Deep Science Publishing
https://doi.org/10.70593/978-93-7185-164-0_4

Chapter 4: Synthesis and applications of tartaric acid in asymmetric catalysis

Ramchandra Thorat,* Owais Mujawar

Abstract: This chapter presents recent advances in the synthesis and application of tartaric acid derivatives in asymmetric catalysis. Tartaric acid, a naturally occurring C_2-symmetric diol, serves as a versatile chiral pool compound for the preparation of diverse ligands and catalysts. Dimethyl (2R,3R)-tartrate and its modified derivatives are employed as key chiral building blocks in the development of enantioselective catalytic systems. Their functionalized forms have been utilized in a variety of asymmetric transformations, including aldol reactions, epoxidations, Diels–Alder reactions, and hydrogenations. Structural modifications at the carboxylic acid and hydroxyl positions of tartaric acid have led to highly selective chiral auxiliaries, organocatalysts, and metal–ligand complexes. These derivatives offer efficient access to enantiomerically pure compounds and continue to play a critical role in modern stereoselective synthesis.

Keywords: Asymmetric catalysis, chirality, enantioselective synthesis, resolving agents, stereoselective reactions, tartaric acid.

1 Introduction

The concept of molecular chirality, a cornerstone of stereochemistry, was first discovered by Louis Pasteur in 1848 through the manual separation of enantiomorphic crystals of (±)-ammonium tartrate (Gal, 2011). This seminal discovery not only laid the foundation for stereochemical understanding in organic chemistry but also underscored the critical role of molecular asymmetry in biological systems. Chirality has since emerged as a central concept in synthetic organic chemistry, materials science, and pharmaceutical development (Eliel & Wilen, 1994).

Ramchandra Thorat

Department of Chemistry, University of Mumbai, Kalina, Mumbai-400098.
ramthorat@chemistry.mu.ac.in

Owais Mujawar

Department of chemistry, University of Mumbai, Kalina, Mumbai-400098

Tartaric acid is one of the most significant naturally occurring chiral compounds, renowned for its structural simplicity, commercial availability, and high enantiomeric purity (Seebach & Kalinowski, 1984). It exists in two enantiomeric forms—(2R,3R)-(+)-tartaric acid and (2S,3S)-(–)-tartaric acid as well as in the achiral meso form (Clayden, Greeves, & Warren, 2012). The (2R,3R)-enantiomer is commonly found in nature, particularly in grapes and tamarind, and is biosynthesized *via* the ascorbic acid pathway (Davies & Morton, 2011). With its C_2 symmetry, two stereocenters, and multiple functional groups (dihydroxyl and dicarboxylic acid), tartaric acid provides a versatile scaffold for asymmetric catalysis (Noyori, 2002).

Asymmetric catalysis has become an essential tool in modern organic synthesis, enabling the preparation of enantiomerically enriched compounds with high atom economy and selectivity (Ojima, 2010). Early approaches to chirality induction involved chiral auxiliaries and optical resolution of racemates (Oppolzer, 1987). While effective, these methods are often inefficient and wasteful, requiring stoichiometric amounts of chiral reagents and generating undesired by-products (Sheldon, 2007). Catalytic asymmetric methodologies—particularly those utilizing chiral ligands and organocatalysts have thus become the preferred strategy for constructing complex chiral molecules (Mikami & Lautens, 2007).

Tartaric acid-derived compounds have played a pivotal role in this transformation. Their ability to form stable chelating ligands and coordinate with various transition metals has enabled the development of a wide range of chiral catalysts (Tang & Zhang, 2003). For example, tartaric acid-derived esters and amides are widely used in Sharpless asymmetric epoxidation (Katsuki & Sharpless, 1980), asymmetric dihydroxylation (Kolb et al., 1994), and hydrogenation reactions (Knowles, 2002). These systems typically rely on the precise configuration of the tartaric acid backbone to induce chirality in the substrate (Noyori, 2008).

One of the earliest and most influential uses of tartaric acid in catalysis is the modification of heterogeneous metal surfaces. (R,R)-Tartaric acid-modified nickel or Raney nickel catalysts have shown excellent performance in the enantioselective hydrogenation of β-ketoesters such as methyl acetoacetate (Blaser & Schmidt, 2010). These systems are industrially relevant and serve as models for heterogeneous enantioselective catalysis (Mallat & Baiker, 2004).

Tartaric acid has also been used to generate highly effective C_2-symmetric diphosphine ligands, which have enabled high enantioselectivity in palladium-, ruthenium-, and rhodium-catalyzed reactions (Togni & Grützmacher, 1998). These ligands have been employed in asymmetric additions, hydrogenations, and carbon–carbon coupling

reactions (Trost, 1991). Their structural rigidity, resulting from chelation, provides a highly defined chiral environment around the metal center (Xie & Zhou, 2012).

In organocatalysis, tartaric acid-derived scaffolds have been used to develop chiral Brønsted acids, such as chiral phosphoric acids (Akiyama & Mori, 2015), which are among the most versatile catalysts for enantioselective transformations including Mannich reactions, imine additions, and transfer hydrogenations (Terada, 2008). The dual functionalization of tartaric acid also allows for the introduction of bifunctional catalytic motifs, enhancing both reactivity and stereocontrol (Schreiner, 2003).

Recent studies have expanded the applications of tartaric acid derivatives beyond traditional asymmetric synthesis into the development of advanced chiral polymers that exhibit high enantioselectivity and mechanical robustness (Rajca, 1994). These chiral polymers have shown promising utility in areas such as enantioselective separation and catalysis, thereby broadening the scope of tartaric acid as a versatile monomeric unit. Additionally, tartaric acid-based frameworks have been integral in designing optically active materials with tailored electronic and photophysical properties, contributing to innovations in chiral optoelectronics and molecular recognition (Han, Zhao, & Yang, 2017). These materials demonstrate enhanced chiroptical responses and stability, which are essential for practical applications in sensing and asymmetric catalysis. Furthermore, the supramolecular assembly of tartaric acid derivatives has been exploited in the construction of highly selective and recyclable catalysts, harnessing noncovalent interactions to achieve substrate specificity and catalytic efficiency (Bräse, Höfener, & Zimmermann, 2010). The ability of these supramolecular systems to mimic enzyme-like behavior while maintaining operational simplicity under mild conditions underscores the importance of tartaric acid in sustainable catalyst design. Collectively, these advances highlight tartaric acid's expanding role as a foundational scaffold in the synthesis of environmentally benign and highly selective catalytic systems.

