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Enzyme- and Chemo-enzyme-Catalyzed Stereodivergent Synthesis

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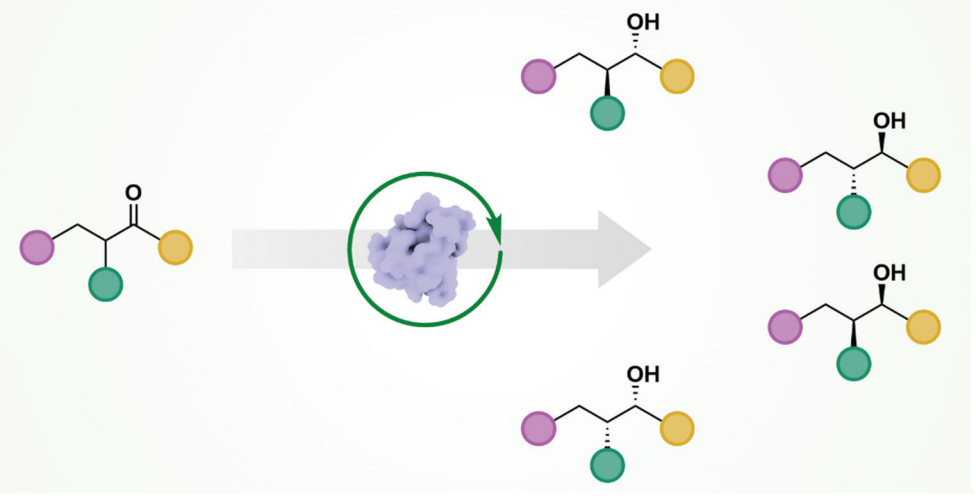

Abstract

Multiple stereoisomers can be found when a substance contains chiral carbons in its chemical structure. To obtain the desired stereoisomers, asymmetric synthesis was proposed in the 1970s and developed rapidly at the beginning of this century. Stereodivergent synthesis, an extension of asymmetric synthesis in organic synthesis with the hope to produce all stereoisomers of chiral substances in high conversion and selectivity, enriches the variety of available products and serves as a reference suggestion for the synthesis of their derivatives and other compounds. Since biocatalysis has outstanding advantages of economy, environmental friendliness, high

Keywords

- stereodivergent synthesis
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- enzymatic approach
- chemo-enzymes

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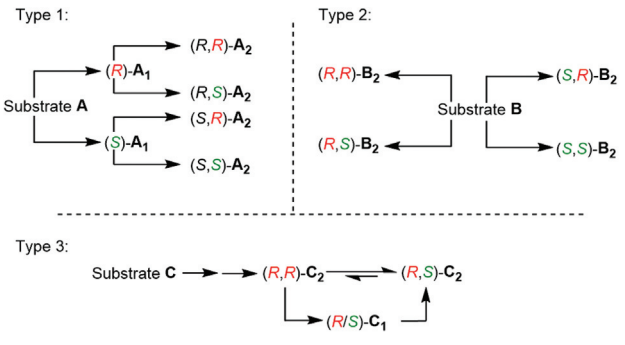
efficiency, and reaction at mild conditions, the biocatalytic reaction is regarded as an efficient strategy to perform stereodivergent synthesis. Thus, in this review, we summarize the stereodivergent synthesis catalyzed by enzymes or chemo-enzymes in cases where a compound contains two or three chiral carbons, i.e., at most four or eight stereoisomers are present. The types of reactions, including reduction of substituent ketones, cyclization reactions, olefin addition, and nonredox transesterification reactions, are also discussed for the understanding of the progress and application of biocatalysis in stereodivergent synthesis.

Introduction

In organic synthesis, if chiral carbons are involved in the reactions without regio or stereo control, multiple stereoisomers would be produced. Although several methods, such as high-performance liquid chromatography[1–5] and optical resolution,[6–8] can separate the desired products from other isomeric impurities, it still leads to an inevitable decline of yields. To improve the traditional synthesis methods, a new method called asymmetric synthesis began to rise gradually after a seminal article reported by Mosher and colleagues[9,10] in the 1970s, and rapidly developed at the beginning of this century.[11,12] During this period, Macmillan and colleagues[13] and List et al[14] independently developed the third type of catalyst—chiral organocatalysts distinct from metal catalysts and enzymes—in 2000, spurring rapid advances in asymmetric synthesis and winning the Nobel Prize in chemistry 2021. The core purpose of asymmetric synthesis represented by metal catalysis, chiral organocatalysis, and enzyme catalysis is to improve the selectivity of the desired product's configuration in high efficiency, that is, to increase the enantiomeric excess (*ee*) or diastereomeric excess (*de*).

Stereodivergent synthesis, established precisely based on asymmetric synthesis, allows access to any given stereoisomer of a product with multiple stereocenters from the same set of starting materials.[15] In the process of stereodivergent synthesis, whether using biocatalysis alone or a combination of biocatalysis and other methods, the reactions performed fall broadly into three categories (**Scheme 1**). In reaction type 1, there is usually no chiral carbon in the substrate **A** or the functional group participating in the reaction, such as the reduction of carbonyl groups and C=C double bonds. The two chiral centers of the products are generally produced in successive steps by different catalysts. However, the preparation of (*R*/*S*)-$\mathbf{A_1}$ from substrate **A** can sometimes not be performed due to limitations in technical development. Thus, occasionally enantiomeric or *Z*/*E*(*cis*/*trans*) isomeric $\mathbf{A_1}$ are also used as the substrates, leading to the preparation of four stereoisomeric products $\mathbf{A_2}$. Reaction type 2 is commonly found in condensation reactions, such as olefin addition reactions, reduction reactions of α-substituent ketones, and β-substituent ketones as well as transesterification reactions. In addition to olefin addition reactions where the substrate **B** carries C=C double bonds, the substrate **B** is usually used in racemic forms in other reactions, which produces the other chiral carbon based on one already existing chiral carbon under the catalysis of different stereoselective catalysts. If the two enantiomers of a racemic substrate **B** are capable of rapid interconversion spontaneously or by inducers, i.e., maintaining a dynamic equilibrium of configurational proportions, then product $\mathbf{B_2}$ with possible 100% conversion and high selectivity can be obtained by asymmetric reaction of only one enantiomer, which is known as dynamic kinetic resolution (DKR).[16,17] Otherwise, the conversion of the racemic substrate was ideally at most 50%. What's more, high percentage preparation of one stereoisomer can also be carry out by epimerization (or chiral inversion[18]) of chiral carbon, which converts other isomers to the desired isomer, shown as reaction type 3. The common methods used in epimerization includes crystallization induction,[19,20] chemical reagent induction,[21,22] and biocatalysis.[23–26]

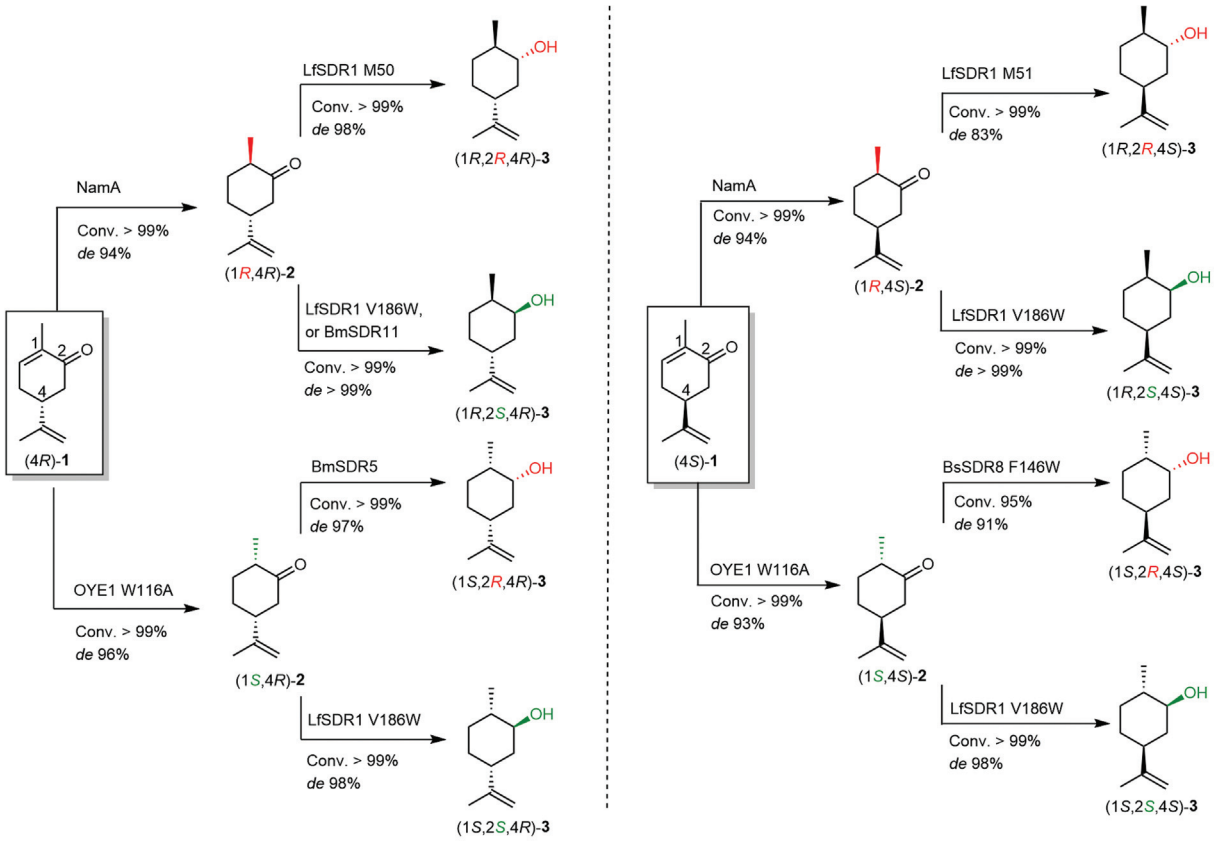


Scheme 1 Three common reaction types of stereodivergent synthesis.

