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Exploring the synthetic potential of epoxide ring opening reactions toward the synthesis of alkaloids and terpenoids: a review

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Epoxides are oxygen containing heterocycles which are significantly employed as crucial intermediates in various organic transformations. They are considered highly reactive three-membered heterocycles due to ring strain and they undergo epoxide ring opening reactions with diverse range of nucleophiles. Epoxide ring-opening reactions have gained prominence as flexible and effective means to obtain various functionalized molecules. These reactions have garnered substantial attention in organic synthesis, driven by the need to comprehend the synthesis of biologically and structurally important organic compounds. They have also found applications in the synthesis of complex natural products. In this review article, we have summarized the implementation of epoxide ring opening reactions in the synthesis of alkaloids and terpenoids based natural products reported within the last decade (2014–2023).

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Introduction

Epoxides are 3-membered oxygen containing heterocycles that play an important role in the synthesis of natural products. Epoxides are considered highly reactive molecules due to ring strain¹ and they undergo enantioselective ring opening reaction with a diverse range of reagents (Gilman reagent²) and nucleophiles³ such as carbon⁴ and oxygen nucleophiles *i.e.*, trimethylsilyl cyanides,⁵ aryllithiums,⁶ trialkylsilyl halides,⁷ alkylamines,⁸ carboxylic acids⁹ and phenols¹⁰ in the presence of numerous catalysts. The general reaction of epoxide ring opening reaction in the presence of nucleophile is shown in the Fig. 1.

Similarly, π -nucleophiles *i.e.*, allylsilanes, olefins,¹² and arenes¹³ have also been used for the ring opening reactions of epoxides. Sulfur nucleophiles¹⁴ also play an important role towards the epoxide ring opening reactions *i.e.*, alkanes and arene-thiols can also be used for the ring opening reaction of epoxides to synthesize β -hydroxy mercaptans or regioselective

products *i.e.*, β -hydroxysulfides.¹⁵ Similarly, α -azido ketone is prepared by the reaction of chloroepoxide with sodium azide.¹⁶

The epoxide ring opening reactions are highly employed in the synthesis of various natural products such as alkaloids, steroids, terpenoids, biopolymers, carotenoids, polyketides and flavonoids *etc.* which exhibit medicinal value. In 1963, an epoxide was first time reacted with heteroaromatic π -nucleophile to synthesize a natural product named as Indolmycin (an antibiotic).¹⁷ Vinyl epoxides are important synthetic precursors in organic synthesis¹⁸ as they lead towards the synthesis of (–)-(4*R*,5*R*)-Muricatacin (a natural acetogenin) *via* regio or stereoselective ring opening reaction of epoxide.¹⁹ Syntheses of numerous biological active compounds such as Sphingofungin,²⁰ Zoanthenol,²¹ marine ladder polyethers,²² Zampanolide,²³ *epi*-Muscarine,²⁴ Molestin E,²⁵ (–)-Epicoccin G and (–)-Rostratin A,²⁶ homoisoflavonoids,²⁷ Chlorotonils,²⁸ Lingzhiol,²⁹ Phomarol,³⁰ Isoandrographolide,³¹ Citrinadins,³² Iso-silybin,³³ polyester,³⁴ Mupirocin³⁵ and Bisfuranoxide³⁶ *etc.* have been accomplished by involving epoxide chemistry.

Predominantly, biologically active natural products *i.e.*, Epothilone A³⁷ 3 (antitumor activity), methyl-L-Callipeltose³⁸ 6 (cytotoxic activity against NSCLC N6 and P388 cell lines),

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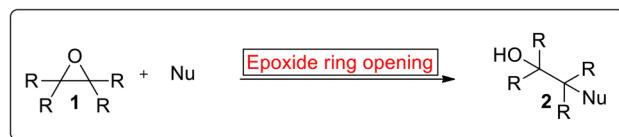


Fig. 1 General reaction of epoxide ring opening reaction.¹¹



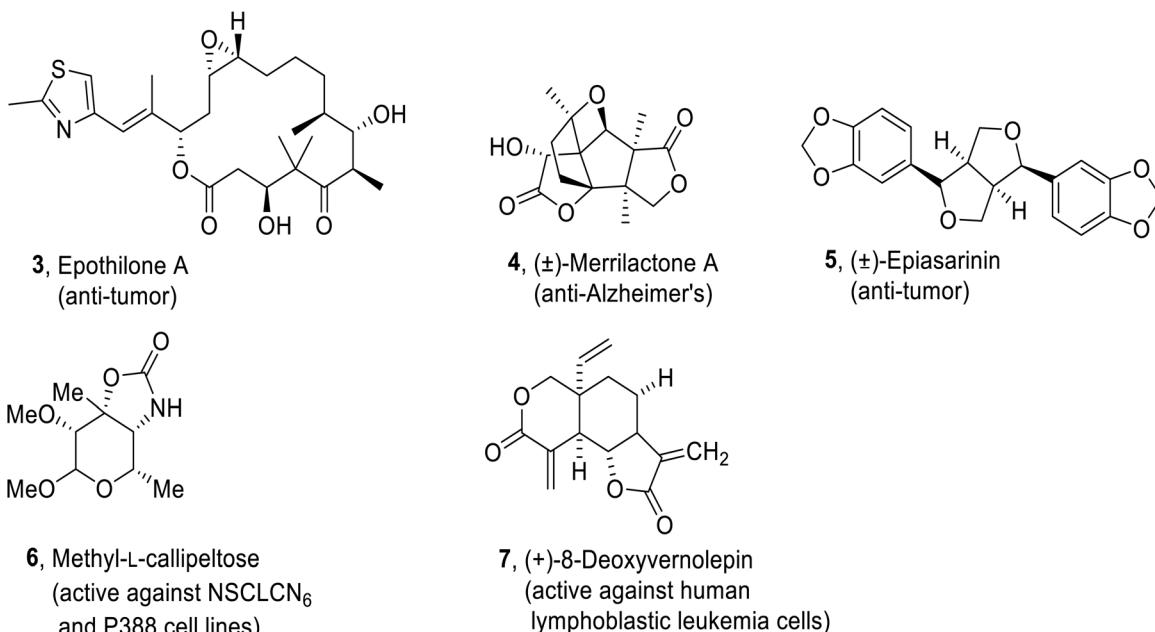


Fig. 2 Structures of some biologically active natural products (Epothilone A 3, (±)-Merrilactone A 4, (±)-Epiasarinin 5, Methyl-L-callipeltose 6, (+)-8-Deoxyvernolepin 7).

(-)Dactylolidole,³⁹ Petuniasterone D⁴⁰ (insecticidal), (±)-Merrilactone A⁴¹ 4 (active against Alzheimer's disease), (−)-Preussomerin,⁴² (+)-8-Deoxyvernolepin⁴³ 7 (active against human lymphoblastic leukemia cells), (±)-Epiasarinin⁴⁴ 5 (antitumour activity), Laulimalide,⁴⁵ (−)-Nakamurol A,⁴⁶ Prenylbisabolane,⁴⁷ (−)-Delobanone and (−)-*epi*-Delobanone⁴⁷ are generated by employing epoxide ring opening reactions (Fig. 2).

In 2006, research group of Oltra⁴⁸ reviewed the synthesis of natural products by involving epoxide opening reaction in the presence of titanocene (III). Vilotijevic and Jamison overviewed the syntheses of polycyclic polyether natural products and marine polycyclic polyethers by employing epoxide-opening reactions and endo-selective epoxide-opening pathways in 2009 (ref. 49) and 2010 (ref. 50) respectively. Similarly, Bugarin and allies, provided a review on the syntheses of polypropionates and other bioactive natural products by using epoxide chemistry in 2023.⁵¹ Our review focuses on the formation of alkaloids and terpenoids due to the comprehensive work reported on the syntheses of these natural products by involving epoxide ring opening reaction as one of the key steps, reported within the past decade (2014–2023).

Review of literature

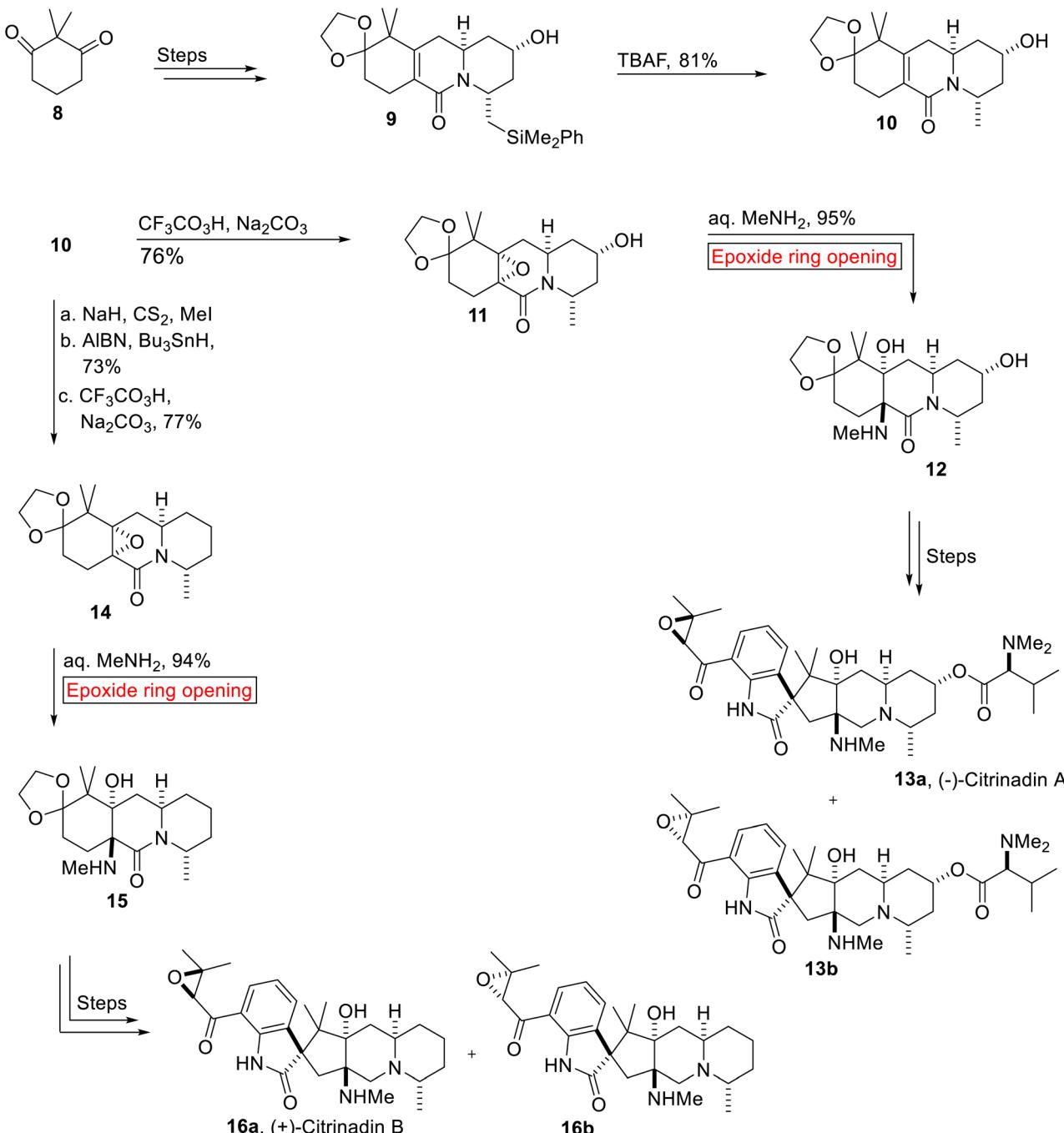
Syntheses of alkaloid-based natural products