This review aims to provide a comprehensive overview of tartaric acid derivatives in asymmetric catalysis, including their synthesis, structural modifications, and catalytic applications across various reaction classes such as aldol condensations, Michael additions, Mannich reactions, Diels–Alder cycloadditions, asymmetric reductions, and epoxidations. The enduring utility of tartaric acid-based systems underscores their role as indispensable tools in stereoselective synthesis.

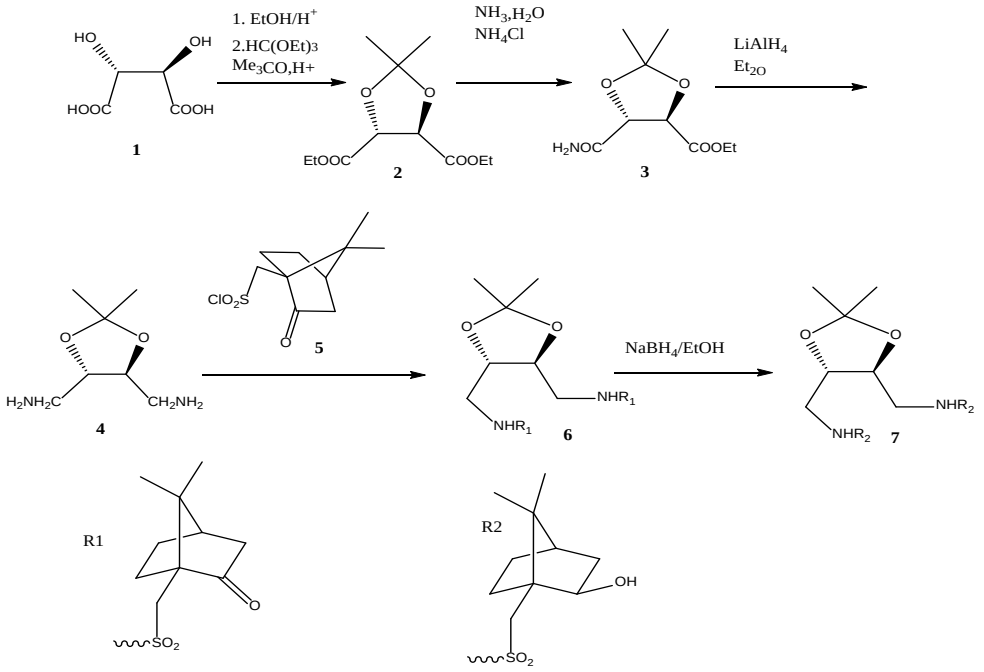
2 Tartaric acid derivatives and their applications in asymmetric synthesis

Enantioselectivity in the presence of tartaric acid derivatives

Enantiosective reactions are those reactions where one of the isomer forms predominantly. Enantioselective addition of alkylation group is fundametically important transformation in organic synthesis.

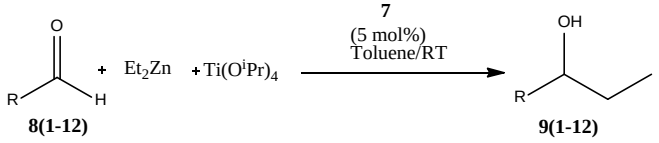
In order to apply the enantioselective addition of diethyl zinc to aldehydes and ketones, Ailing hui and coworkers (Hui, Zhang, Fan, & Wang, 2006) created chiral sulfonamide-based ligands on tartaric acid (**6** & **7**) in 2006. Diethylzinc was added to

p-chlorobenzaldehyde using a typical enantioselective addition process using the synthesised ligands **6** and **7**, which had a 5 mol% toluene ligand loading. With ligand **6** they obtained a poor enantiomeric excess of 20% ee, while ligand **9** achieved moderate enantioselectivity of 70% ee under the same condition.



Scheme 1: Synthesis of chiral sulfonamide based ligands

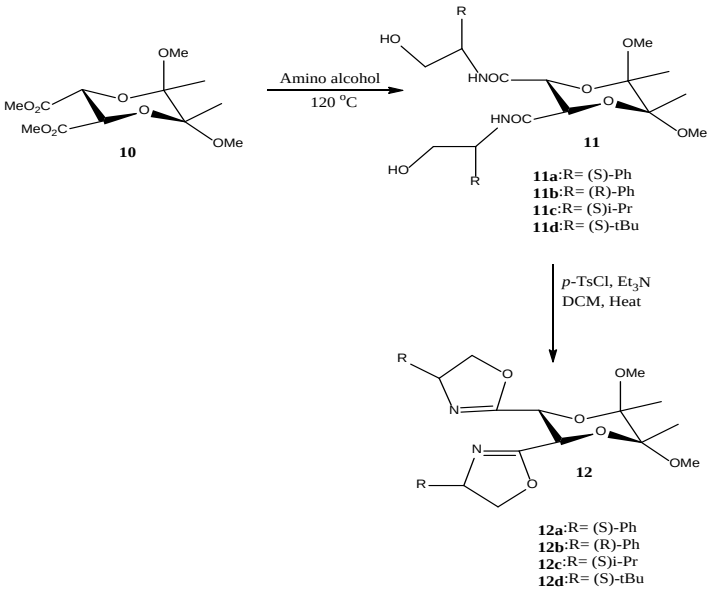
Table 1. Addition of diethylzinc to aldehydes in the presence of ligand