Reduction of α,β-Unsaturated Ketones

Preparation of Carveols, Dihydrocarvones, and Dihydrocarveols

Carvone (**1**), dihydrocarvone (**2**), and dihydrocarveol (**3**), a class of natural terpenoids that can be obtained in plants such as mint and parsley, are valuable additives in the flavor industry.[27,28] Among related reports, the stereodivergent synthesis of eight stereoisomers of dihydrocarveol (**3**) catalyzed by two enzymes was first achieved by Guo et al.[29] As shown in **Scheme 2**, (4*R*)-**1** and (4*S*)-**1** were first reduced by ene-reductases to four stereoisomeric dihydrocarvones (**2**) with conversions (Conv.) greater than 99% as well as *de* value ranging from 93 to 96%. Subsequently, dihydrocarvones (**2**) were further reduced to eight stereoisomeric



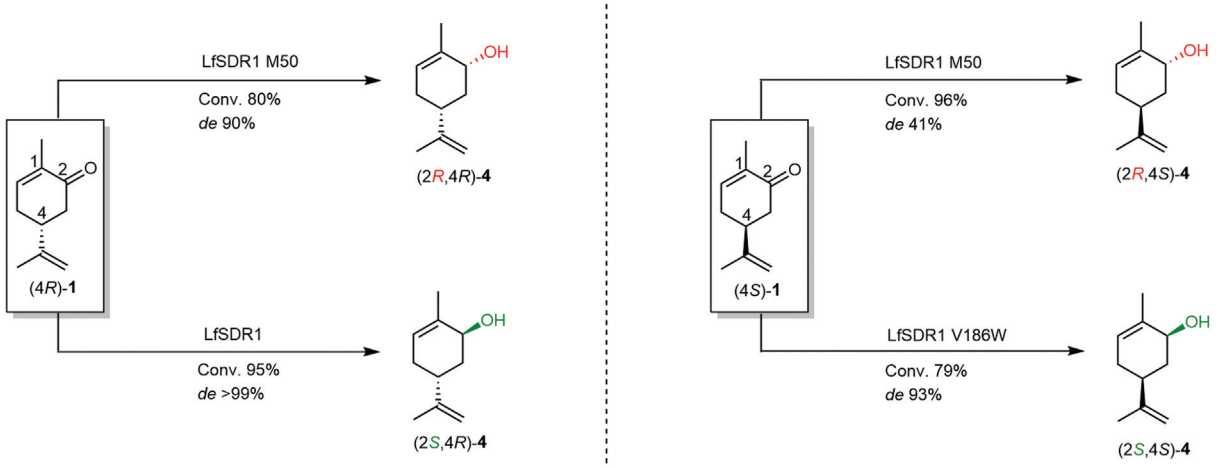
Scheme 2 Stereodivergent synthesis of eight stereoisomers of dihydrocarveol.

dihydrocarveols (**3**) with likewise excellent conversions and *de* values with ketoreductases. The genes encoding the ene-reductases OYE1 and NamA can be obtained from *Saccharomyces pastorianus* and *Bacillus megaterium*, respectively, and the recombinant ketoreductases LfSDR, BmSDR, and BsSDR can be obtained from *Lactobacillus fermentum*, *B. megaterium*, and *Bacillus subtilis*, respectively.

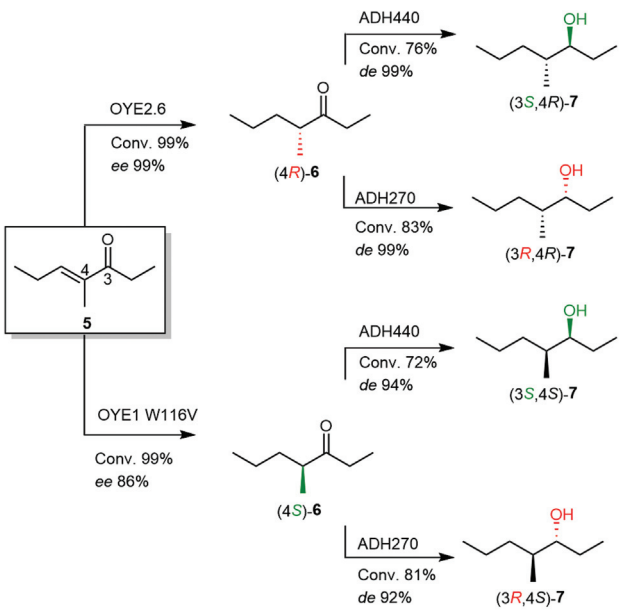
Similarly, four stereoisomeric carveols (**4**) can also be obtained from enantiomeric carvones (**1**) catalyzed by ketoreductases (**Scheme 3**). However, the *de* of product (2*R*,4*S*)-**4** was not ideal in this process. Moreover, under the influence of conjugated olefins, the reduction efficiency of the carbon group, i.e., the conversions of (2*R*,4*R*)-**4** and (2*S*,4*S*)-**4**, is lower than that in **Scheme 2**.

Preparation of 4-Methylheptane-3-ols

4-Methylheptane-3-ol (**7**) is an insect pheromone that has four stereoisomers and the biological activities of each isomer are quite different.[30–34] Although the asymmetric synthesis of (3*S*,4*S*)-**7** and the resolution of the four



Scheme 3 Stereodivergent synthesis of four stereoisomers of carveol.



Scheme 4 Stereodivergent synthesis of four stereoisomers of 4-methylheptane-3-ol.

stereoisomers with chromatography[35] or lipase[36] were accomplished as early as the end of the last century, the stereodivergent synthesis of **7** was only reported in recent years by Crotti and colleagues.[37] They achieved stereodivergent synthesis of four stereoisomeric **7** in one pot using a cascade of alcohol dehydrogenases and ene-reductases taken from *Pichia stipitis*, *S. pastorianus* as well as *Saccharomyces cerevisiae* (**Scheme 4**), while the conversions of reactions ranged from 72 to 83% and *de* values of obtained products were ranged from 92 to 99%.

Preparation of Michael Addition Products

RA95, first reported by Althoff et al,[38] is an artificial retro-aldolase generated by computational design. Building on this, Giger et al[39] obtained novel mutant RA95.5–8 by directed evolution. Subsequently, Garrabou et al[40] designed RA95.5–8 into four stereo-complementary catalysts, M-R.R, M-R.S, M-S.R, and M-S.S, capable of catalyzing Michael addition reactions. Under the action of the above four computationally designed enzymes (**Scheme 5**), the tertiary carbanion reacts with (*E*)-4-(4-methoxyphenyl)but-3-en-2-one (**8**) to produce four stereoisomeric ethyl 2-cyano-3-(4-methoxyphenyl)-2-methyl-5-oxohexanoates (**9**). Since four stereoisomers are inevitably produced in the Michael addition reactions, the isomer percentage was used to characterize the stereoselectivity of these enzymes, rather than *de*. As indicated in this study, the isomer percentages of the four stereoisomers ranged from 80.4 to 84.7%. Furthermore, the only reported yield among four stereoisomers was 47% for (2*S*, 3*R*)-**9**.