Spirooxindole alkaloid. (−)-Citrinadin A 13a and (+)-Citrinadin B 16a are spirooxindole alkaloids which were isolated and reported by research group of Kobayashi in 2004 and 2005. They were found to demonstrate significant efficacy against human epidermoid carcinoma KB (13a, IC₅₀ = 10 µg mL^{−1}) and murine leukemia L1210 (13a, IC₅₀ = 6.2 µg mL^{−1}; 16a, IC₅₀ = 10 µg mL^{−1})⁵² cells. In 2014, Martin and co-workers disclosed the

concise, enantioselective syntheses of Citrinadins A 13a and B 16a that resulted in the revision of their stereochemical structures. Their strategy minimized protection/deprotection processes, refunctionalization and showed high diastereoselectivity. The stereochemistry of Citrinadins was based on the substrate-controlled reactions involving stereoselective epoxidation and epoxide ring opening reaction as key steps.⁵³ Total synthesis of (−)-Citrinadin A 13a and (+)-Citrinadin B 16b was accomplished from common intermediate lactam 10. The synthetic scheme initiated with the preparation of 9 from 2,2-dimethylcyclohexane-1,3-dione 8 over few steps. Then, 9 experienced tetra-*n*-butylammonium fluoride (TBAF)-mediated desilylation to produce unsaturated lactam 10 (81%) which was further subjected to peroxytrifluoroacetic acid-mediated diastereoselective epoxidation in order to furnish epoxide 11 (76%). In the next step, 11 underwent base-catalyzed diastereoselective epoxide ring opening reaction to generate amino alcohol 12 (95%) which forged (−)-Citrinadins A 13a over few steps. Similarly, synthesis of (+)-Citrinadin B 16a commenced with the formation of epoxide 14 (77%) from lactam 10 upon Barton deoxygenation followed by CF₃CO₂H-mediated epoxidation. Then, epoxide 14 was exposed to similar base (Me₂NH₂)-catalyzed epoxide ring opening reaction to generate another amino alcohol 15 (94%) which was further converted into a mixture of (+)-Citrinadin B (dr = 2.5 : 1) 16a and 16b over few steps (Scheme 1).

Cruciferane 27 (alkaloid) was extracted from the roots of plant (*Isatis indigotica*)⁵⁴ by the research group of Shi in 2012. It is used in traditional medicines to treat encephalitis B, carbuncles, erysipelas, influenza, and epidermic hepatitis. It has antipyretic properties as well. Total synthesis of Cruciferane was first reported in 2013 by research groups of Nair⁵⁵ and then





Scheme 1 Synthesis of (-)-Citrinadin A 13a and (+)-Citrinadin B 16b.

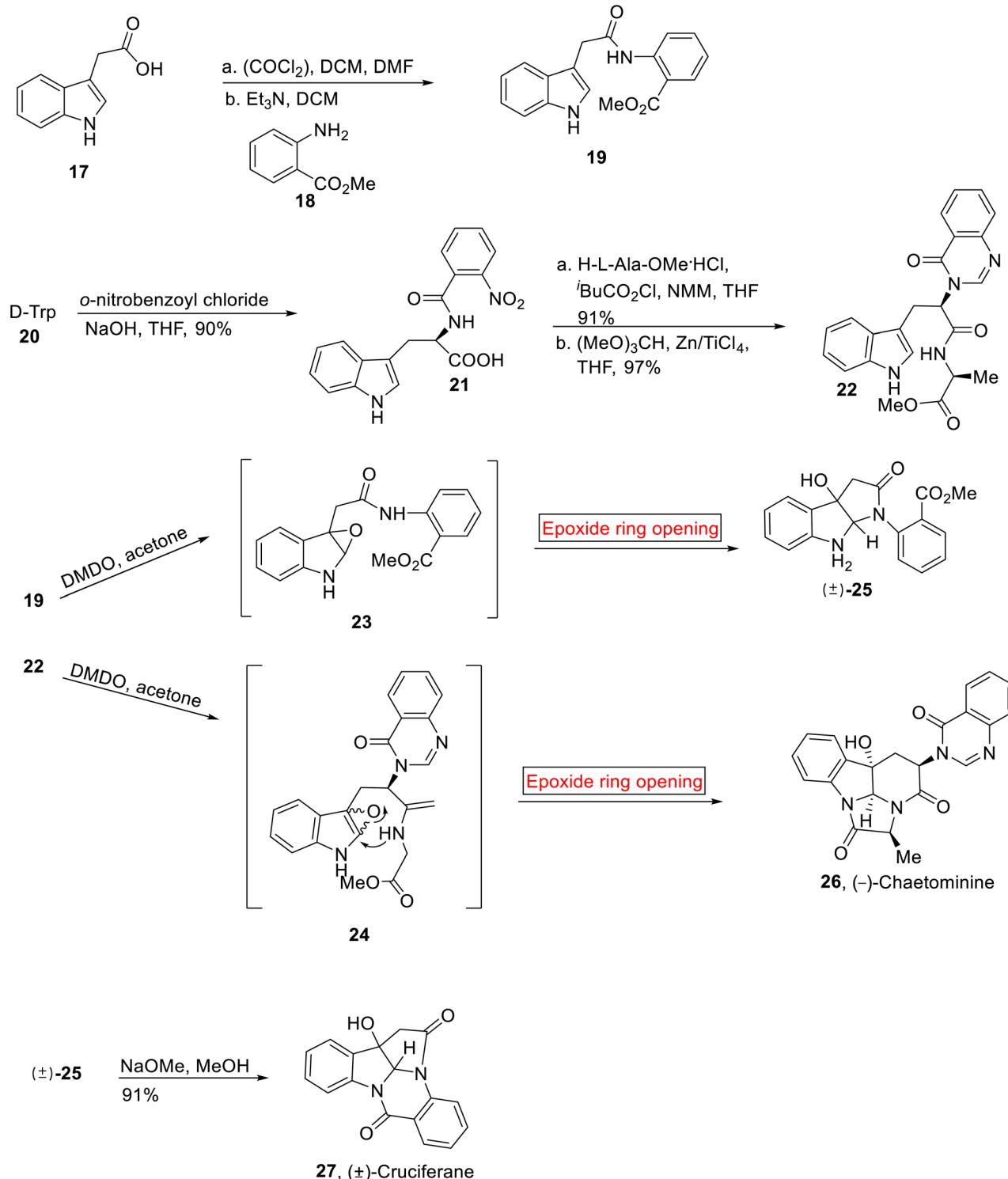
by Argade.⁵⁶ Further, Ji⁵⁷ has developed the synthesis of Cruciferane from complex and expensive starting materials and reagents. In the present work, Ghosh and Nagarajan in 2014 have reported the synthesis of (\pm)-Cruciferane 31 from simple route and economical starting materials by employing epoxide ring opening reaction as a key step (60.3%, overall yield).⁵⁸ Similarly, (-)-Chaetominine 36 is an alkaloid which was isolated by research group of Tan from *Chaetomium* sp. IFB-E015 (fungus present on the leaves of *Adenophora axilliflora*) in 2006.⁵⁹ It exhibits strong activity opposite to human colon

cancer SW1116 (28 nM)⁵⁹ and human leukemia K562 (21 nM) cell lines. The first total synthesis of (-)-Chaetominine 26 has been previously reported by research group of Snider,⁶⁰ second by Evano,⁶¹ third by Papeo.⁶² Then, the fourth approach was reported by Evano and colleagues in nine steps (14% overall yield).⁶³ In 2014, Huang *et al.*, reported the asymmetric, protecting group free total synthesis of (-)-Chaetominine 26 that features excellent overall yield (33.4%) as compared to other approaches, in one-pot sequence reactions. They devised the facile and shorter synthetic route by employing epoxide ring



opening reaction as one of the key steps.⁶⁴ Total synthesis of Cruciferane 27 was initiated by the reaction between indole 3-acetic acid 17 and oxalyl chloride, followed by base (Et_3N)-catalyzed amidation in the presence of methyl antranilate 18 to afford amidation product 19 (78%). The synthesis towards (–)-Chaetominine 36 began with the preparation of aroylated

product 21. The aroylated product 21 (90%) was obtained by the treatment of D-tryptophan 20 with *o*-nitrobenzoyl chloride which was further treated with L-alanine methyl ester hydrochloride and $^1\text{BuCO}_2\text{Cl}/\text{NMM}$ (*N*-methylmorpholine) followed by reaction with $\text{HC}(\text{OMe})_3$ and *in situ* generated TiCl_4 to provide quinazolinone 22 (97%). Then, compound 19 and 22



Scheme 2 Synthesis of (–)-Chaetominine 26 and (±)-Cruciferane 27.



were individually subjected to DMDO-mediated epoxidation to provide epoxides **23** and **24** (96%) respectively which further experienced intramolecular epoxide ring opening reaction to furnish (\pm)-**25** (85%) and (–)-Chaetominine **26** (42%) respectively. Then, the compound (\pm)-**25** was reacted with NaOMe (MeOH) to render racemic (\pm)-Cruciferane **27** in 91% yield (Scheme 2).

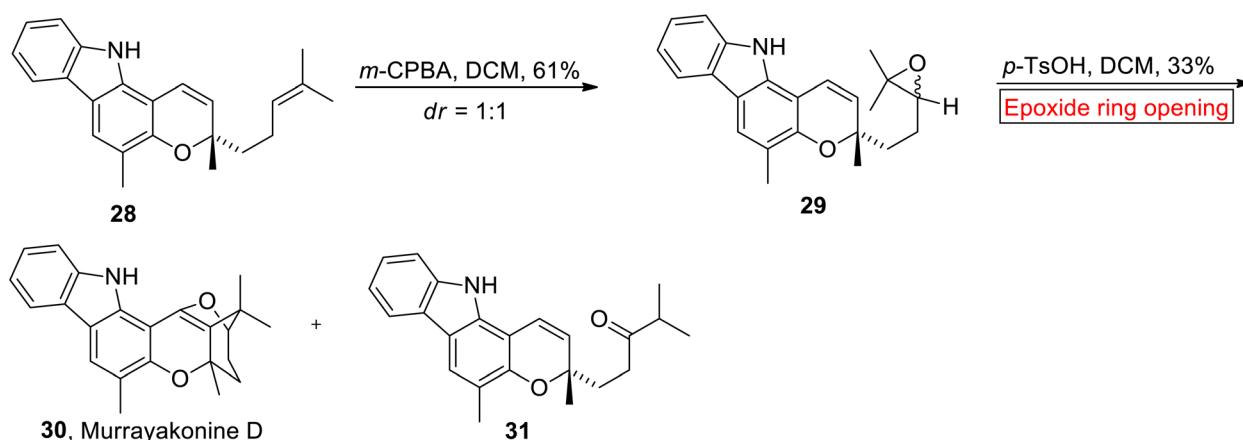
Carbazole alkaloids. Carbazole alkaloids (with a pyrrole moiety) are prevalent natural substances derived from multiple plant species as well as bacteria and fungi.⁶⁵ Murrayakonine D **30** (carbazole alkaloid) has 6/6/6/5 ring system which was extracted from *Murraya koenigi* (medicinal plant).⁶⁶ Research group of George has reported the synthesis of Murrayakonine D **30** (33% overall yield) in 2017 *via* epoxide ring opening reaction.⁶⁷ In the first step, Mahanimbine **28** (which was prepared according to research group of Knölker⁶⁸) went through meta-chloroperoxybenzoic acid (*m*-CPBA)-mediated epoxidation to generate **29** (61%). The compound **29** was further subjected to acid (*p*-TsOH)-catalyzed epoxide ring opening reaction in DCM to provide inseparable mixture of **30** and undesired ketone **31**. The mixture was washed with cold MeOH to separate Murrayakonine D **30** (Scheme 3).