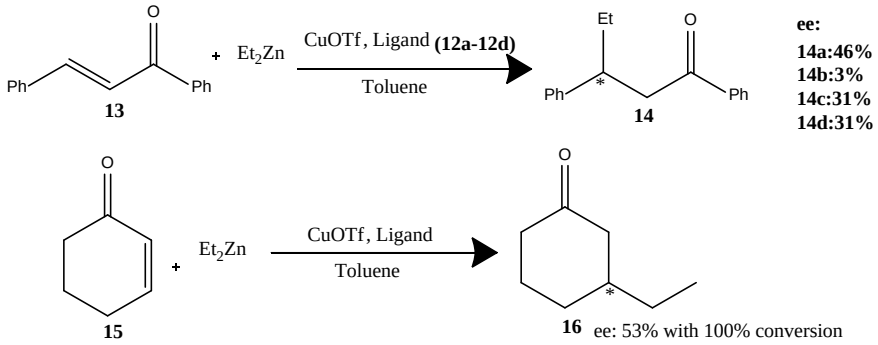
Sr. No.	R	Yields in (%)	Time (h)	ee (%)
1	4-MeC_6H_4	81	12	60
2	4-ClC_6H_4	95	1	70
3	C_6H_5	90	2	65
4	4-FC_6H_4	93	1	75
5	4-MeOC_6H_4	83	12	58

6	4-$MeOC_6H_4$	97	2	63
7	2-ClC_6H_4	92	3	38
8	2-MeC_6H_4	96	2	81
9	2-$MeOC_6H_4$	90	3	54
10	2-$MeOC_6H_4$	95	2	63
11	1-Naphthyl	85	3	83
12	Cinnamyl	95	3	31

A method for synthesising chiral bis(oxazolines) generated from tartaric acid was published by M T. Barros et al (Barros, Phillips, & Ventura, 2005). In order to create the bis(hydroxy) amide derivatives, cyclic diacetal diester (**10**) must condense with the appropriate 1,2-amino alcohols. The hydroxyl groups in the bis(hydroxy) amides (**11a-d**) were then activated as tosylates using *p*-toluenesulfonyl chloride in the presence of a significant excess of base (Et_3N). The activation and cyclization occur in one pot, allowing for the direct production of the bis(oxazolines) in equal or better yields when hected. The copper-catalyzed addition of diethylzinc to an acyclic and a cyclic enone was used to examine their ability to function as chiral ligands in metal-catalyzed processes (Scheme 2). Out of these four ligands, the ligand **12a** exhibit good enantioselective addition of diethyl zinc on chalcone with 46% ee. Additions to the cyclic enone i.e., 2-cyclohexenone **(15)** was also found to be more efficient with 53% ee with 100% reaction conversion.

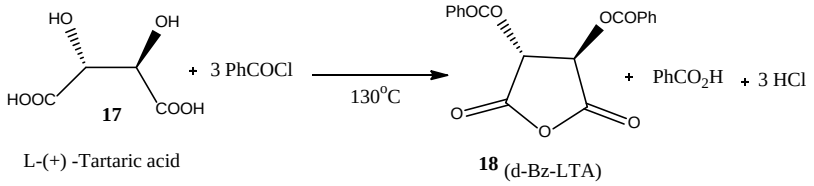


Scheme 2: Synthesis of bis(oxazolines)

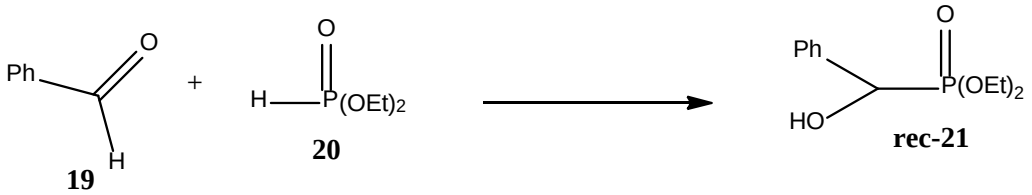


Scheme 3: Enantioselective addition of diethylzinc to chalcone and cyclohex-2-enone catalyzed by $Cu(OTf)_2$: chiral bis (oxazoline) ligands

In order to separate racemic alcohols and amines, Kaboudin reported that L-Tartaric anhydride and O,O'-dibenzoyl-L-tartaric anhydride (**18**, d-Bz-LTA) (Scheme 4) were used as effective chiral resolving agents. By reacting benzaldehyde with diethyl phosphite in the presence of magnesium oxide, racemic diethyl 1-hydroxy-1-phenylmethylphosphonate (rec-**23**) was produced in a quantifiable yield (Scheme 5).