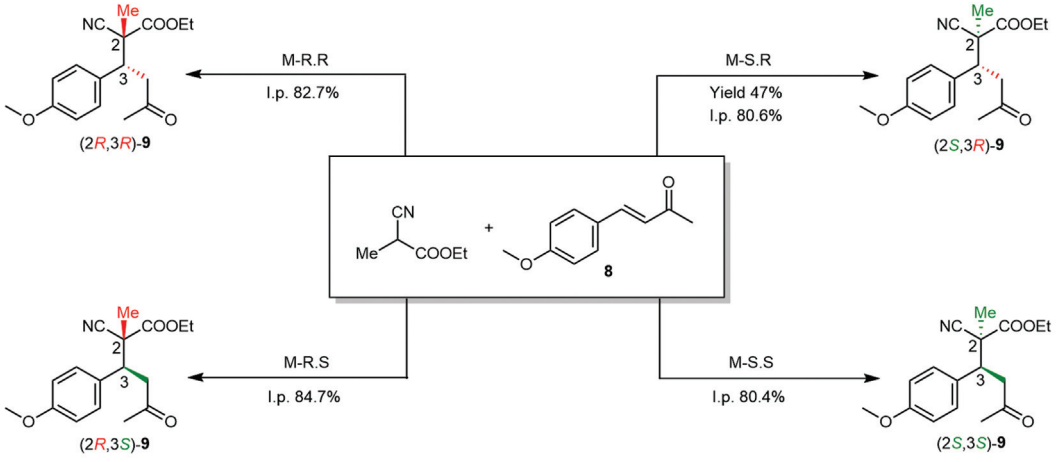
Reduction of α-Substituted Ketones

Preparation of 3-Hydroxyprolines and 3-Hydroxypipecolic Acids

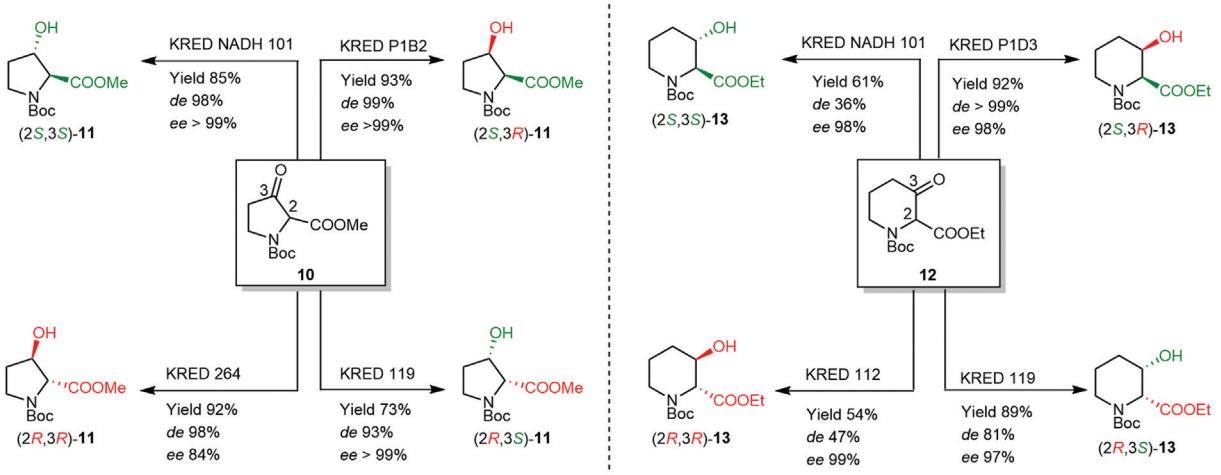
Hydroxyproline and hydroxypipecolic acid are both important intermediates in organic synthesis[41] and privileged pharmacophores in many drugs.[42,43] In a recent study, Prier et al[44] prepared four stereoisomers of 3-hydroxyproline (**11**) in satisfactory yields, as well as *ee* and *de* values by DKR of amino-protected methyl 3-oxopyrrolidine-2-carboxylate (**10**) using commercial ketoreductases (**Scheme 6**). Similarly, DKR of amino-protected ethyl 3-oxopiperidine-2-carboxylate (**12**) with similar ketoreductases also produced four stereoisomeric 3-hydroxypipecolic acids (**13**). Although the catalytic efficiencies of the four ketoreductases used for the six-membered ring substrates were not as high as the five-membered ring substrates, products with high *ee* values were still accessible.

Reduction of *S*-(2-Acetamidoethyl) 2-methyl-3-oxopentanethioates and Its Derivatives

Complex polyketides are a broad class of natural products[45,46] that are synthesized from simple precursors catalyzed by polyketide synthases (PKSs).[47] Among them, EryKR1, TylKR1, AmpKR2, and RifKR7, KR domains derived from erythromycin PKS, tylosin PKS, amphotericin PKS, and



Scheme 5 Stereodivergent synthesis of four Michael addition products.



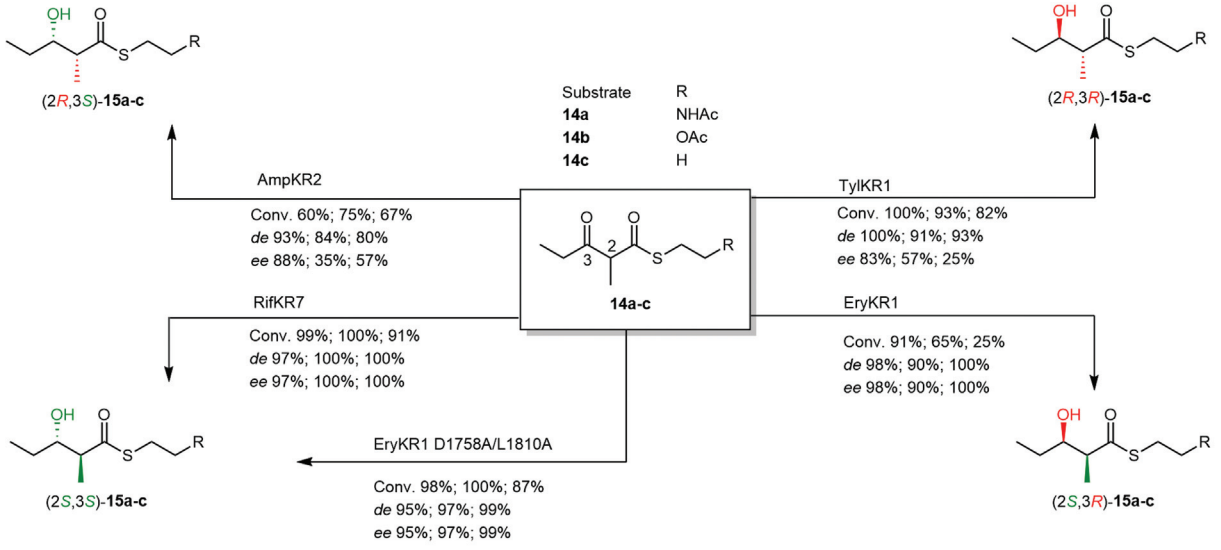
Scheme 6 Stereodivergent synthesis of four stereoisomers of 3-hydroxyproline and 3-hydroxypipecolic acid.

rifamycin PKS, respectively, have been reported as excellent ketoreductases in the preparation of complex polyketides.[48] Results showed that they can catalyze the DKR of *S*-(2-acetamidoethyl) 2-methyl-3-oxopentanethioate (**14a**) and its derivatives (**14b**, **14c**), leading to corresponding four reduced products (**15a–c**) (**Scheme 7**). Subsequently, Bailey et al continued to conduct in-depth research on the protein engineering of these reductases. Their results showed that in EryKR1, the 1,810th amino acid was found to be critical for the conformational shift of the products, and mutation of this residue from leucine to alanine resulted in a shift of the stereoselectivity from the original (2*S*,3*R*)-**15a–c** to (2*S*,3*S*)-**15a–c** with improved conversion as well. In addition, changing the amino acids at other sites also resulted in increased conversions of (2*S*,3*S*)-**15a–c**, among which, the combinatorial mutation EryKR1 D1758A/L1810A exhibited the best catalytic activity. It is worth mentioning that the *ee* reported in **Scheme 7** is not the commonly used ratio of the desired product to its enantiomer, but the desired product to the other three stereoisomers.

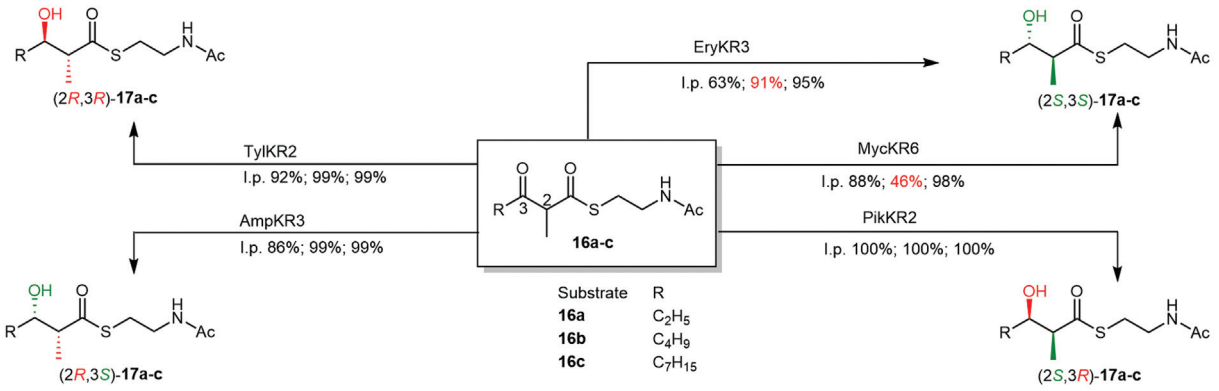
Recently, Robles and coworkers[49] also used six ketoreductases, PikKR2, MycKR6, TylKR2, AmpKR3, EryKR3, and EryKR7, to catalyze the DKR of *S*-(2-acetamidoethyl) 2-methyl-3-oxopentanethioate (**16a**) and two other derivatives (**16b**, **16c**) and finally obtained the corresponding four stereoisomers (**17a–c**) with high isomer percentages, respectively (**Scheme 8**). Unexpectedly, in **Scheme 8**, a blunted fall in the catalytic selectivity toward the product (2*S*,3*S*)-**17b** by MycKR6 occurs with the isomer percentage of only 46%, which is much lower than those of substrates **17a** and **17c**. Based on this deficiency, EryKR3 was used to enhance this catalytic reduction reaction, giving the desired product with an isomer percentage of 91%. In addition, the yields for reduction of ethyl substituted **17a** and butyl substituted **17b** were approximately 65%, while that of **17c** was 35%.