Diterpenoid alkaloids. Weisaconitine D **35**, Cochlearenine **39**, Paniculamine **40** and *N*-ethyl-1 α -hydroxy-17-Veratroyldictyzine **42** are polycyclic diterpenoid alkaloids which are extracted from *Aconitum*, *Delphinium*, and *Consolidum* plants. These diterpenoid alkaloids exhibit anti-arrhythmic, anti-inflammatory, analgesic, and other medicinal properties.^{69–71} Owing to the structural complexity and pharmacological activities of diterpenoid alkaloids with varying oxygenation and substitution patterns, research group of Sarpong in 2017 reported the first syntheses of C-18, C-19 and C-20 diterpenoid alkaloids by involving ring opening reaction of epoxide.⁷² The synthetic route towards C-18 diterpenoid alkaloid (Weisaconitine D) **35** initiated with the formation of epoxy ether **33** from allylic alcohol **32** over few steps. The epoxy ether **33** underwent titanium-mediated epoxide ring opening reaction regioselectivity, followed by methylation, which rendered **34** (66%, 2 steps, rr = 14 : 1). The compound **34** was subjected to KOH-catalyzed hydrolysis, acetylation, LiAlH₄-mediated

reduction and subsequent deprotection using aq. HCl to furnish Weisaconitine D **35** (54%, 4 steps). Similarly, the synthetic endeavor towards C-20 diterpenoid alkaloids (Cochlearenine **39**, Paniculamine **40**, Veratroyldictyzine **42**) was commenced with the preparation of demethylated products **36** and **37** (51%) from allylic alcohol **32** over few steps. Then, compound **36** and **37** were subjected to KOAc-catalyzed epoxide ring opening reaction to render α -hydroxyketone **38** which was further exposed to Pd/C hydrogenation accompanied by reduction (LiAlH₄) to forge Cochlearenine **39** (63–77%, 3 steps). Then, further treatment of **39** with H₂O₂ furnished Paniculamine **40**. Finally, *N*-ethyl-1 α -OH-17-Veratroyldictyzine **42** (quant.) was attained by veratroylation of **39** with **41** in DMAP followed by titration with trifluoroacetic acid (TFA) (Scheme 4).

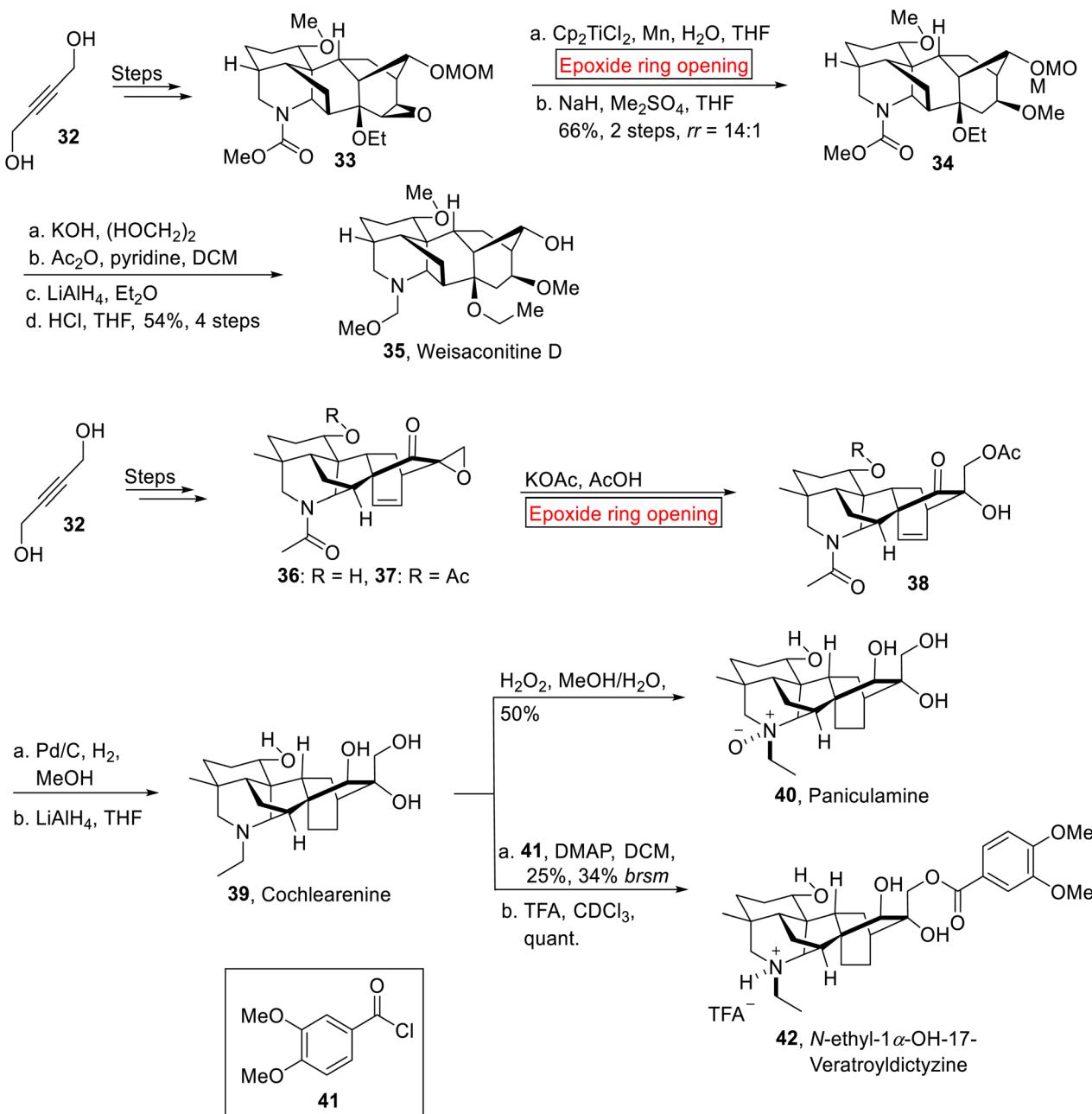
Guaiipyridine alkaloid. Cananodine **49a** is a rare⁷³ guaiipyridine alkaloid which was isolated from *Cananga odorata*⁷⁴ (ylang-ylang). In South Asia, *C. odorata* has been used in folk medicines. Recently, Cananodine **49a** was isolated from *Cyperus scariosus*.⁷⁵ It is biologically potent opposite to Hep 2,2,15 hepatocarcinoma ($IC_{50} = 3.8 \mu\text{g mL}^{-1}$) and Hep G2 ($IC_{50} = 0.22 \mu\text{g mL}^{-1}$) cell lines.⁷⁶ Various transition metals-mediated cross-coupling reactions have been employed to carry out the synthesis of several intricate organic compounds.^{77,78} In 2017, Shelton *et al.* reported the synthesis of optically active Cananodine **49a** by utilizing palladium-mediated cross coupling and epoxide ring opening reaction as significant steps.⁷⁹ In the first step, pyridyl iodide **43** and dienylboronate **44** were reacted under Pd-catalyzed cross coupling reaction in the presence of Ag₂O to afford **45** in excellent yield (81%). Next, **45** underwent asymmetric dihydroxylation to furnish diol **46** (52%). In the next step, diol **46** was converted into epoxide **47** (57%) which was further subjected to *n*-butyllithium-mediated intramolecular epoxide ring opening reaction as a key step to provide **48** (33%). Lastly, compound **48** underwent hydrogenation of methylene group in the presence of Wilkinson's catalyst to synthesize Cananodine **49a** and its epimer **49b** as a 1:1 inseparable mixture of diastereomers in 49% yield (Scheme 5).

Akuammiline alkaloid. Alstolactine A **54** belongs to a family of akuammiline alkaloids which is genetically related to indole monoterpenoids. It was isolated by Liu and research group of



Scheme 3 Synthesis of Murrayakonine D **30**.



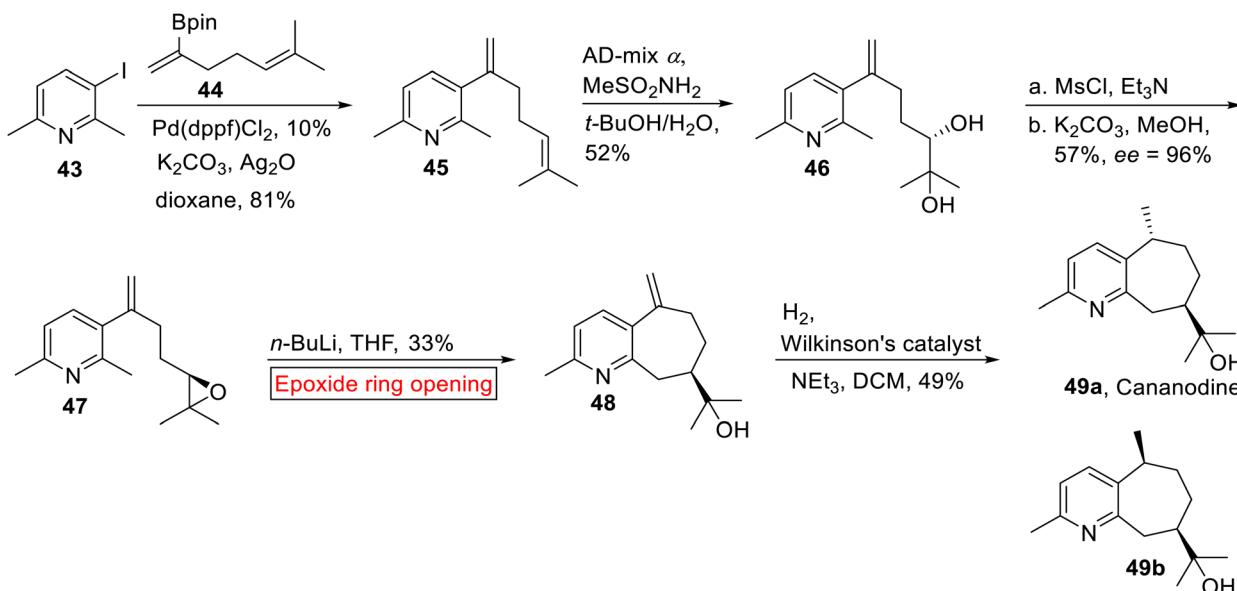


Scheme 4 Synthesis of Weisaconitine D 35, Cochlearenine 39, Paniculamine 40, Veratroyldictyzine 42.

