethyl 3-(4-methoxyphenyl)butanoate (±)-3h. This was prepared following the procedure described for (±)-**1a** from *Pseudomonas fluorescens* (100 mg) and ethyl 3-(4-methoxyphenyl)butanoate (±)-**3h** (498 mg, 2.24 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL). The reaction mixture was shaken at 750 rpm for 64 h at 30 °C to produce an orange oil (428 mg). Conversion estimated at 51%.[34] Purification by column chromatography using hexane/ethyl acetate as eluant (gradient elution 10–40% ethyl acetate) gave ester (*R*)-**3h** (212 mg, 43%) as a clear oil $[\alpha]_D^{20} = -30.03$ (*c* 1.034, $CHCl_3$), 99% ee and acid (*S*)-**1h** (99 mg, 23%) as a yellow oil $[\alpha]_D^{20} = +26.25$ (*c* 1.0, EtOH), 97% ee, lit[55] $[\alpha]_D^{25} = +27.5$ (*c* 1.0, EtOH) 94% ee. ^{1}H NMR spectra were identical to the racemic materials previously prepared.

4.11.1.9. Preparative scale hydrolysis of (±)-ethyl 3-(4-fluorophenyl)butanoate (±)-3i. This was prepared following the procedure described for (±)-**1a** from *Pseudomonas fluorescens* (45 mg) and ethyl 3-(4-fluorophenyl)butanoate (±)-**3i** (221 mg, 1.05 mmol) in 0.1 M phosphate buffer, pH 7 (20 mL). The reaction mixture was shaken at 750 rpm for 64 h at 30 °C to produce a yellow oil (171 mg). Conversion estimated at 51%.[34] Purification by column chromatography using hexane/ethyl acetate as eluant (gradient elution 10–40% ethyl acetate) gave ester (*R*)-**3i** (71 mg, 32%) as a clear oil $[\alpha]_D^{20} = -24.3$ (*c* 1.0, $CHCl_3$), ⩾99% ee and acid (*S*)-**1i** (67 mg, 35%) as a brown oil $[\alpha]_D^{20} = +30.5$ (*c* 1.016, $CHCl_3$), 97% ee. ^{1}H NMR spectra were identical to the racemic materials previously prepared.

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