Preparation of 2-Amino-2-(5-bromopyridin-3-yl)-1-(2,5-difluorophenyl) ethane-1-ols

2-Amino-2-(5-bromopyridin-3-yl)-1-(2,5-difluorophenyl) ethane-1-ol (**19**) is a synthetic intermediate for positive



Scheme 7 Stereodivergent synthesis of 12 reduced products catalyzed by 4 ketoreductases.



Scheme 8 Stereodivergent synthesis of 12 reduced products catalyzed by 5 ketoreductases.

allosteric modulators of metabotropic glutamate receptors.[50] During the synthesis of **19**, the amino groups in the structure usually need to be protected, and the commonly used protective agents are *tert*-butoxy carbonyl (Boc),[51] benzyloxy carbonyl, etc. Hanson et al[52] used three commercial ketoreductases and four microorganisms to catalyze the DKR of amino-protected 2-amino-2-(5-bromopyridin-3-yl)-1-(2,5-difluorophenyl) ethane-1-one (**18**), obtaining four stereoisomeric chiral alcohols (**Scheme 9**). It should be emphasized that the *Pichia methanolica* ATCC56508 exhibited excellent catalytic activity and selectivity in the preparation of (1*R*,2*S*)-**19**, even exceeding the screened commercial ketoreductase ES KRED-112.

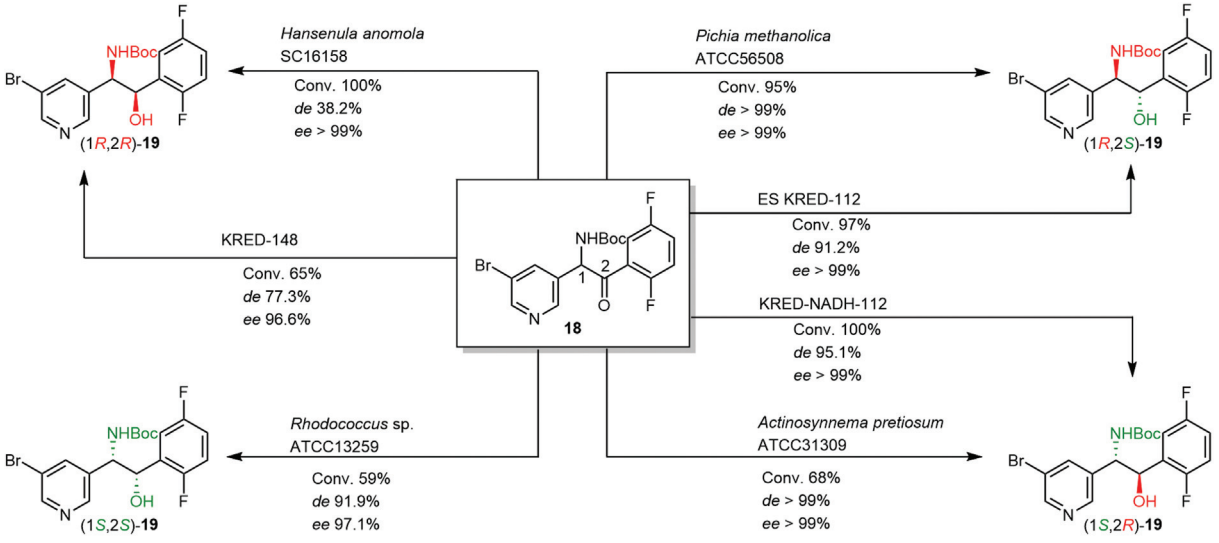
Reduction of β-Substituted Ketones

Preparation of 3-Phenylcyclohex-1-ols

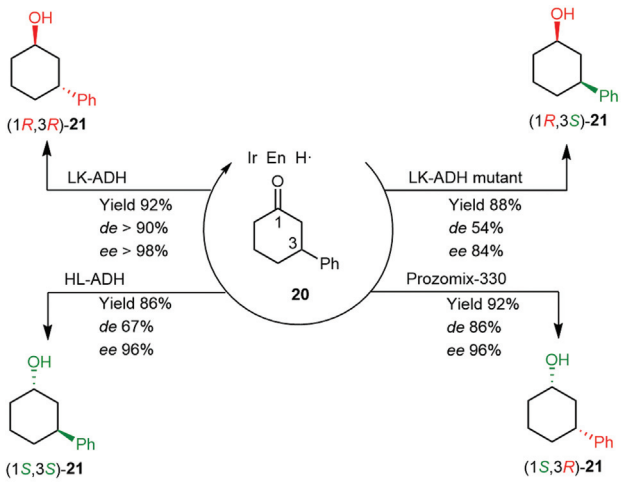
As mentioned in the Introduction, racemic substrates need to be able to undergo interconversion of configurations in DKR. These spontaneously transformed or able to be induced dynamic centers usually attach active groups, such as hydroxyl group, amino group, carbonyl group, etc., at the chiral carbon.[53] However, Dehovitz et al[54] broke this restriction and used photocatalysts and commercial ketoreductases to reduce 3-phenylcyclohexan-1-one (**20**), producing four stereoisomeric 3-phenylcyclohexan-1-ols (**21**) in good yields (**Scheme 10**). Besides, the LK-ADH and its mutant, i.e., LK-ADH E145F/F147L/Y190C, used in the synthesis scheme are obtained from *Lactobacillus kefir*.

Preparation of 1-(Substituted Phenyl) Butane-1,3-diols

1,3-Diols are important starting materials for the synthesis of pharmacologically active compounds,[55] and these structures also widely exist among natural products.[56,57] In addition, 1,3-diols can also be used to synthesize chiral 1,3-diphosphines that are enantiopure ligands in asymmetric catalysis.[58] In the related reports of 1,3-diols, Baer et al,[59] using organocatalysts as well as alcohol dehydrogenases with *R*/*S*-type stereoselectivity (**Scheme 11**), first completed the stereodivergent synthesis of four stereoisomeric 1-(4-chlorophenyl) butane-1,3-diols (**24**). As reported in this study, 4-chlorobenzaldehyde (**22**) and acetone, catalyzed by chiral organocatalysts, were used to synthesize a pair of enantiomeric 4-(4-chlorophenyl)-4-hydroxybutan-2-ones (**23**). Subsequently, the carbonyl



Scheme 9 Stereodivergent synthesis of four stereoisomers of chiral alcohol.



Scheme 10 Stereodivergent synthesis of four stereoisomers of 3-phenylcyclohexan-1-ol.

groups of 4-hydroxybut-2-ones were stereoselectively reduced by alcohol dehydrogenases in *R*-type or *S*-type, respectively, to finally make four 1,3-diols. In addition, the enzymatic activity curve of (*S*)-ADH in the presence of chiral organocatalyst was also determined. The result shows that the (*S*)-ADH still retains high activity over a certain range of organocatalyst concentrations and enables the one-pot preparation of (1*R*, 3*S*)-**24**.

In addition to the organo-enzymatic catalysis method described above, the method of producing 1,3-diols employing metal-enzyme catalysis was also reported. The process was described by Sonoike et al,[60] using chiral zinc complex catalysts and purchased oxidoreductases to make three structures totaling twelve 1-(substituted phenyl) butane-1,3-diols (**Scheme 12**, **26a–c**).