Luo, from leaves of *Alstonia scholaris*.^{80,81} In the present research, Gao and co-workers have used an epoxide ring opening reaction for the first total synthesis of Alstolactine A 54 in 2017.⁸² The strategies described by research group of Gao may offer a unique perspective in the synthesis of akuammilines and their derivatives for future medicinal studies. The synthetic endeavor commenced with the synthesis of 51 from L-2-allylglycine 50 over several steps, which further experienced base-mediated epoxidation in MeOH to forge epoxide 52 (80%). In the next step, epoxide 52 underwent acid-catalyzed epoxide ring opening reaction to afford compounds 53a (31%) and 53b (42%). Finally, compound 53a was subjected to Pd/C-mediated

hydrogenation followed by methylation to furnish asymmetric Alstolactine 54 in 79% yield (Scheme 6).

Bis-indole alkaloid. (–)-Melodinine K 60 is a bis-indole alkaloid which belongs to the class of *Aspidosperma-Aspidosperma* which was isolated from *Melodinus tenuicaudatus* (plant) by Luo and colleagues in 2010.⁸³ It displays strong cytoidal activity opposite to cell line of breast cancer ($IC_{50} = 2.7 \mu\text{M}$) as compared to cisplatin ($IC_{50} = 18.7 \mu\text{M}$) and vinorelbine ($IC_{50} = 17.2 \mu\text{M}$). In 2020, Andrade and allies disclosed the first synthesis of (–)-Melodinine K 60 by employing epoxide ring opening reaction as one of the key steps.⁸⁴ Due to structural complexity and low isolation yield from natural source, they



Scheme 5 Synthesis of optically active Cananodine 49a.

developed an efficient method for the synthesis of (–)-Melodinine K **60** for future research on its biological functions. In the first step, (–)-tabersonine **55** was treated with NaH and TrocCl (2,2,2-trichloroethoxycarbonyl chloride) followed by stereo divergent oxidation in the presence of TFA and *m*-CPBA to afford *N*-Troc pachysiphine **56** (38%). In the next step, compound **56** was treated with *m*-CPBA and then with trifluoroacetic anhydride (TFAA) to afford iminium ion **57**. Then, the stereo divergent attack of iminium ion **57** at the C-15 of (–)-16-allyloxytabersonine **58** followed by Pd (PPh_3)₄-catalyzed deprotection afforded alcohol **59**. Finally, alcohol **59** went through epoxide ring opening reaction with subsequent deprotection reaction to forge (–)-Melodinine K **60** in 40% yield (Scheme 7).

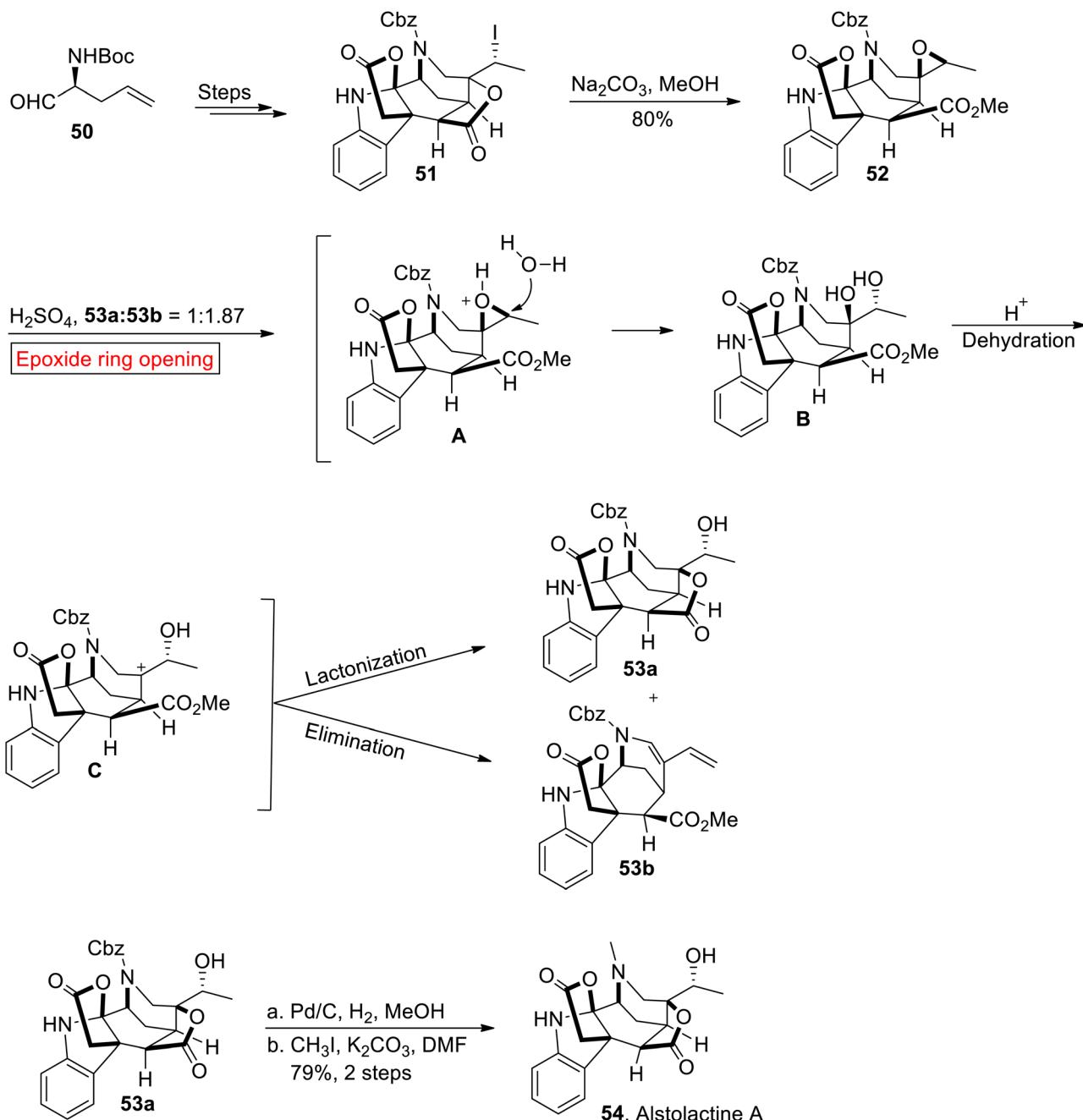
Quinolone alkaloid. Virdicatin **65** is a quinolone alkaloid (secondary metabolites) which exhibits antiviral, antibacterial, antiallergic, and antitumor activities.^{85,86} Quinolone core containing Virdicatin **65** acts as a scaffold for synthesis of natural and synthetic compounds.⁸⁷ In 2021, Chang *et al.* reported the synthesis of Viridicatin **97** by involving epoxide ring opening reaction as one of the key steps.⁸⁸ Their research work demonstrates the utilization of natural and synthetic processes for the efficient synthesis of quinolone alkaloids that would suggest promising directions for exploring their biological activities in future studies. In the first step, cyclopeptin **63** was obtained by Asqk (methyl transferase)-mediated cyclization with subsequent treatment (methylation) of **61** with **62**. Then, cyclopeptin **63** was subjected to desaturation accompanied by asymmetric epoxidation in the presence of 2-oxoglutarate (Fe/2OG) dependent oxygenase and AsqJ to synthesize cyclopenin **64**. In the next step, cyclopenin **64** experienced AsqJ-catalyzed epoxide ring opening reaction to render Virdicatin **65** (Scheme 8).

Isoquinolones such as Siamine **69**, Cassiarin A **71** and Rupreschstyryl **75** are biological active compounds. Research

groups of Glorius⁸⁹ (2014), Huang⁹⁰ (2017) and Kou⁹¹ described the synthesis of isoquinolones in different ways but their synthetic route faced several drawbacks due to coupling partners. In 2021, Wang and coworkers reported the syntheses of isoquinolones by employing epoxide ring opening reaction as one of the key steps for the first time in efficient yield within fewer steps.⁹² In the first step, Pd-catalyzed ring opening of epoxide **67** occurred with *N*-methoxybenzamide **98** to render *N*-methoxyisoquinolone **68** in the presence of hexafluoroisopropanol (HFIP) and appropriate base *i.e.*, triethylamine (TEA). In the next step, isoquinolone **68** was converted into Siamine **69** (76%, 2 steps) *via* sequential reduction and demethylation. Similarly, isoquinolone **68** underwent reduction (NaH) followed by coupling with *in situ* prepared propyne to afford alkyne **70** (87%). Finally, Cassiarin A **71** (37%, overall yield) was obtained from alkyne **70** *via* demethylation (BBR₃) with subsequent 6-*endo*-dig cyclization. The synthetic endeavor towards Rupreschstyryl **75** was initiated with the formation of isoquinolin-1-one **74** from **72** and epoxide **73** through epoxide ring opening reaction under optimized conditions. Lastly, compound isoquinolin-1-one **74** experienced reduction followed by deprotection (MOM) reaction to afford Rupreschstyryl **75** in 83% yield over 2 steps (Scheme 9).

Broussonetine alkaloid. The Glyphaeaside C **84** (iminosugars) having polyhydroxylated phenylalkyl chain belongs to broussonetine alkaloid family which was extracted from *Glyphaea brevis*.⁹³ Because of side-chain character of Glyphaeaside C **84**, it inhibits almond β -glucosidase, rice α -glucosidase and snail β -mannosidase. In 2021, Pyne *et al.* reported the synthesis of Glyphaeaside C **84** by utilizing epoxide ring opening reaction.⁹⁴ For stereochemical reasons, they synthesized **79** by utilizing epoxide ring opening reaction instead of carbonyl addition. Firstly, β -D-arabinofuranose **76** rendered vinylpyrrolidine **77** (28%) *via* treatment over few steps which