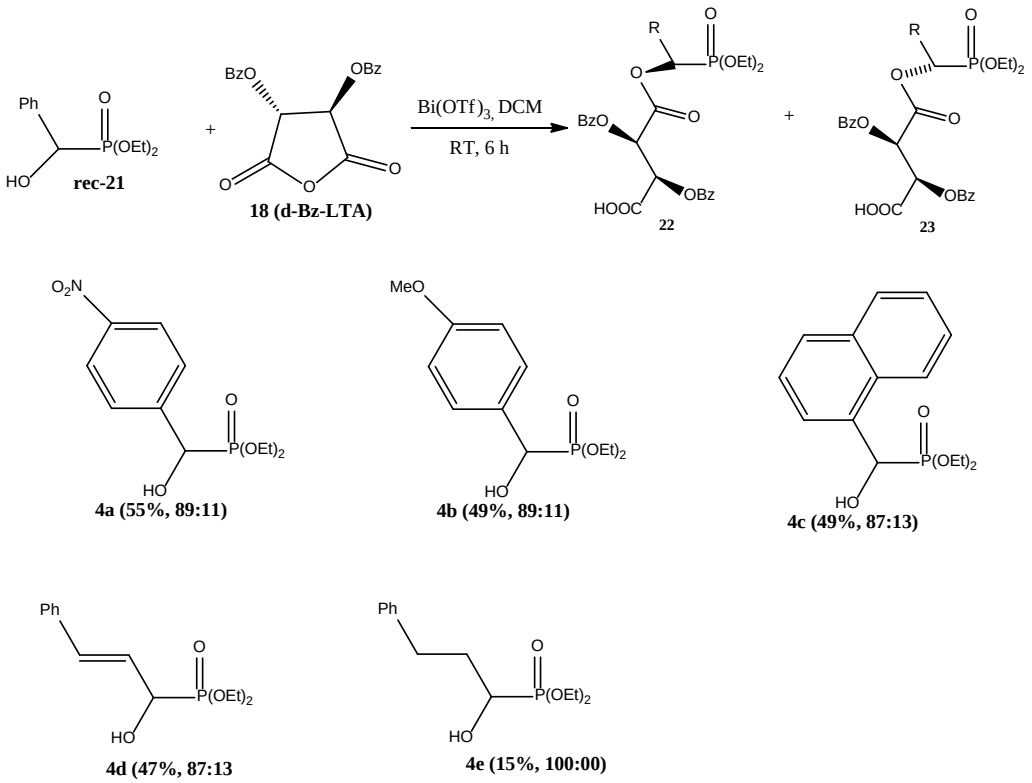


Scheme 4: Synthesis of O,O'-dibenzoyl-L-tartaric anhydride



Scheme 5: Synthesis of racemic alcohol

Thermal heating of a combination of L-tartaric acid and benzoyl chloride was used to create II-Bz-LTA (**18**). Racemic diethyl treatment in the presence of bismuth triflate (15 mol%) in an 86:14 ratio, 1-hydroxy-1-phenylmethylphosphonate (**21**) and (+)-dibenzoyl-L-tartaric anhydride (**18**) yielded two diastereomeric esters **22** and **23** (Scheme 6).



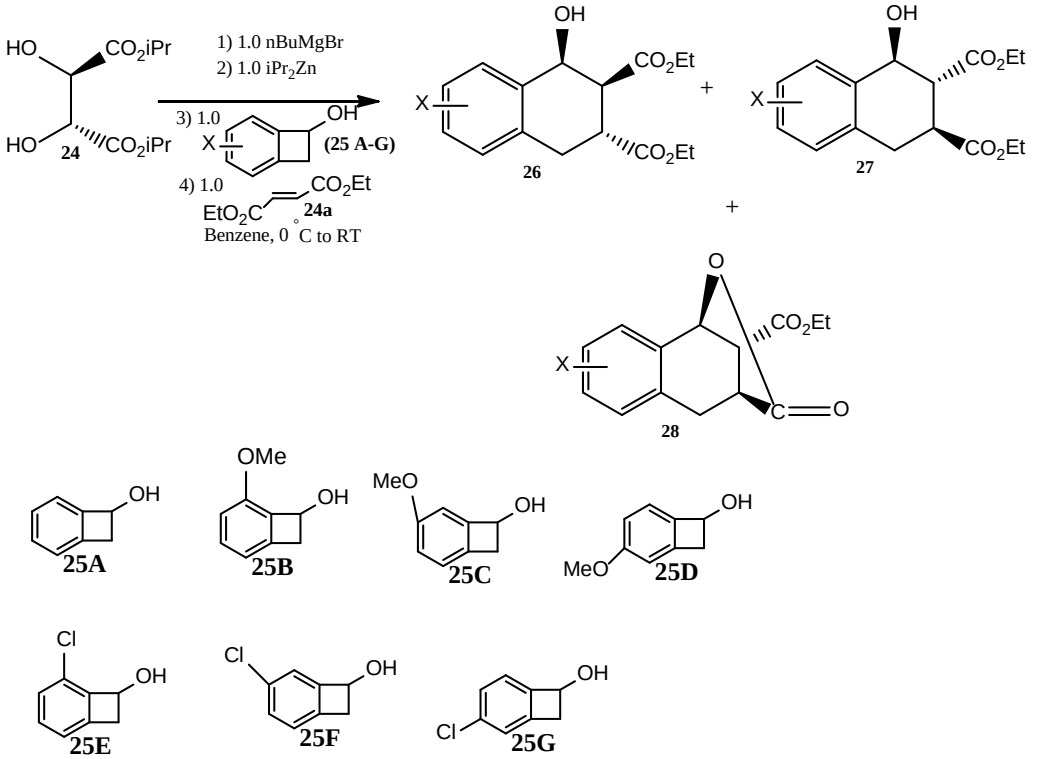
in parenthesis (conversion %, ratio of 21:22)

Scheme 6: Diastereoselective reaction of compound rec-**21** with **18** (d-Bz-LTA) in the presence of $Bi(OTf)_3$

Using tartaric acid ester, M. Takinami et al. (Takinami, Ukaji, & Inomata, 2006) have created optically active tetrahydronaphthalene. A magnesium and zinc bridging intermediate is created when disopropyl (R,R)-tartrate **24** is progressively treated with butylmagnesium bromide, dialkylzinc, and benzocyclobutenol **25A**. Fumaric acid ester was added after. **24a** by electrocyclic ring-opening process, *o*-quinodimethane is produced, and then Diels-Alder reaction is used to produce the equivalent optically active tetrahydronaphthalene(s) **26** and/or **27**. Initially, the first, dimethylzinc was used to analyse the Diels-Alder reaction with diethyl fumarate **24a** in CH_2Cl_2. At room temperature, the cycloaddition slowly produced primarily 1.2-cis-tetrahydronaphthalene **26**, as well as 1,2-trans-isomer **27** and cyclized lactone **28**.