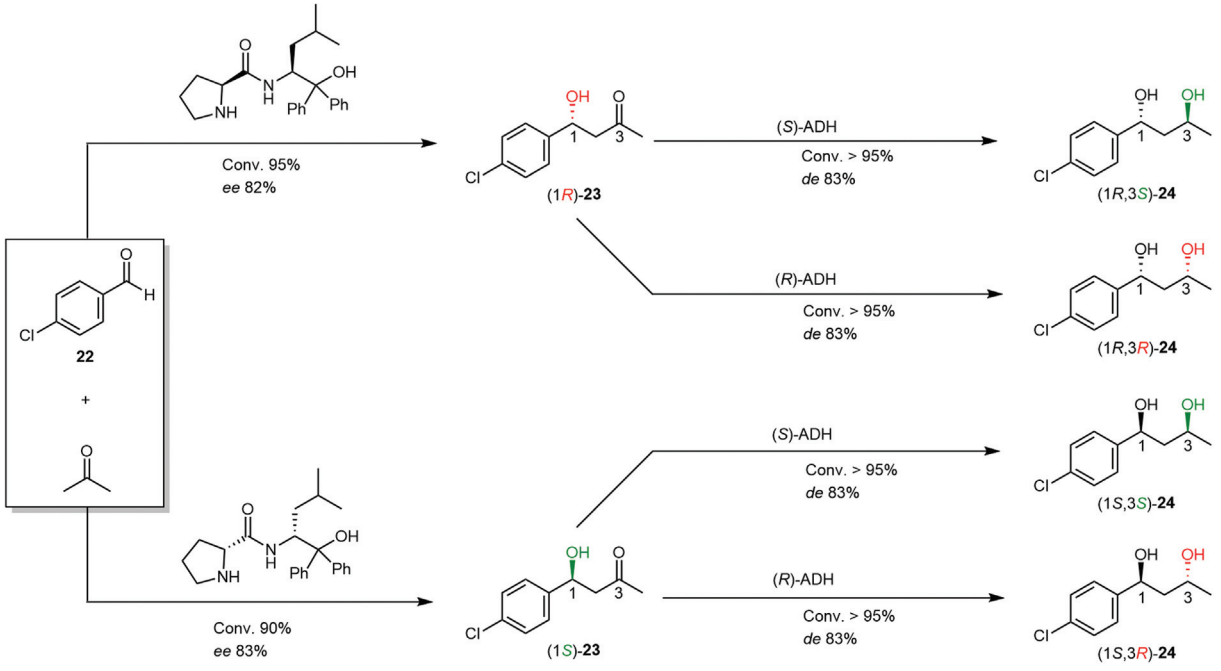
Cyclization Reaction

Cyclization reactions are a rather important branch in synthetic chemistry and are widely applied in various fields. The multiple types, mechanisms, and corresponding rules of cyclization reactions have been connectively reported in the past half century of research.[61–63] Here, we mainly report stereodivergent synthesis of three types of cyclized compounds, including intramolecular transesterification reactions as well as nucleophilic substitution reactions and intermolecular epoxidation reactions. Of these, only the cyclopropanation reactions of C = C double bonds with a diazo compound produce chiral centers during the ring formation process, whereas the other chiral cyclization products were obtained based on the already existing chiral centers catalyzed by biocatalysts.

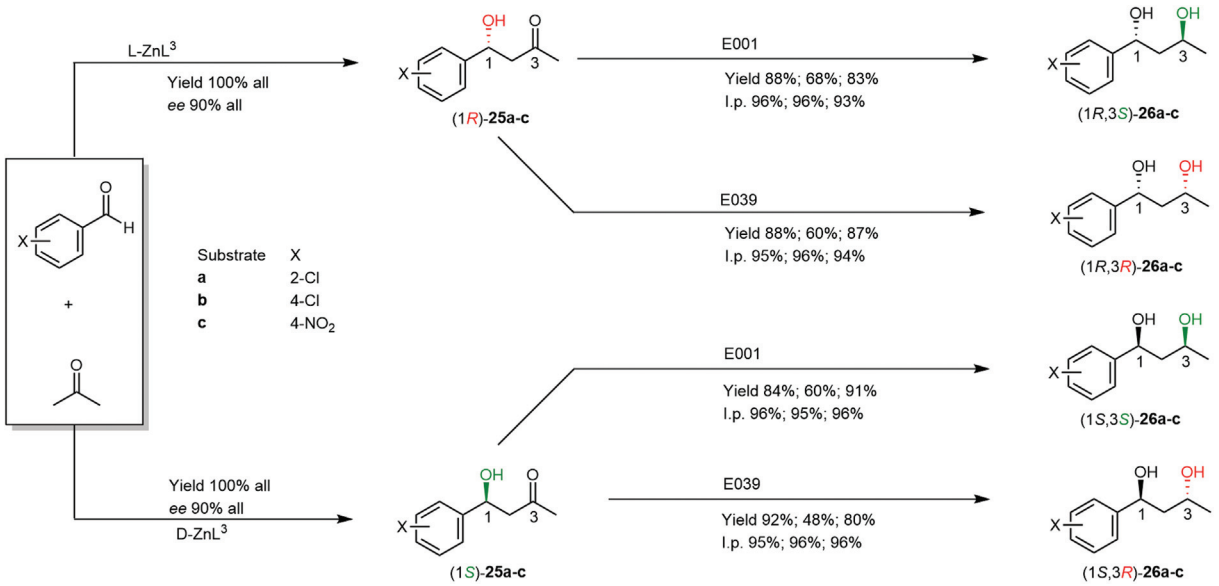
Preparation of Substituted γ-Butyrolactones

Substituted γ- butyrolactones serve both as chiral building blocks for synthetic products and as core groups for many natural compounds and chemical agents.[64–66] The stereodivergent synthesis of substituted γ-butyrolactones using a one-pot two-enzyme method was first reported by Classen et al.[67] In the one-pot process (**Scheme 13**), α,β-unsaturated ketones (**27**) were first reduced by an ene-reductase and subsequently reduced by alcohol dehydrogenase, and finally underwent transesterification with a smooth cyclization to produce a variety of substituted γ-butyrolactones (**29**). Since the ene-reductase used in the first step of the reaction is not stereoselective, substrate **27** was required in diastereomerically pure form to prepare (*S*/*R*)-**28** in high optical purity.

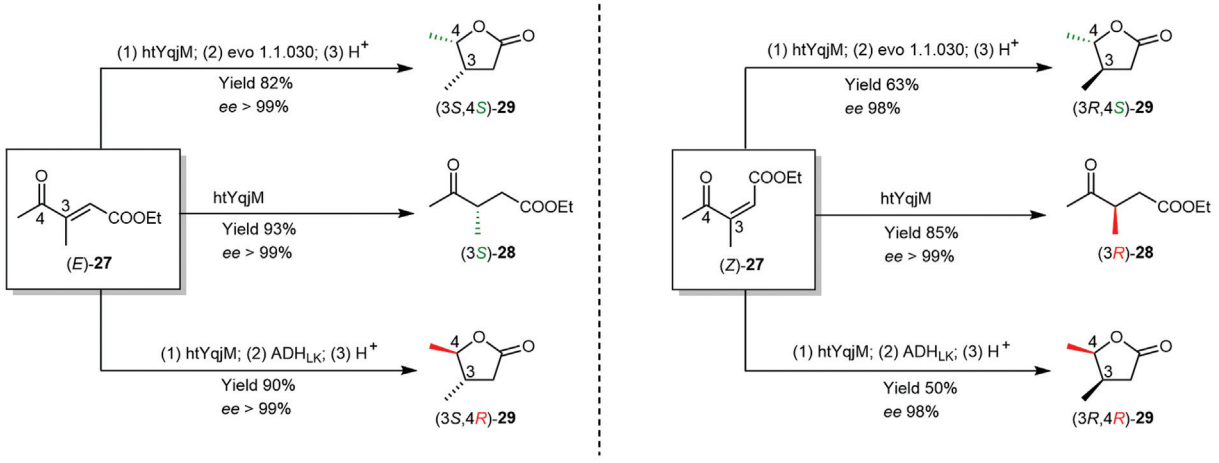
In September of the same year, a method for the preparation of substituted γ-butyrolactones utilizing chiral organocatalysts and alcohol dehydrogenases was subsequently reported by Simon et al.[68] In their proposed scheme (**Scheme 14**), *para*-



Scheme 11 Stereodivergent synthesis of four 1,3-diols by organo-enzymatic catalysis.



Scheme 12 Stereodivergent synthesis of twelve 1,3-diols by metal-enzyme catalysis.



Scheme 13 Stereodivergent synthesis of four substituted γ-butyrolactones catalyzed by ene-reductases and alcohol dehydrogenases.