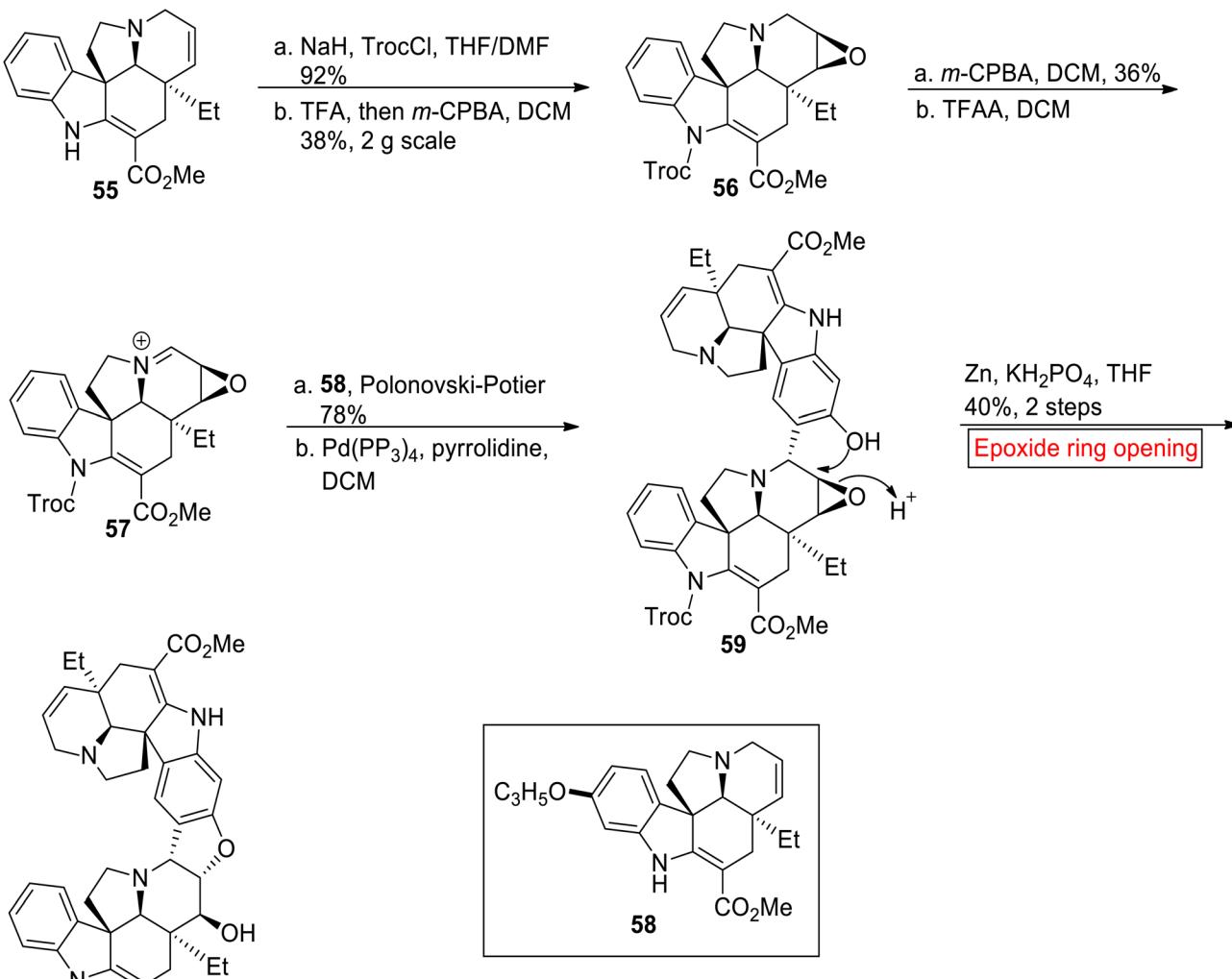
Scheme 6 Total synthesis of Alstolactine A 54.

upon epoxidation (*m*-CPBA) furnished epoxides **78a** (57%) and **78b** (29%). In the next step, **78a** underwent epoxide ring opening reaction in the presence of Gilman reagent in THF to synthesize alcohol **79** in a good yield (84%). Secondly, 4-allylanisole **80** was subjected to *O*-demethylation with BBr_3 (in DCM) accompanied by benzylation (acetone) to yield **81** (44%). In the next step, alkene **82** was prepared by the Grubbs' I-catalyzed reaction of **79** with **81**. Finally, alkene **82** was reacted with AD-mix- α /AD-mix- β (Sharpless asymmetric dihydroxylation) with subsequent deprotection reaction to furnish four enantiomers **83a/83a'**, and **83b/83b'** respectively. According to the specific

rotation data, it was suggested that **83a** was the enantiomer of Glyphaeaside C **84** (Scheme 10).

Syntheses of terpenoid-based natural products

Diterpenoid. Eurifoloid A **94** is a diterpenoid, belongs to a phorboid family of natural product which was extracted from *Euphorbia nerifolia*.⁹⁵ It exhibits biological activities⁹⁶ such as antitumor and anti-HIV. Synthesis of Eurifoloid A **94** has remained a challenging task⁹⁷ for chemists due to the presence of congested stereogenic centers such as quaternary stereocenter, angeloyloxy and tigloyloxy groups in its structure. Liu⁹⁸

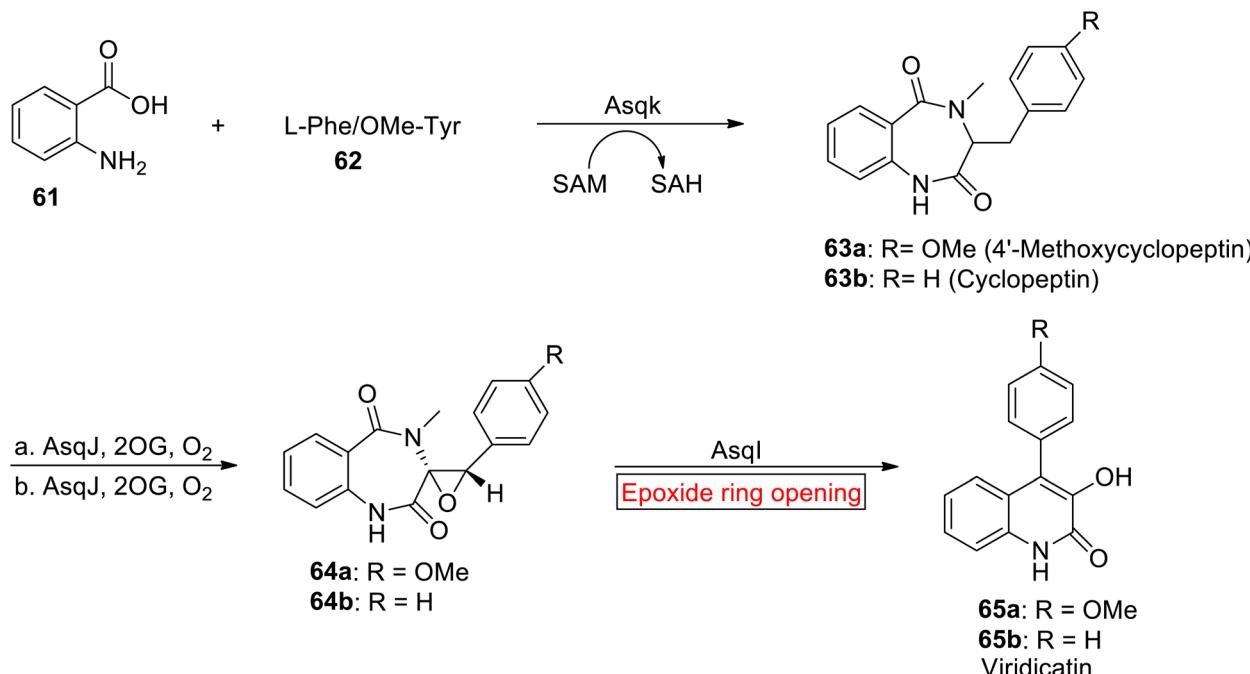


Scheme 7 Synthesis of (-)-Melodinine K 60.

and colleagues, first time reported the synthesis of tricyclic core **93** of Eurifoloid A **94** by employing ring opening reaction of epoxide as one of the key steps in 2017. The synthetic route initiated by the reaction of compound **85** with alkyl bromide **86** using Mg, THF (*in situ* Grignard reagent) followed by Wittig reaction to generate *Z*-vinyl iodide **87** (70%). In the next step, bromofuran carbaldehyde **88** underwent reduction (DIBAL-H), followed by protection and then Br-Sn exchange yielded tin reagent **89** (90%). Further, *Z*-vinyl iodide **87** and tin reagent **89** were reacted under Stille coupling conditions. Later, TBS group deprotection rendered coupled product **90** (70%). The coupled product **90** further experienced oxidative rearrangement and then type II intramolecular [5 + 2] cycloaddition reaction in the presence of tetramethylpiperidine (TMP) to provide the compound **91** (30%) having [5-7-7] tricyclic core. Compound **91** was then subjected to sequential diastereoselective reduction and *m*-CPBA-mediated oxidation (DCM) to furnish the epoxide **92** (79%). Finally, the ring opening reaction of epoxide **92** in the presence of BF₃·Et₂O using DCM as solvent, resulted in the core structure **93** (that contains reduced strain bicyclo[4.4.1]undecane ring system featuring *cis*-bridgehead) of Eurifoloid A **94** but with opposite stereochemistry at C8 (Scheme 11).

(±)-Brussonol **104** and (±)-Komarovquinone **106** belong to a family of ictexane diterpenes, isolated from terrestrial plants containing fused tricyclic skeleton (6-7-6). (±)-Brussonol **104** and (±)-Komarovquinone **106** display antiprotozoal, anticancer and cytotoxic activities. These natural products were synthesized by a number of reactions such as Ga(III)-catalyzed cycloisomerization,⁹⁹ tandem C-H oxidation/cyclization/rearrangement,¹⁰⁰ intramolecular Marson-type cyclization,¹⁰¹ Pd-catalyzed intramolecular Heck reaction,¹⁰² intramolecular nucleophilic cyclization,¹⁰³ cationic ring expansion,¹⁰⁴ TiCl₄-catalyzed Friedel-Crafts cyclialkylation^{105,106} and Pt-mediated hydrative cyclization.¹⁰⁷ In 2019, Burtoloso and Ahmad¹⁰⁸ disclosed the syntheses of (±)-Brussonol **104** (18.4%, overall yield) and (±)-Komarovquinone **106** (7% overall yield) by utilizing regioselective epoxide ring-opening reaction. The method developed by Burtoloso and Ahmad facilitated the efficient synthesis of these compounds till date, in order to achieve high yields in less steps as compared to previous approaches by employing similar starting materials. The synthetic approach





Scheme 8 Synthesis of Virdicatin 65.