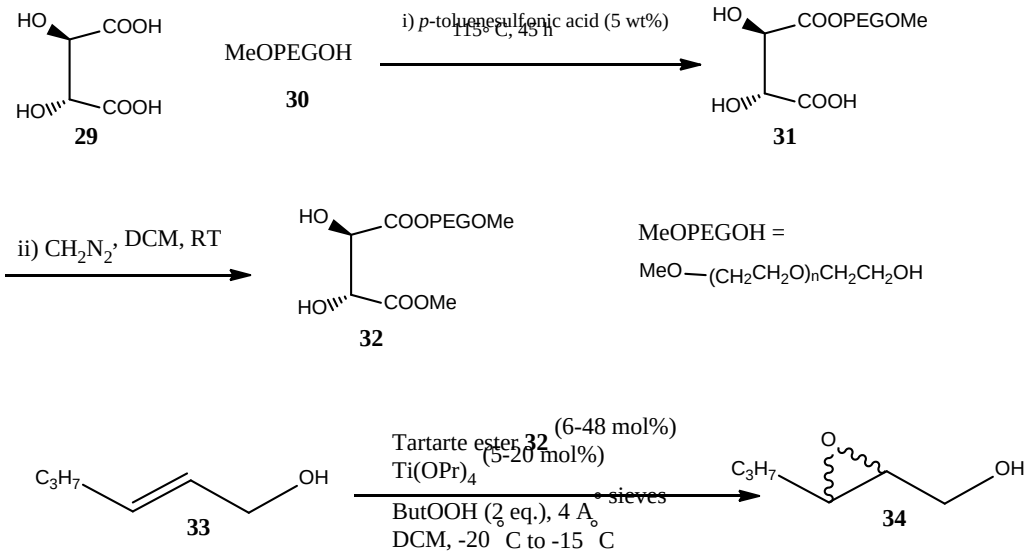
According to HPLC analysis, of the **28** produced, diisopropylzinc provided the greatest yields and enantioselectivities among the dialkylzincs studied. Solvent effects were also investigated. Higher enantioselectivities were obtained by the reaction in aromatic

solvents than in ether solvents. Finally, when the reaction was carried out in benzene, the 1, 2-cis-tetrahydronaphthalene **26** was generated in 83% ee.



Scheme 7: Assymetric Diels-Alder reaction of several *o*-quinomethanes generated from the corresponding benzocyclobutenols **27A-G**

H. Gau and cowokers (Fan, et al., 2002) synthesized Tartrate esters **31** and **32**. The $Ti(O^iPr)_4$/*tert*-butyl hydroperoxide was utilised to epoxidize trans-hex-2-en-1-ol. When trans-hex-2-en-1-ol is oxidised using $Ti(O^iPr)_4$ and *tert*-butyl hydroperoxide, significant chemical yields and good enantiomeric excesses up to 98% are achieved (Scheme 8).



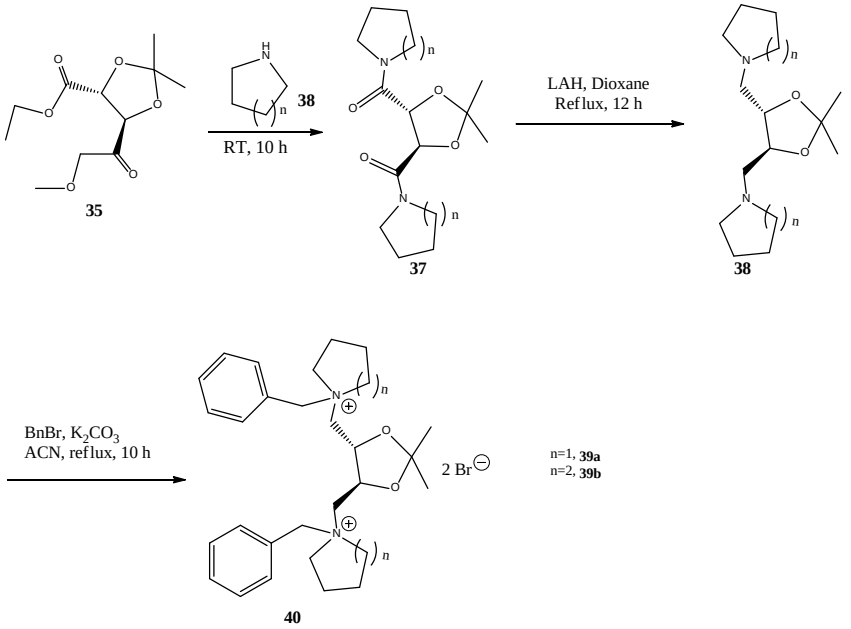
Scheme 8: Epoxidation of trans-hex-2-ene-1-ol with t-BHP catalysed by –(+)-tartrate ester and $Ti(OPr^i)_4$

Ca-Jie Zhu and coworkers (Zhu et al., 2013) have synthesized chiral cyclic phase transfer catalyst **39a** and **39b** using dimethyl acetal tartaric acid ester **35** (Scheme 9). Various malonate esters **(41a-e)** were subjected to Michael addition to benzalacetophenone **40** by using 5 to 10 mol% of chiral PTC (**39a & 39b**) in the presence of K_2CO_3 in toluene to get the Michael adduct (**42a-e**) (Scheme 10). Effective phase transfer catalysis was achieved with 95% yield and 84% ee for enantioselective Michael additions (Table 2).

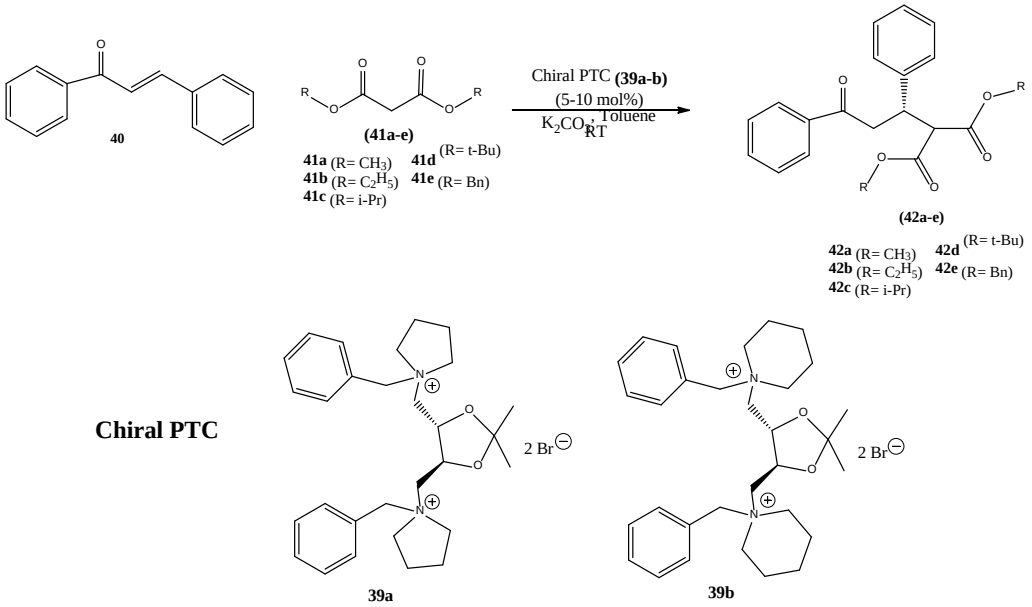
Table 2: Michael addition of malonate esters (**41a-e**) to benzalacetophenone **40** by using 5 to 10 mol% of chiral PTC (**39a** and **39b**) in the presence of K_2CO_3 in toluene to get Michael adduct (**42a-e**)