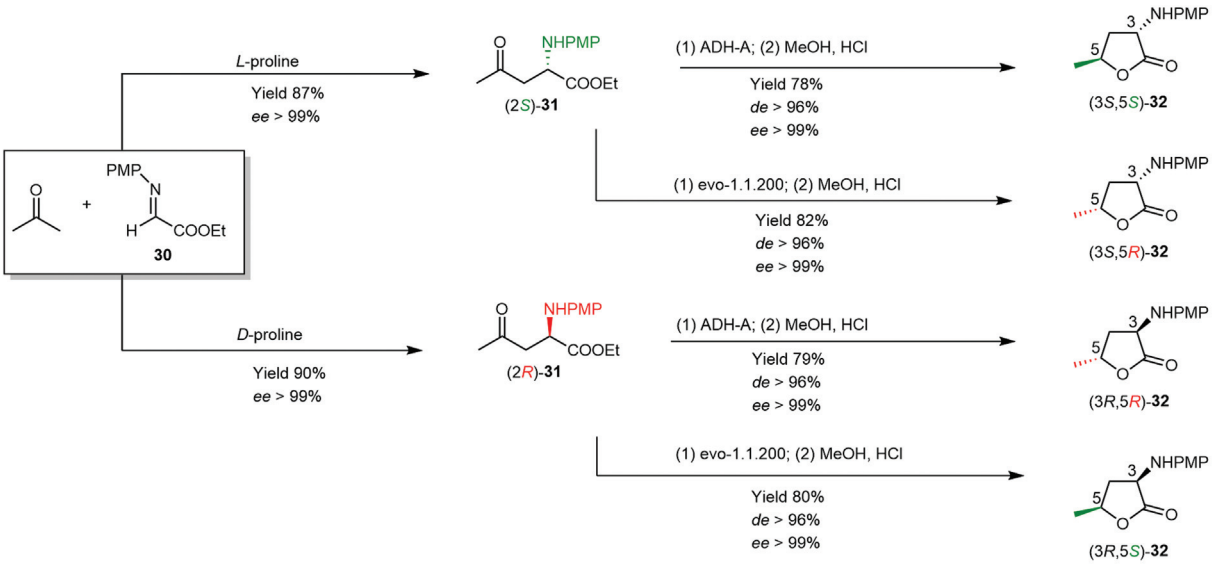
methoxyphenyl-protected ethyl 2-iminoacetate (**30**) and acetone, catalyzed by proline, undergo the Mannich reaction to give ethyl 2-amino-4-oxopentanoates (**31**). Subsequently, the enantiomeric products **31** were reduced to four stereoisomers of substituted γ-butyrolactones (**32**) by the commercial ketoreductases evo-1.1.200 or by ADH-A derived from *Rhodococcus ruber* along with hydrochloric acid.

Preparation of 2-Methyl-3-pentyloxiranes

Veschambre is one of the pioneers of stereodivergent synthesis utilizing chemical and biocatalytic methods. The preparation of four stereoisomeric 2-methyl-3-pentyloxiranes (**37**) starting from 2-octanone (**34**) was accomplished as early as the end of the last century by Veschambre and colleagues.[69] Limited by the lack of development of asymmetric synthesis techniques at that time, 3-bromo-2-octanone (**35**) was obtained in the racemic form in the preparation process (**Scheme 15**), so the resultant 3-bromooctan-2-ols (**36**) were a mixture of diastereomers and required silica gel column chromatography for product separation to obtain the optically pure products. In addition, the authors also used a similar procedure to prepare four stereoisomeric 3-azido-2-ols. Although the yield of the product now appears to be relatively low, the combination of chemical and enzymatic approaches was undoubtedly groundbreaking at the time and had a profound impact on the subsequently biocatalytic asymmetric synthesis.

Preparation of Ethyl 2-Substituted Cyclopropane-1-carboxylates

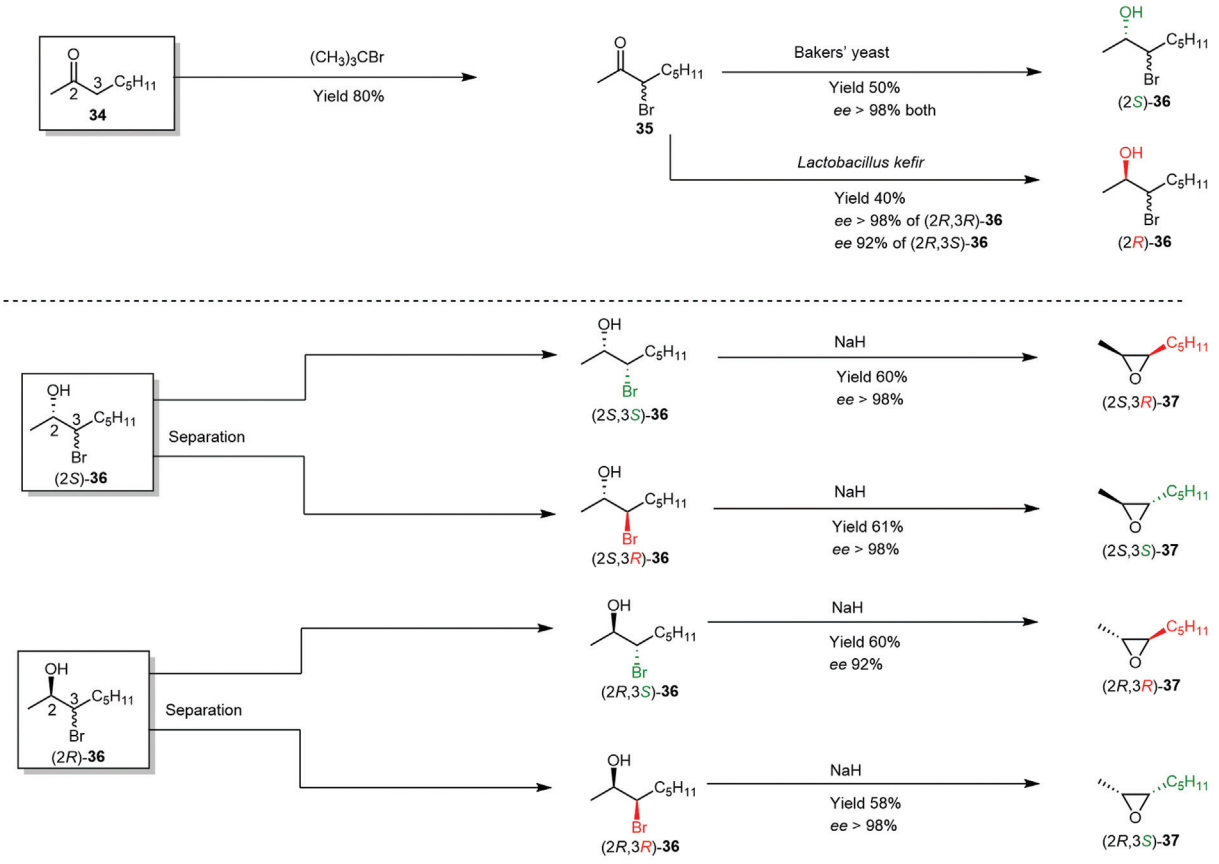
Iron (II)-porphyrin, also known as hemoprotein, which is present in cytochrome P450 and hemoglobin, was reported by Brustad and colleagues[70] to be a biocatalyst that can be used for the cyclopropanation of active alkenes (**39**) such as styrene with ethyl diazoacetate (**38**). In their subsequent report,[71] the stereodivergent synthesis of four stereoisomers



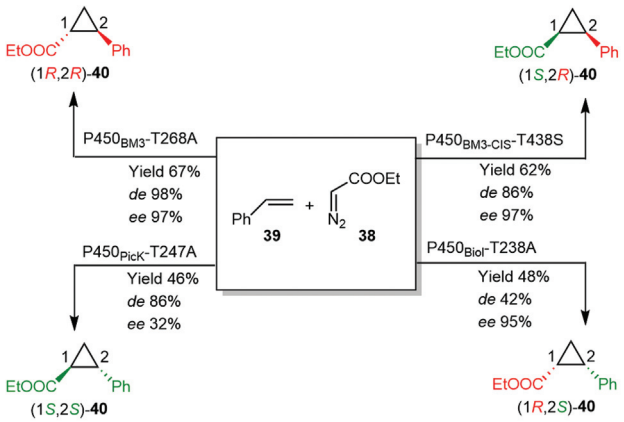
Scheme 14 Stereodivergent synthesis of four substituted γ-butyrolactones catalyzed by chiral organocatalysts and alcohol dehydrogenases.

of ethyl 2-phenylcyclopropane-1-carboxylate (**40**) and its derivatives could be accomplished under the catalysis of $P450_{BM3}$ variant from *B. megaterium* as well as other cytochrome enzymes (**Scheme 16**).

Stereodivergent cyclopropanation using less active aliphatic alkenes with ethyl diazoacetate (EDA) was first reported by Knight et al.[72] Four enzymes with excellent activity and catalytic complementation from 11 heme proteins and their mutants extracted from thermophilic and hyper-thermophilic bacteria and archaea were used for catalysis of a wide range of substrates (**41a–c**, **Scheme 17**). Among them, *Ape*Pgb AGW and *Rma*NOD are abbreviations of *Aeropyrum pernix* protoglobin W59A Y60G F145W and *Rhodothermus marinus* nitric oxide dioxygenase, respectively.



Scheme 15 Stereodivergent synthesis of four stereoisomers of 2-methyl-3-pentyloxirane.



Scheme 16 Stereodivergent synthesis of four stereoisomers of ethyl 2-phenylcyclopropane-1-carboxylate.

P411-UA-V87C and P411-UA-V87F are two variants of the engineered, serine-ligated cytochrome $P450_{BM3}$. In addition, the total turnover number (TTN) is used to characterize the catalytic activity of these enzymes, and these yields were calculated under conditions designed to demonstrate the catalysts' potential TTNs.