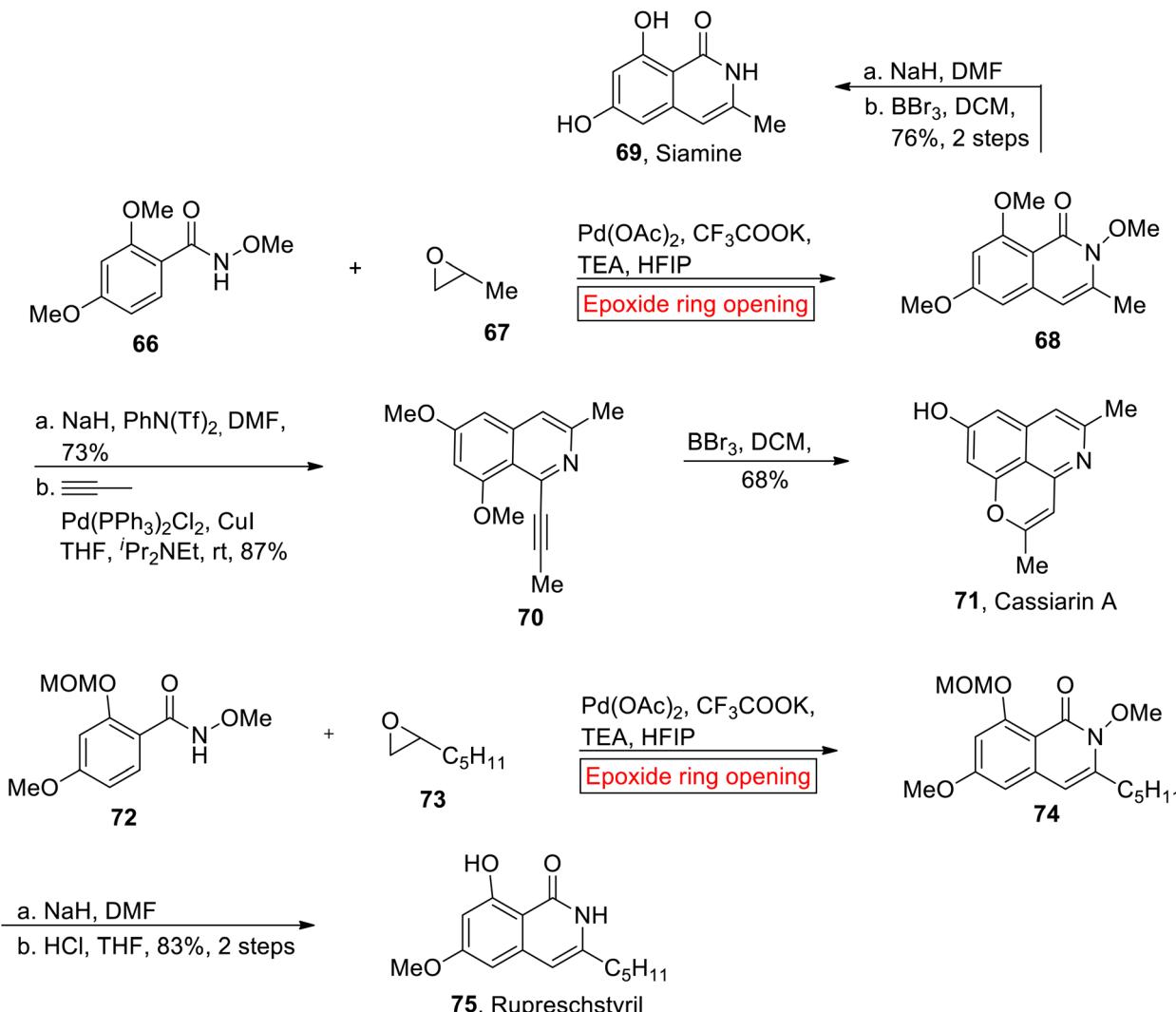
towards (\pm)-Brussonol **104** and Komarovquinone **106** was initiated with the formation of coupling fragment **98**. In the first step, α , β -unsaturated ketone **95** experienced Michael addition reaction with MeMgBr in the presence of DPMU and CuBr·SMe₂, followed by enolate quenching with allyl bromide **96** and Corey–Chaykovsky epoxidation to forge single diastereomer of epoxide **97** (88%). In the next step, epoxy-aldehyde **98** (89%) was obtained by Lemieux–Johnson oxidation of epoxide **97**. Then, aryl ester **99** underwent nucleophilic addition reaction (MeMgBr) followed by dehydration/hydrogenation reaction and selective bromination in the presence of tetramethylethylenediamine (TMEDA) and Et₂O to afford aryl bromide **100** (65–81%). Similarly, the coupling partner 1-bromo-4-isopropyl-2,3,5-trimethoxybenzene **102** was synthesized from 1,2,4-trimethoxybenzene **101** over few steps. Then, the epoxide **98** was coupled with aryl bromide **100** and trimethoxybenzene **102** individually *via* Zn-catalyzed epoxide ring opening reaction in the presence of NaI, Et₃N·HCl and 4,4'-dimethoxy-2,2'-bipyridine (DMBP) to yield acetals **103** (40%) and **105** (25%) respectively. Acetal **103** was then subjected to Friedel–Crafts cyclization followed by sodium thiolate-mediated demethylation to furnish (\pm)-Brussonol **104** (89%). Similarly, diastereoselective (\pm)-Komarovquinone **106** was obtained from acetal **105** over few steps (Scheme 12).

($-$)-Scabrolide A **116** is a norcembranoid diterpenoid which belongs to the family of marine natural products.¹⁰⁹ In 2002, it was isolated for the first time from *Sinularia scabra* (soft coral) by the research group of Sheu.¹¹⁰ ($-$)-Scabrolide A **116** acts as an anti-inflammatory agent¹¹¹ as it inhibits the production of IL-6 and IL-12. In 2020, Stoltz¹¹² reported the first total synthesis of ($-$)-Scabrolide A **116** by employing epoxide ring opening reaction as one of the key steps. This research report represented the

first synthesis of any member of polycyclic furanobutenolide-derived norcembranoid diterpenoid family that have remained elusive to synthetic efforts for over two decades since their original discovery. The synthetic route began with the preparation of dihydroxyvinyl cyclopentene **108** and ynoic acid **110** which were utilized as the starting materials for the synthesis of ($-$)-Scabrolide A **116**. In the first step, cyclopentene **108** and ynoic acid **110** were synthesized individually from enone **107** and monoprotected dialdehyde **109** respectively over few steps. Compounds **108** and **110** were reacted under Steglich conditions followed by Diels's reaction to yield Diels's alder adduct with subsequent epoxidation to furnish intermediate **111** (94%). In the next step, intermediate **111** was exposed to Cp₂TiCl₂-mediated epoxide ring opening reaction in the presence of collidine·HCl, 1,4-cyclohexadiene (1,4-CHD), THF and Mn⁰ to render diol **112** (86%, dr = 20 : 1). The diol **112** was further treated with 2-iodoxybenzoic acid (IBX) accompanied by selective epoxidation to afford mixture of epimers in good yield **113** (87%, 1.7 : 1). Then, the mixture **113** experienced Ru-mediated hydrosilylation to generate diastereomeric mixture of **114** (85%). In the next step, compound **114** was subjected to irradiation in the presence of PhH followed by Cp₂TiCl₂-mediated reductive epoxide ring opening reaction by utilizing earlier mentioned conditions (1,4-CHD, collidine·HCl, THF) to produce diol **115** (dr = 1.7 : 1, 70%). The resulting diol **115** was converted to ($-$)-Scabrolide A **116** over few steps (Scheme 13).

Flowering plants that belong to genus *Marrubium* are found in temperate and Mediterranean region.¹¹³ These plants are used as a local medicine in Eurasian zone due to the presence of Marrubiin **122** (furanoid) compound as it acts as analgesic, vasorelaxant, antispasmodic, anti-diabetic, hypoglycemic and anti-inflammatory agent.¹¹⁴ Marrubiin **122** is a labdane



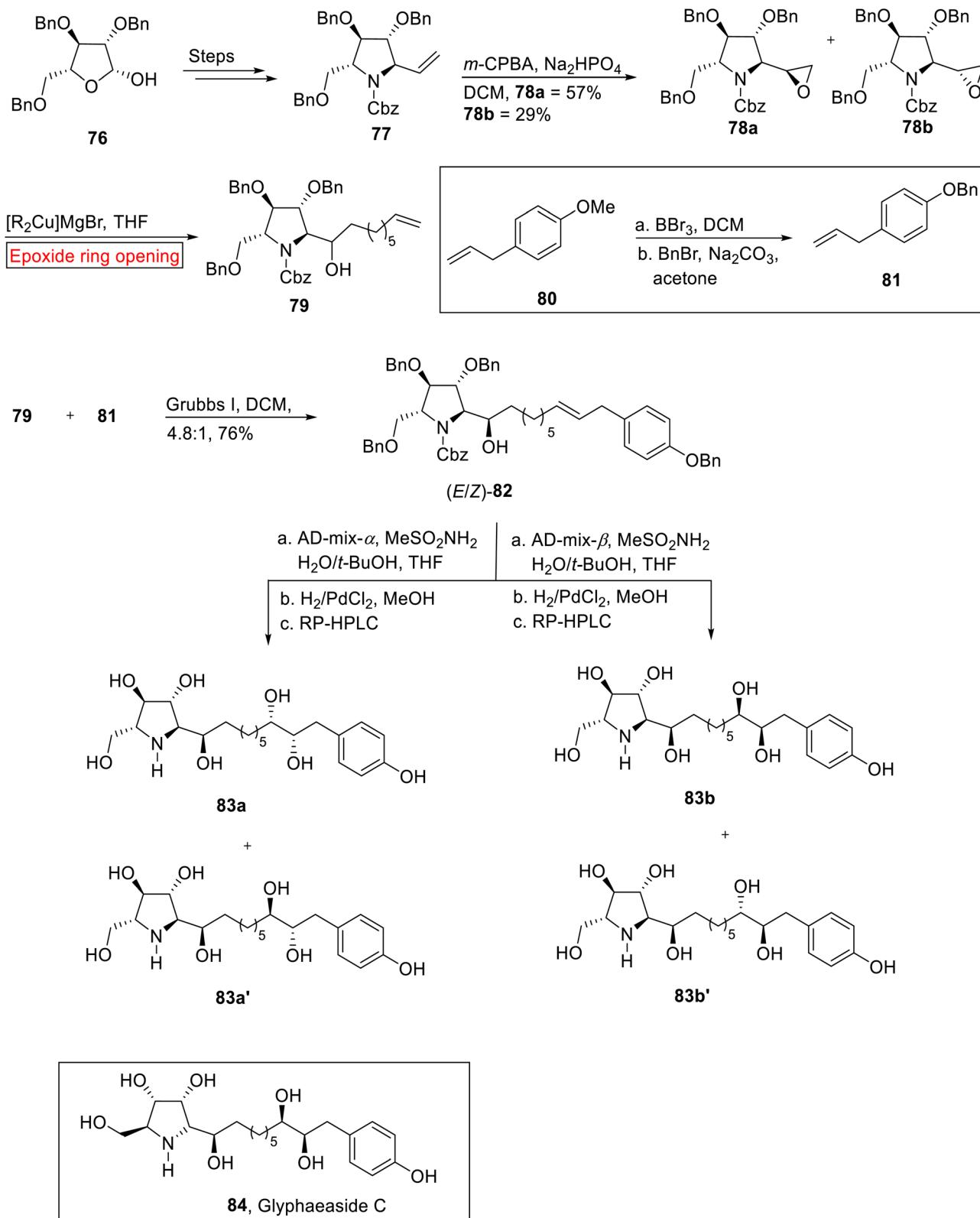


Scheme 9 Synthesis of Siamine 69, Cassiarin A 71, and Rupreschstyryl 75.