Malonate ester	**Catalyst**	**Mol%**	**Time (h)**	**Yield (%)**	**Optical purity (ee)**
Dimethyl malonate (**41a**)	**39a**	5	3	95	83.5%
		10	2	94	83.4%
	39b	5	3	95	84.0%
		10	2	95	84.3%
Dimethyl malonate (**41b**)	**39a**	5	5	93	84.7%
		10	3	93	84.6%
	39b	5	5	94	85.2%
		10	3	93	85.3%
Dimethyl	**39a**	5	11	89	85.7%

malonate (**41c**)		10	8	90	85.9%
	39b	5	11	90	86.2%
		10	8	89	86.4%
Dimethyl malonate (**41d**)	**39a**	5	38	85	87.6%
		10	31	84	87.8%
	39b	5	38	85	89.2%
		10	30	85	89.0%
Dimethyl malonate (**41e**)	**39a**	5	4	94	86.3%
		10	3	93	86.5%
	39b	5	4	93	88.0%
		10	3	94	87.9%



Scheme 9: Synthesis of chiral phase transfer catalyst using tartaric acid (**39a** & **39b**)

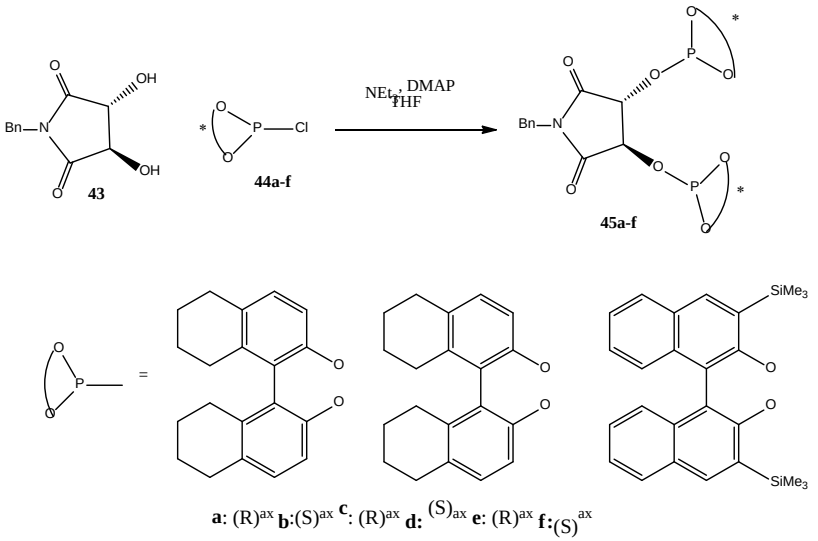


Scheme 10: Michael addition of malonates (**41a-e**) to benzalacetophenone (**40**) to get Michael adduct (**42a-e**)

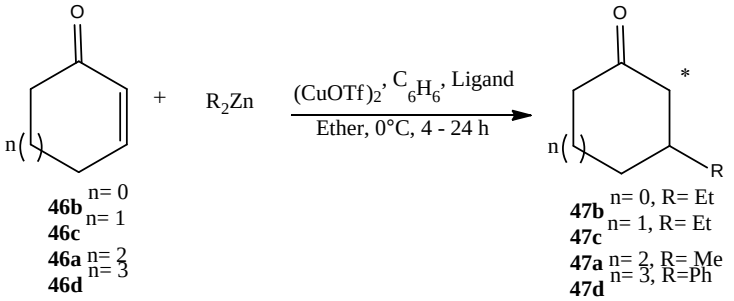
A-P Xing et al (Xing et al., 2013) synthesized diphosphate ligands (**45a-f**) form the reaction of (3R,4R)-*N*-benzyltartaric acid derivative and various chlorophosphoric acid diaryl ester (i.e., R or S 8H binaphthol, R or S binaphthol, Me_3Si-binaphthol) under triethylamine/DMAP condition (Scheme 11). The synthesized ligands were employed for the Cu-catalyzed asymmetric 1,4-conjugate addition (ACA) of organozincs to 2-cyclopentenone and 2-cyclohexenone. The R^{ax} binaphthol based ligand (**45c**) showed the highest enantioselectivity (up to 95% ee) in Cu catalysed reaction of cyclic enones (Scheme 12). The excellent ee was obtained because of synergic effect of L–(+) tartaric acid skeleton and the axially chiral binaphthol moiety of the ligand (**45c**) (Table 3).