Other Types of Reactions

The variety of reaction types reported above are reduction, addition, and cyclization reactions that take the monocarbonyl group as the main functional group and simultaneously unite olefins, α-substituent groups, and β-substituent groups, respectively. However, there are other types of reactions, such as olefin addition reaction without carbonyl participation, continuous reduction reaction of poly-carbonyl, amino substitution reaction, and nonredox transesterification reaction, which are also an indispensable part of stereodivergent synthesis technology.

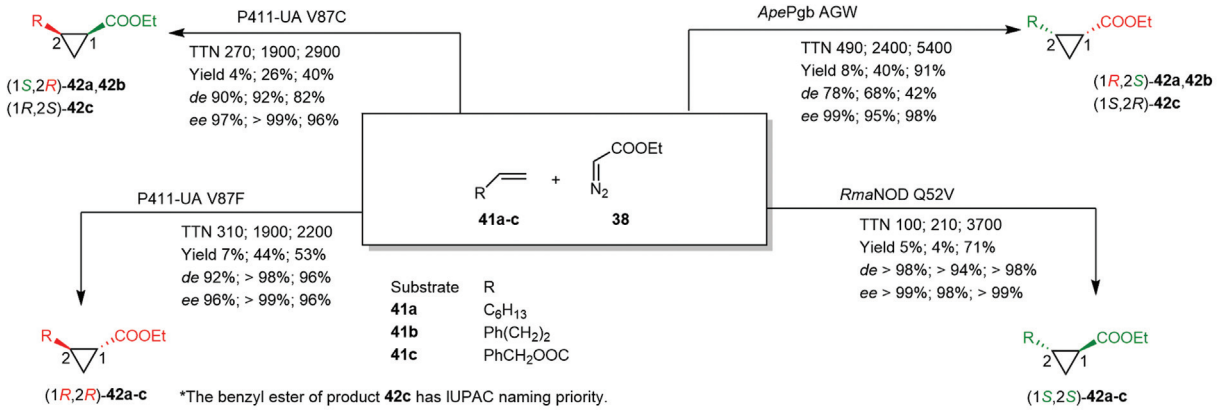
Preparation of 3-Hydroxy-5-methoxyheptanoic Acids

Similar to the stereodivergent reduction of **14a** and its various derivatives mentioned above, Keatinge-Clay and colleagues[73] used *S*-(2-acetamidoethyl) 3-oxopentanethioate (**43**) as a substrate and performed sequential reduction of carbonyl groups (**Scheme 18**) using McyKR6 and TylKR2 from mycolactone PKS and tylosin PKS, respectively, to produce four stereoisomeric 3-hydroxy-5-methoxyheptanoic acids (**46**). In the scheme, the reductive products **44** were added a carbonyl group and a methyl protecting group after a series of chemical reaction steps. In addition, the protective effect of the methyl group was proved to be more beneficial for the progress of this reaction compared with other protective groups such as an acetyl group.

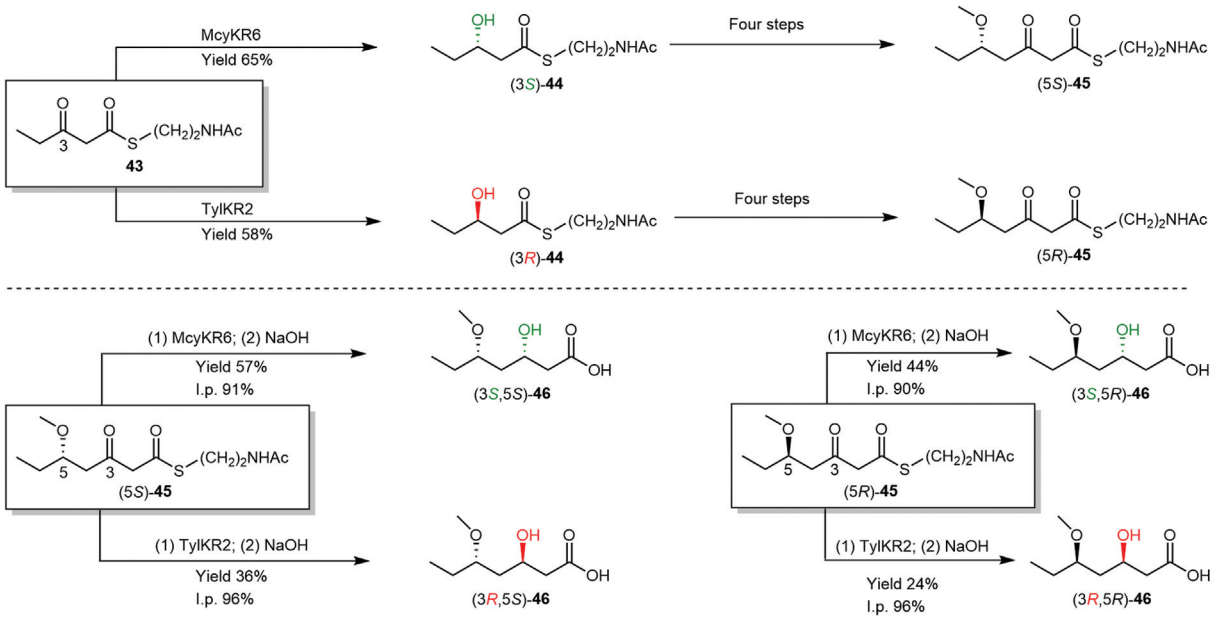
Preparation of 1-Phenylpropane-1,2-diols and 2-Amino-1-phenylpropan-1-ols

Chiral amino alcohols are a class of chemical structures with outstanding pharmaceutical activity, which are commonly found in hormones, antibiotics, alkaloids, adrenergic blockers, and other drugs.[74–76] Among them, the enzyme-catalyzed stereodivergent synthesis of four stereoisomeric 2-amino-1-phenylpropan-1-ols (**50**) that could serve as synthetic intermediates or final drug products was pioneered by Corrado et al.[77] *Z*/*E* isomeric prop-1-en-1-ylbenzenes (**47**) were first oxidized to 2-methyl-3-phenyloxiranes (**48**) by fused styrene monooxygenase (SMO) from *Pseudomonas* sp. VLB120 with oxygen (**Scheme 19**). The fused SMO used was designed to be co-expressed with formate dehydrogenase. Subsequently, **48** were hydrolyzed to four stereoisomeric 1-phenylpropan-1,2-diols (**49**) by epoxide hydrolases, Sp(*S*)-EH from *Sphingomonas* sp. HXN200, and St(*R*)-EH from *Solanum tuberosum*, respectively. It is worth mentioning that the above two-step reaction is capable of being performed in one pot.

Building on the successful preparation of **49**, Corrado et al[78] went on to use multiple sources of alcohol dehydrogenases and transaminases to convert the four isomeric diol compounds into 2-amino-1-phenylpropan-1-ols (**50**, **Scheme 20**). In the scheme, Aa-ADH, Ls-ADH, Bs-BDHA (2,3-butanediol dehydrogenase), Bm (*S*)-ωTA, As(*R*)-ωTA, At(*R*)-ωTA, and Cv(*S*)-ωTA were obtained from *Aromatoleum aromaticum*, *Leifsonia* sp., *B. subtilis* BGSC1A1, *B. megaterium* SC6394, *Arthrobacter* sp., *Aspergillus terreus*, and *Chromobacterium violaceum* DSM30191, respectively. However, there is a ubiquitous 5 to 20% difference between the conversion and the actual yield of the desired isomer due to the multistep reaction proceeding and the existence of side reaction pathways



Scheme 17 Stereodivergent synthesis of four stereoisomers of three ethyl 2-substituted cyclopropane-1-carboxylates.

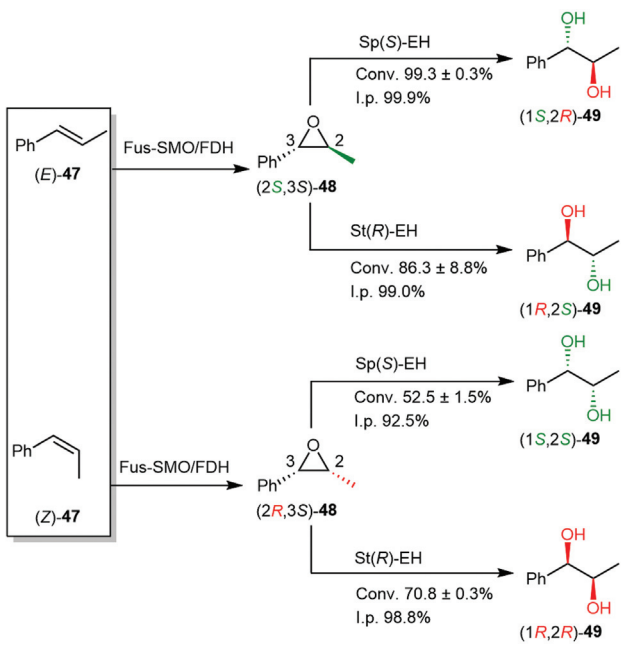


Scheme 18 Stereodivergent synthesis of four stereoisomers of 3-hydroxy-5-methoxyheptanoic acid.

that give rise to multiple by-products in the reaction system. In addition, the preparation of diverse **50** from one **49** can also be achieved by combining different alcohol dehydrogenases and transaminases. For example, Ls-ADH and At(*R*)-ωTA could produce (1*R*,2*R*)-**50** from (1*R*,2*R*)-**49** rather than (1*R*,2*S*)-**49** with conversion, *ee*, and *de* >99%.