diterpene lactone which was extracted from *Marrubium vulgare* in 1842 for the first time and later its effect on rat aorta¹¹⁵ was also explored. The phytochemical analysis of this family (mints) also led to the isolation of various labdane diterpene lactones.¹¹⁶ Previously, research group of Mangoni¹¹⁷ described the total synthesis of Marrubasch F, Marrulibanoside, Premarrubiin (semi-syntheses) and Marrubiin (racemic form). Nakamura *et al.* disclosed the stereoselective total syntheses of Marrubasch F 121, Marrubiin 122, Desertine 124b, Marrilibacetal 159a, Marrilibacetal A 125b, Marrulactone 129, Marrulanic acid 130 and Cylleneine C 132 in 2020.¹¹⁸ Their synthetic approach features the extention of C-9 side chain of 118 *via* nucleophilic epoxide ring opening reaction with high level of malleability and convergency. The synthetic route initiated with the preparation of epoxide intermediate 118 from the enyne 117 over few steps. In the next step, intermediate 118 underwent epoxide ring opening reaction with Grignard reagent 119 in the presence of CuBr·SMe₂ (Et₂O) to afford 120 (76%) which was then exposed to oxidation (*m*-CPBA, DCM) to furnish Marrubasch F 121 (57%). In the same way, Marrubiin 122 (70%) was obtained

by the deprotection (BuNF, THF) of TMS group of 120. Marrubiin 122 went through oxidative acetalization (pyridine·HBr) followed by reaction with NMO (4-methylmorpholine N-oxide) in aq. THF to provide Desertine 124b along other isomers. Mixture of diols 123a and 124a were treated with TsOH and PhH to generate Marrilibacetal 125a and Marrilibacetal A 125b respectively. Some other isomers and diastereomers were also formed with them. In accordance, intermediate 118 experienced Cu-catalyzed epoxide ring opening reaction with Grignard reagent 127 to render alcohol 128 (48%), which was further exposed to desilylation with subsequent oxidation to forge Marrulactone 129 (91%). Then, the Marrulactone 129 was converted to Marrulanic acid 130 (84%) *via* LiOH-mediated regioselective saponification. Synthesis of Cylleneine C 132 (96%) was achieved by nucleophilic epoxide ring opening reaction of intermediate 118 in the presence of lithium acetylidy ethylenediamine in dimethyl sulfoxide (DMSO) to afford alcohol 131 (95%) followed by gold(I)-mediated cycloisomerization/oxidation sequence (Scheme 14).

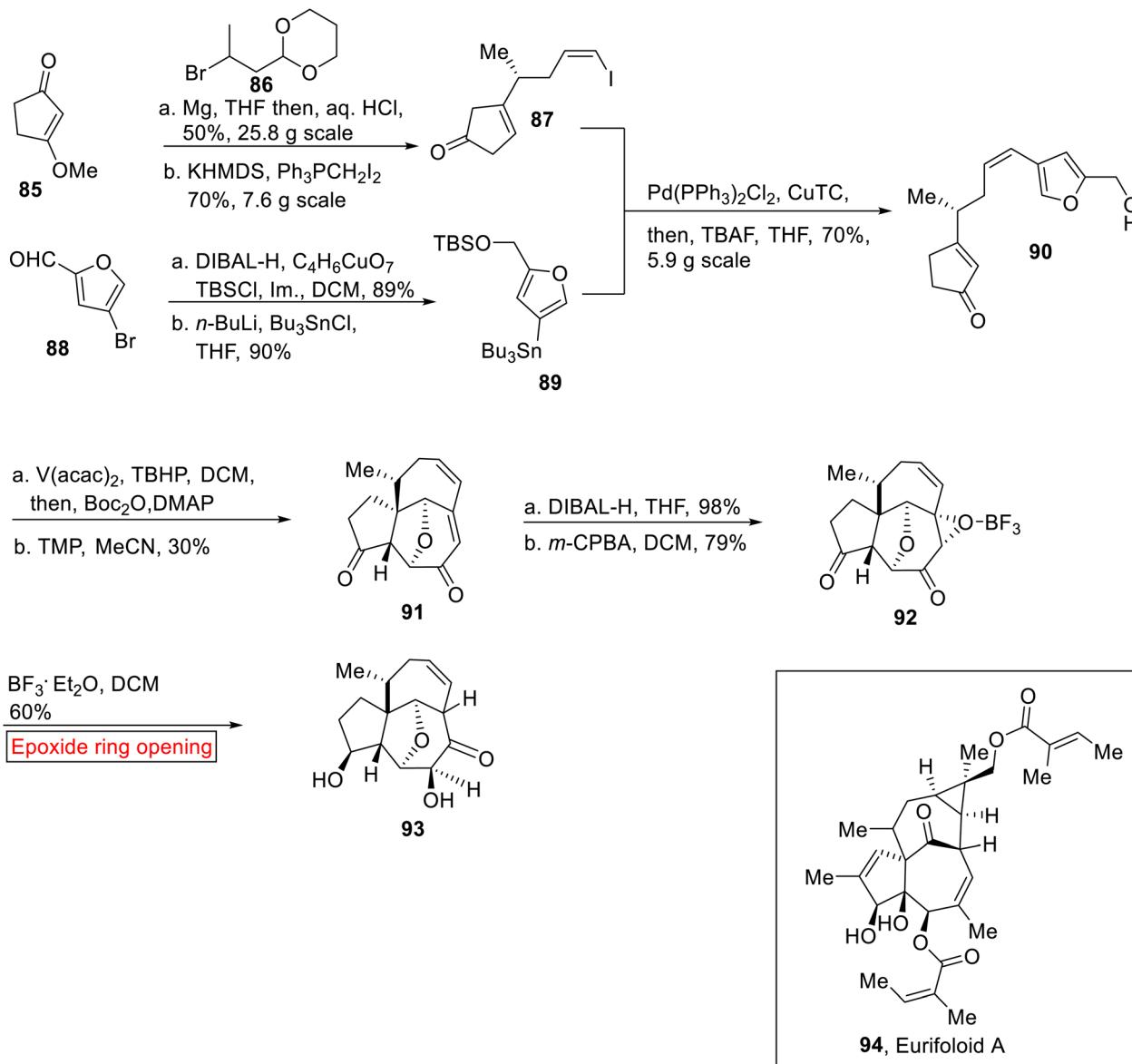




Scheme 10 Synthesis of Glyphaeaside C 84.

(\pm)-Rameswaralide **140** is a diterpene related to the class of secondary metabolites¹¹⁹ (a marine cembranoid), which was extracted in 1998 (ref. 120) from *Sinularia dissecta* (soft coral)

featuring a tricyclic skeleton. It exhibits anti-inflammatory and anti-cancer activity.¹²¹ In this regard, development of various anticancer agents has been the focus of researchers.¹²² In 2022,

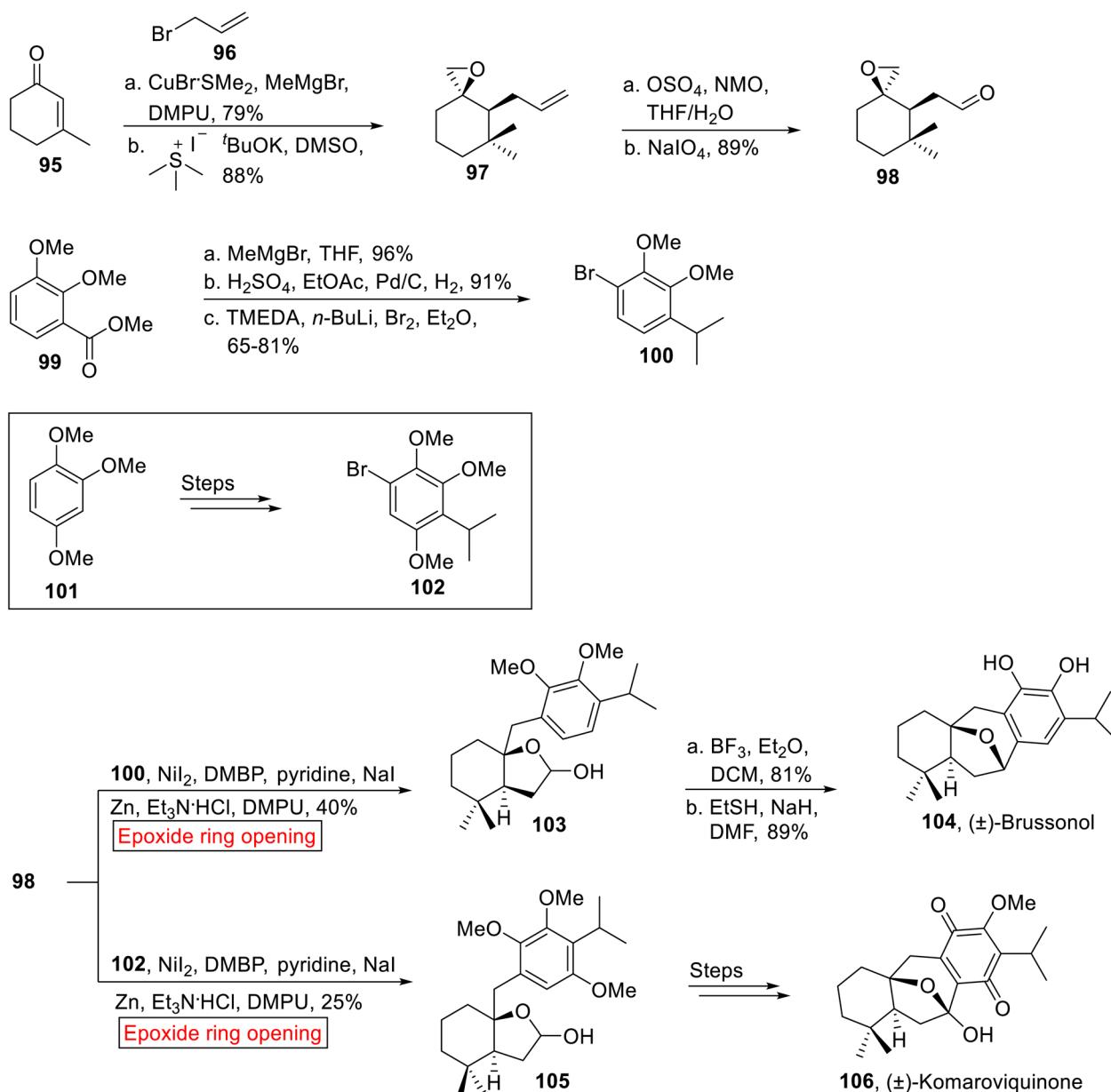


Scheme 11 Synthesis of tricyclic core 93 of Eurifoloid A 94.

research group of Romo developed an elegant approach toward the first total synthesis of (\pm) -Rameswaralide **140** by employing ring opening reaction of epoxide as one of the key steps.¹²³ The synthetic route initiated with the syntheses of epoxy α -bromo enone **134** from **133** over few steps. The stannane **136** was obtained from vinyl iodide **135** via sequential alkylation, treatment with *n*-BuLi and tributyl tin chloride. In the next step, epoxy α -bromo enone **134** and stannane **136** upon Stille coupling followed by base-catalyzed oxidation with subsequent ring opening reaction of epoxide under desilylation conditions afforded α -methylene butyrolactone **137** (44%, 2 steps). The compound **137** was further subjected to Pd(OAc)₂-catalyzed oxidation followed by Stork enamine cyclization to render **138a** (26%) and **138b** (4%) diastereomers. In the next step, major diastereomeric ketone **138a** was treated with **139** under Julia-Kocienski olefination by utilizing optimized conditions to forge (\pm) -Rameswaralide **140** in 32% yield (Scheme 15).