Table 3. The Cu-catalyzed enantioselective 1,4-addition of R_2Zn to cyclic enones

Entry	Subs.	Product	Time (h)	Conc. (%)	Yield (%)	ee (%)
1	**46b**	**47b**	4	>99	21	95(R)
2	**46c**	**47c**	4	39	25	63(R)
3	**46a**	**47a**	24	30	21	67(R)
4	**46b**	**47d**	24	99	34	22(R)

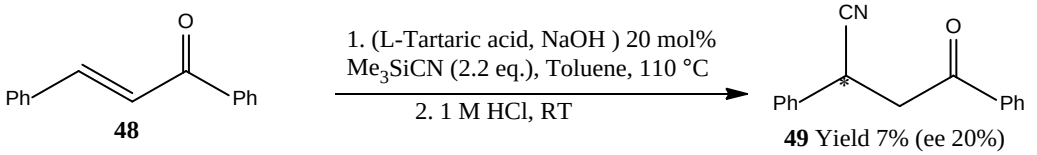


Scheme 11: Synthesis of diphosphite ligands



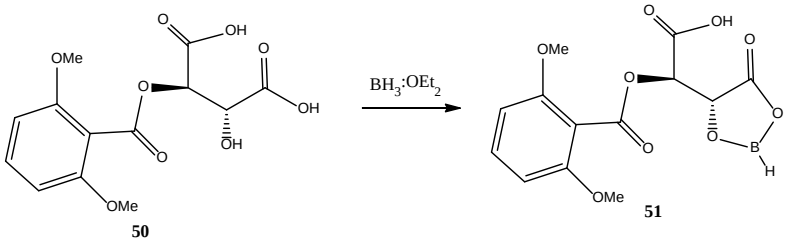
Scheme 12: Enantioselective 1,4-addition of R_2Zn to cyclic enones by Cu-catalyst

Jingya Yang et al (Yang, Wu, & Chen, 2010) used disodium salt of L-tartaric acid (which was *in situ* generated by the reaction of L-tartaric acid with NaOH in toluene) for enantioselective 1,4-addition of TMSCN to aromatic enones. The disodium salt of L-tartaric acid bearing two chiral centres yielded the product **49** in low yield with 20% ee (Scheme 13).



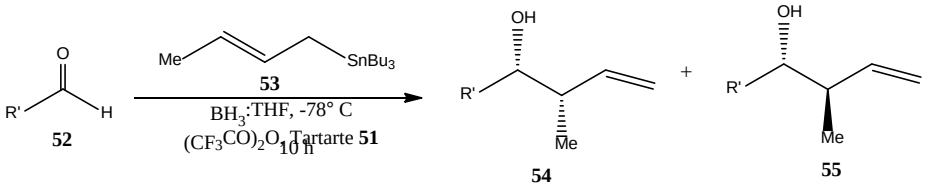
Scheme 13: 1,4-Addition of TMSCN to aromatic enones

A modified Yamamoto Lewis acid (CAB, 53) was created by James A. Marshall et al. (Marshall & Liao, 1998) by combining tartaric acid's 2,6-dimethoxybenzoic ester with 1.5 equiv. of BH_3 (Scheme 13). In the presence of 2 equiv. of CAB, crotyltributyltin (**53**) undergoes addition with typical achiral aldehydes (Scheme 14). The syn adducts **54** and trans adducts **55**, had enantioselectivity and diastereoselectivity of good to exceptional (78:22-92:8). Authors conclude that the strongly complex-controlled CAB-promoted additions effectively override the aldehyde substrate's natural facial preference. When enantioselective additions to specific aldehyde-Lewis acid complexes were made, Corey's theory of H-bonded transition states led to the production of syn-selective addition to such a complex, which is what caused the stereochemical outcome that was observed. Different aldehydes **52a-e** were screened for this addition reaction under optimized reaction condition corresponding data are summarized in Table 4.



50 **51**

Scheme 13: Synthesis a modified Yamamoto Lewis acid (CAB, 53)



52 **54** **55**

Scheme 14: Addition of crotyl stannane **53** to achiral aldehydes (**52a-e**)

Table-4: CAB-Promoted addition of crotyl stannane to achiral aldehydes

R'	Yield (%)	**54**:**55**	ee% of **54**
C_6H_{11}**(52a)**	70	92:8(97:3)	91
C_6H_{13} **(52b)**	74	91:9(88:12)	92
E-PrCH=CH **(52c)**	71	78:22(86:14)	89
C_6H_{13}C=C **(52d)**	70	79:21 (79:21)	71

$DPSOCH_2CH_2$ **(52e)**	73	88:12 (96:4)[e]	70

Conclusions

One of the most prevalent naturally occurring chiral chemical is tartaric acid. While its use in creating chiral ligands for metal-catalyzed processes has received extensive different research modifications on tartaric acid leading to formation of new chiral ligand which gives unique selectivity in chiral synthesis. Several recent reports including development of chiral ligand synthesis based on tartaric acid and its applications mainly in 1,2-additions, 1,4-additions, chiral reductions, Diels-Alder reactions have been described in respective schemes. Chiral tartaric acid derivatives play a vital role in chiral resolution and asymmetric synthesis and having tremendous scope in the field of pharmaceuticals, agrochemicals, flavour and perfumes.

References

Akiyama, T., & Mori, K. (2015). Stronger Brønsted acids: Recent progress. *Chemical Reviews, 115*(17), 9277–9306. https://doi.org/10.1021/cr5003868

Barros, M. T., Phillips, A. M. F., & Ventura, M. R. (2005). Synthesis of new chiral amines with a cyclic 1,2-diacetal skeleton derived from (2R,3R)-(+)-tartaric acid. *Tetrahedron: Asymmetry, 16*(17), 2946–2950. https://doi.org/10.1016/j.tetasy.2005.07.014

Blaser, H.-U., Schmidt, E. (2010). Asymmetric catalysis on industrial scale (2nd ed.). Wiley-VCH.

Blaser, H.-U., Spindler, F., & Thommen, M. (2007). Industrial applications of asymmetric catalysis. *Accounts of Chemical Research, 40*(12), 1240–1250. https://doi.org/10.1021/ar700134z

Bräse, S., Höfener, S., & Zimmermann, V. (2010). Chirality and optical activity in helicenes. *Chemical Society Reviews, 39*(11), 4030–4044. https://doi.org/10.1039/B921762H

Clayden, J., Greeves, N., & Warren, S. (2012). *Organic chemistry* (2nd ed.). Oxford University Press.