Preparation of 1-Phenylethyl 2-Phenylpropanoates and Its Derivatives

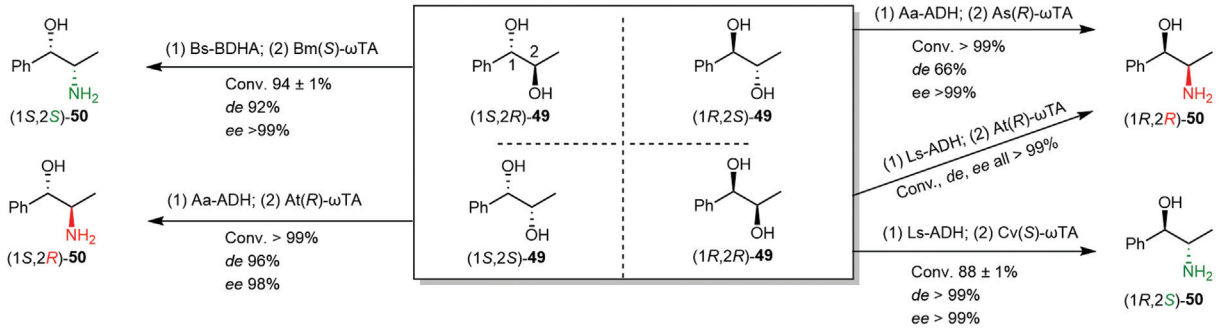
In asymmetric synthesis, lipases, for their ability to catalyze the hydrolysis of esters in aqueous media, are often used for the resolution of racemic intermediates.[36,79] However, one lipase derived from *Candida antarctica* has been reported to be useful for transacylation of secondary alcohols in organic reagents.[80] Based on this, Wu and colleagues[81] successfully constructed four enzymes capable of catalyzing the preparation of four stereoisomeric 1-phenylethyl 2-phenylpropionates (**53a**) using a strategy termed "focused rational iterative site-specific mutation" from wild-type *C. antarctica* lipase B (CALB, **Scheme 21**). This strategy aims to simplify traditional iterative saturation mutations with fewer but representative amino acids, with the hope of similar good result. Since the racemic substrate **51** used in the protocol cannot interconvert rapidly, conversion of the substrate is at most 50% in an ideal situation where only a single isomer is produced. Isopropyl ether proved to be the best choice for these wild-type and mutant lipases in a variety of organic solvents. In addition, various derivatives of **53a** were shown to be produced by the same method. Among them, all four stereoisomers of **53b** and **53c** and three stereoisomers of **53d**, **53e**, and **53f** can be obtained, respectively.



Scheme 19 Stereodivergent synthesis of four stereoisomers of 1-phenylpropan-1,2-diol.

Outlook and Conclusion

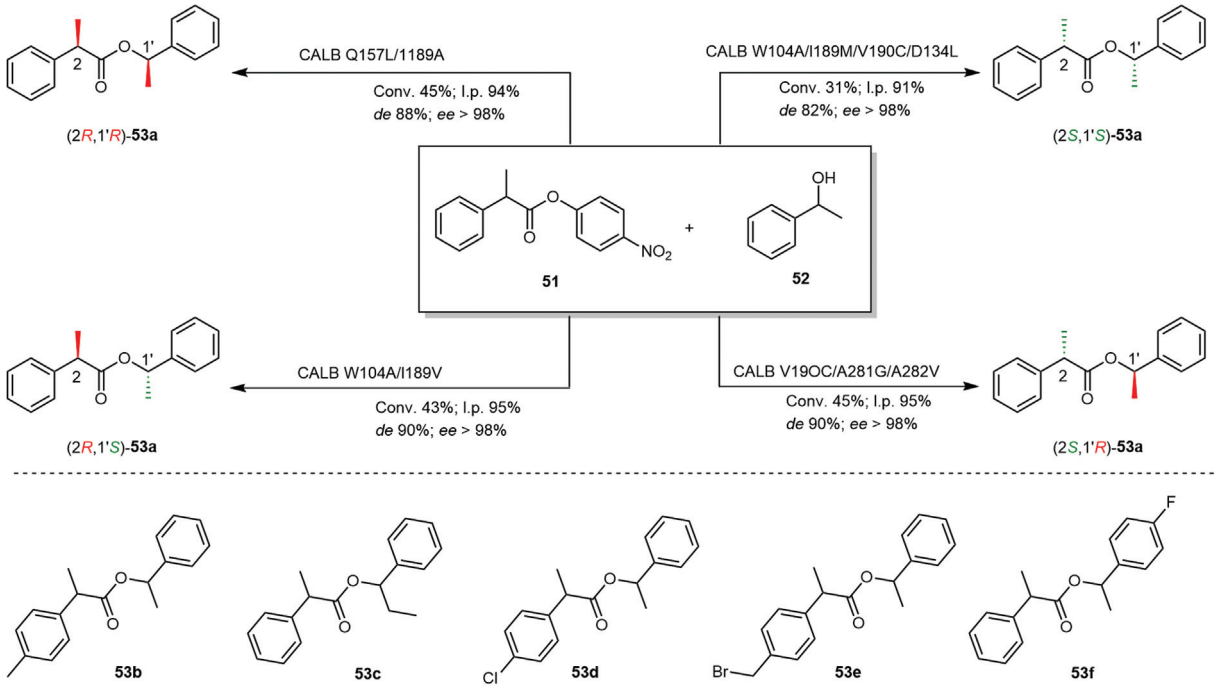
Although the application of biocatalysis, especially enzyme catalysis, in asymmetric synthesis is gradually abundant and the related technologies are also gradually maturing, we still have many difficulties to overcome. Summarizing the above reactions, it is not difficult to find that our control over the chiral centers is confined within two-carbon bridges. This limitation is not just present in biocatalysis, but also being discovered in chiral organocatalysis and metal catalysis.[15] Meanwhile, our control over the number of chiral centers is also usually limited to within two, and stereodivergent synthesis containing three and more chiral centers has rarely been reported. In addition, the number of reports on



Scheme 20 Stereodivergent synthesis of four stereoisomers of 2-amino-1-phenylpropan-1-ol.

stereodivergent synthesis catalyzed by biocatalysts only accounts for about one-tenth, which is much less than chiral organocatalysis and metal catalysis. All in all, whether extending the distance of chiral centers, increasing the number of chiral centers, or enriching the reaction substrate types can undoubtedly lead to further refinement of biocatalytic techniques while also improving for stereodivergent synthesis methods.

Here, we present some suggestions for the development of stereodivergent synthesis by biocatalysts based on hot topics that have been reported in recent years. First, deep optimization of directed evolution is needed. Traditional iterative saturation or degenerate codon mutations are more blind strategies for enzyme evolution that bring about an exponential increase in workload. Thus, the use of computer-aided mutation design is a better approach. Based on this, the development of new ancillary software or the optimization of existing algorithms that enable better structural modeling and outcome prediction will undoubtedly benefit the existing biocatalytic approaches. Second, it is also a general trend for the future to develop new enzymes or to mine the functions of known enzymes. Previously, most of the enzymes used in biocatalysis were wild-type enzymes existing in nature or mutant enzymes designed on them. However, the enzymes evolved by organisms to adapt to the environment are difficult to meet our catalytic needs for the synthesis of complex and diverse compounds, which suggests that we need to develop enzymes that do not exist in nature. Under such demand pitfalls described above, de novo protein design,[82] a rational design based on energy function calculations, is precisely the third protein design approach proposed—distinct from structure prediction and fixed backbone design. In addition, there were some valuable enzymes in the existing or extinct organisms, but these enzymes were gradually eliminated by the host in the process of evolution, which also suggests that we can excavate the ancestral sequences[83] buried in history through calculation and derivation, to enrich the types of enzymes. Finally, the combined



Scheme 21 Stereodivergent synthesis of four stereoisomers of 1-phenylethyl 2-phenylpropanoate.

application of multiple methods or catalysts is similarly an effective way to solve the bottleneck of biocatalysis. Photoenzymatic catalysis[84] is a hot topic in recent years, and this approach to selective transformations using visible light can combine the advantages of biocatalysis and photocatalysis, including new reactivity, high stereoselectivity, green synthesis, and high yields. In addition, applications related to the combination of biocatalysis with electrocatalysis, i.e., bioelectrocatalysis, have been successively reported in recent years.[85,86]

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Conflict of Interest
The authors declare that they have no conflict of interest.

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