Davies, H. M. L., & Morton, D. (2011). Guiding principles for site-selective and stereoselective intermolecular C–H functionalization by donor/acceptor rhodium

carbenes. *Chemical Society Reviews*, *40*(4), 1857–1869. https://doi.org/10.1039/C0CS00014J

Eliel, E. L., & Wilen, S. H. (1994). *Stereochemistry of organic compounds*. Wiley.

Gal, J. (2011). Louis Pasteur, language, and molecular chirality. I. Background and dissymmetry. *Chirality*, *23*(1), 1–16. https://doi.org/10.1002/chir.20866

Guo, H., Fan, Y. C., Sun, Z., Wu, Y., & Kwon, O. (2002). Phosphine-catalyzed [3+2] cycloadditions of allenes with azomethine imines. *Chemical Communications*, *2002*(1), 118–119. https://doi.org/10.1039/B108685A

Han, J., Zhao, Y., & Yang, F. (2017). Helicenes: Synthesis and applications. *Advanced Materials*, *29*(23), 1700553. https://doi.org/10.1002/adma.201700553

Hui, A., Zhang, J., Fan, J., & Wang, Z. (2006). Catalytic asymmetric addition of alkylzinc and functionalized alkylzinc reagents catalyzed by chiral phosphines. *Tetrahedron: Asymmetry*, *17*(14), 2101–2107. https://doi.org/10.1016/j.tetasy.2006.07.003

Katsuki, T., & Sharpless, K. B. (1980). The first practical method for asymmetric epoxidation. *Journal of the American Chemical Society*, *102*(20), 5974–5976. https://doi.org/10.1021/ja00538a077

Kolb, H. C., VanNieuwenhze, M. S., & Sharpless, K. B. (1994). Catalytic asymmetric dihydroxylation. *Chemical Reviews*, *94*(8), 2483–2547. https://doi.org/10.1021/cr00031a009

Knowles, W. S. (2002). Asymmetric hydrogenations (Nobel lecture). *Angewandte Chemie International Edition*, *41*(12), 1998–2007. https://doi.org/10.1002/1521-3773(20020617)41:12<1998::AID-ANIE1998>3.0.CO;2-Q

Lojima, I. (Ed.). (2010). *Catalytic asymmetric synthesis* (3rd ed.). Wiley.

Mallat, T., & Baiker, A. (2004). Oxidation of alcohols with molecular oxygen on solid catalysts. *Chemical Reviews*, *104*(6), 3037–3058. https://doi.org/10.1021/cr0200116

Marshall, J. A., & Liao, J. (1998). Stereoselective total synthesis of pseudopterolide Kallolide A. *Journal of Organic Chemistry*, *63*(13), 4381–4384. https://doi.org/10.1021/jo980296m

Mikami, K., & Lautens, M. (Eds.). (2007). *New frontiers in asymmetric catalysis*. Wiley.

Noyori, R. (2002). Asymmetric catalysis: Science and opportunities. *Angewandte Chemie International Edition, 41*(12), 2008–2022. https://doi.org/10.1002/1521-3773(20020617)41:12<2008::AID-ANIE2008>3.0.CO;2-L

Noyori, R. (2008). Asymmetric catalysis: Science and opportunities revisited. *Chemical Reviews, 108*(7), 2447–2493. https://doi.org/10.1021/cr068373r

Oppolzer, W. (1987). Strategies for the enantioselective synthesis of natural products. *Tetrahedron, 43*(9), 1969–2004. https://doi.org/10.1016/S0040-4020(01)87877-8

Rajca, A. (1994). Organic diradicals: From spin–spin interactions to spin coupling between redox centers. *Chemical Reviews, 94*(4), 871–893. https://doi.org/10.1021/cr00027a008

Schreiner, P. R. (2003). Metal-free organocatalysis through explicit hydrogen bonding interactions. *Chemical Society Reviews, 32*(5), 289–296. https://doi.org/10.1039/B210307A

Sheldon, R. A. (2007). The E factor: Fifteen years on. *Green Chemistry, 9*(12), 1273–1283. https://doi.org/10.1039/B713736M

Takinami, M., Ukaji, Y., & Inomata, K. (2006). Total synthesis of hybocarpone and analogues thereof: A facile route via asymmetric catalysis. *Tetrahedron: Asymmetry, 17*(10), 1554–1560. https://doi.org/10.1016/j.tetasy.2006.05.011

Tang, W., & Zhang, X. (2003). New chiral phosphorus ligands for enantioselective hydrogenation. *Chemical Reviews, 103*(8), 3029–3070. https://doi.org/10.1021/cr020049y

Terada, M. (2008). Chiral phosphoric acids as versatile catalysts for enantioselective transformations. *Chemical Communications, 2008*(35), 4097–4112. https://doi.org/10.1039/B804129H

Togni, A., & Grützmacher, H. (Eds.). (1998). *Catalytic asymmetric synthesis: Ligands and complexes*. Wiley-VCH.

Tsuji, J. (2004). *Palladium reagents and catalysts*. Wiley.

Trost, B. M. (1991). The atom economy—A search for synthetic efficiency. *Science, 254*(5037), 1471–1477. https://doi.org/10.1126/science.1962206

Xie, J. H., & Zhou, Q. L. (2012). Chiral diphosphine and monodentate phosphine ligands on a chiral ferrocene scaffold. *Acta Chimica Sinica, 70*(14), 1427–1436.

Xing, A.-P., et al. (2013). Organocatalytic asymmetric synthesis of 3-substituted isoindolinones. *Tetrahedron, 69*(2), 455–459. https://doi.org/10.1016/j.tet.2012.10.058

Yang, J., Wu, S., & Chen, F.-X. (2010). Chiral sodium phosphate catalyzed enantioselective 1,4-addition of TMSCN to aromatic enones. *Synlett*, *2010*(18), 2725–2728. https://doi.org/10.1055/s-0030-1259107

Zhu, J.-J., et al. (2013). Efficient synthesis of chiral tetrahydroisoquinolines via an organocatalytic asymmetric transfer hydrogenation. *Tetrahedron*, *69*(34), 7253–7257. https://doi.org/10.1016/j.tet.2013.06.055