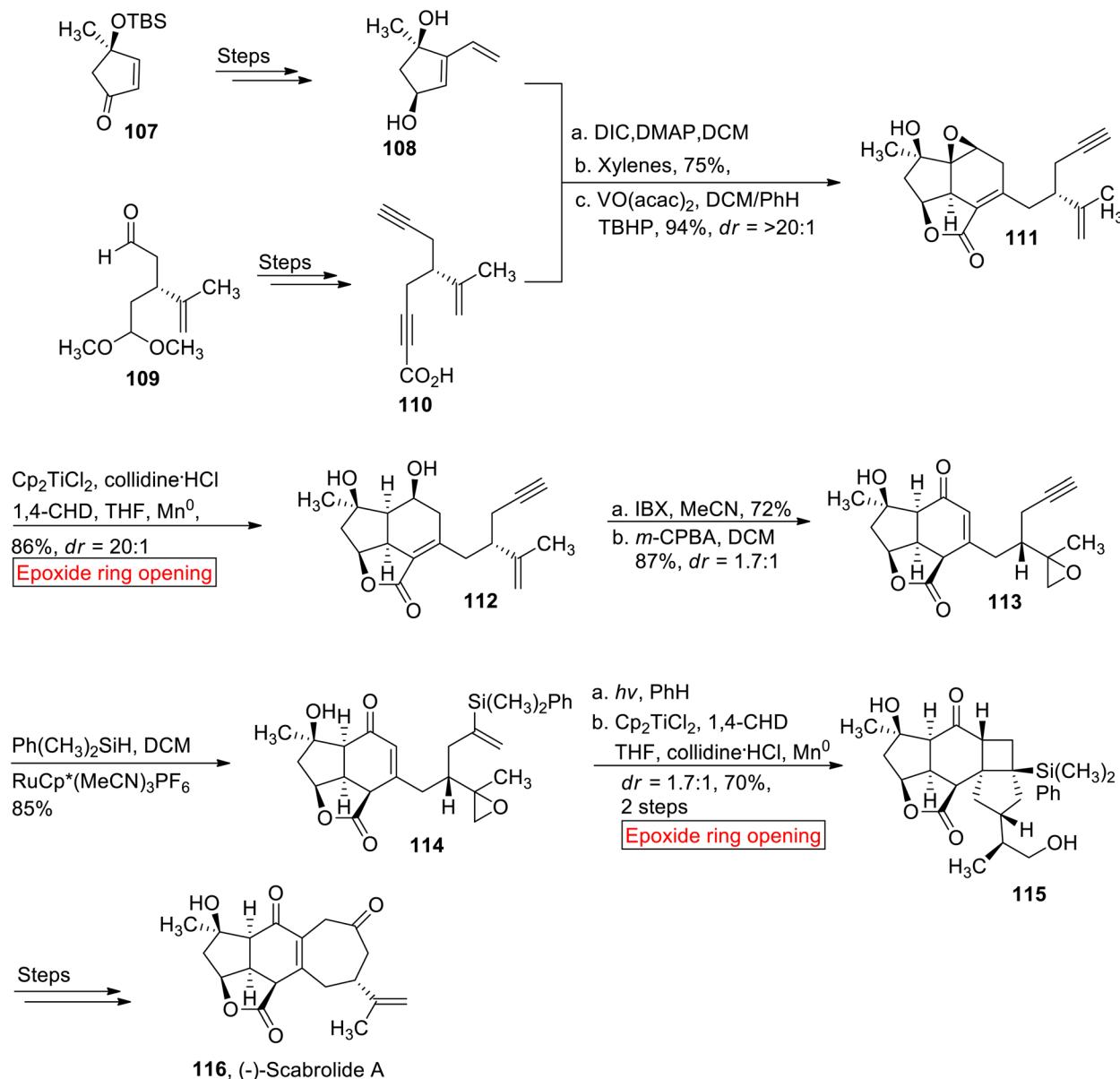
(+)-Ryanodine was extracted from *Ryania speciosa* Vahl (plant) found in South America.¹²⁴ In 1967, ryanodine's structure was disclosed by Wiesner¹²⁵ and afterward reported by Deslongchamps.¹²⁶ The *de novo* synthesis of Ryanodine and Ryanodol (hydrolysis product of Ryanodine) was very difficult because they are composed of eleven stereogenic centers. Previously different efforts have been reported on the preparation of these targets, Ryanodol by Deslongchamps,¹²⁶ Ryanoid by Inoue¹²⁷ and recently Ryanodol by Reisman.¹²⁸ In 2020, Micalizio *et al.* reported the synthetic approach towards the novel synthesis of Ryanodol **146** that was achieved by the synthesis of its degradation product (\pm) -Anhydroryanodol **145**.¹²⁹ They utilized carbocyclic approach for the synthesis of (\pm) -Anhydroryanodol **145** by employing epoxide ring opening reaction as of the key steps. Initially, divinyl epoxide **142** was obtained from alkyne **141** over few steps. In the next step, divinyl epoxide **142** went through sequential deprotection (TASF = trissulfonium



Scheme 12 Synthesis of (\pm) -Brussonol 104 (\pm)-Komarovquinone 106.

difluorotrimethylsilicate), oxidation (TPAP = tetrapropylammonium perruthenate, NMO), base (NaOH)-catalyzed epoxide ring opening reaction in DCM. Then, subsequent ring-closing metathesis afforded a mixture of lactones **143a** and **143b** in equal amount. Compound **143a** was also converted into **143b** (65%) in the presence of base (NaOH). Then, **143b** was silylated selectively by treating it with neat TMS-Im (imidazole) to forge **144**. In the next step, $(+/-)$ -Anhydroryanodol **145** (38%, 2 steps) was obtained by *m*-CPBA-mediated epoxidation, Cp_2TiCl_2 -catalyzed epoxide ring opening reaction in the presence of Et_3SiH followed by TASF-mediated deprotection. Finally, $(+/-)$ -Anhydroryanodol **145** was converted into $(+/-)$ -Ryanodol **146** (38%) *via* site-specific epoxidation ($\text{CF}_3\text{CO}_3\text{H}$) followed by Li/NH_3 -catalyzed epoxide ring opening reaction reported by Deslongchamps¹²⁶ and Reisman¹²⁸ (Scheme 16).

Triterpenoid. Isodehydrothrysiferol **154** belongs to the family of triterpenoid¹³⁰ which was drawn from *Laurencia viridis* (red alga) by Munro and colleagues in 1978.¹³¹ It depicts potent cytoidal activity opposite to P388 cell lines ($\text{IC}_{50} = 17$ nm).¹³⁰ It has unique structural features because it displays partial enantiodivergent as a novel phenomenon in the biosynthesis of natural products. In 2017, research group of Morimoto disclosed the synthesis of Isodehydrothrysiferol **154** by employing epoxide ring opening reaction as a key step.¹³² In the first step, 2,3-epoxy alcohol **147** experienced $\text{Ti}(\text{O}^{\text{i}}\text{Pr})_4$ -mediated epoxide ring opening reaction in the presence of PivOH and toluene to generate pivalate **148** (99%). The resulting pivalate **148** was further converted into another epoxide **149** (87%, 2 steps) by sequential protection and

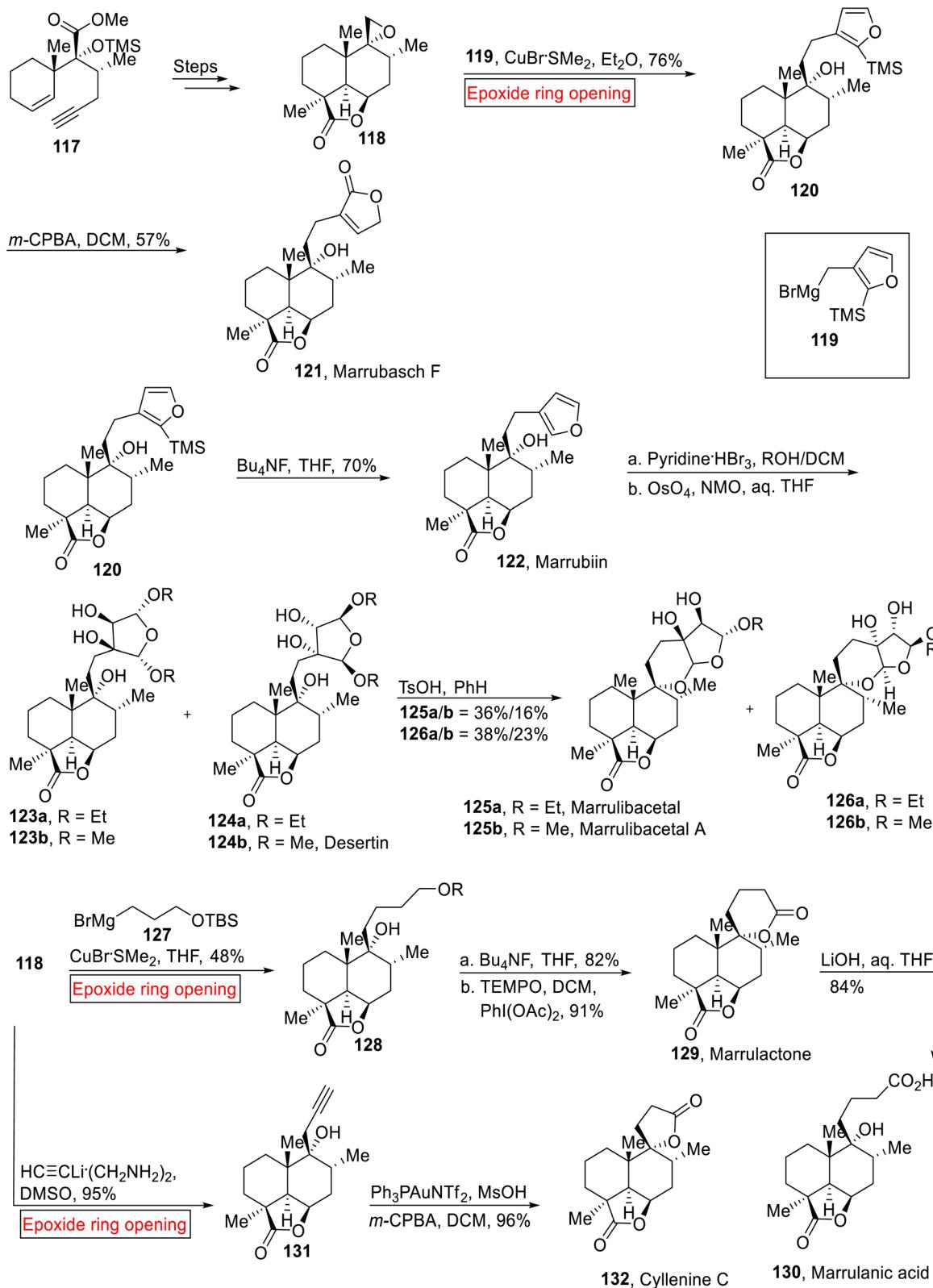


Scheme 13 Synthesis of (-)-Scabrolide A 116.

epoxidation. Next, geranyl phenyl sulfide 150 was added to 149 followed by reaction with Na, i PrOH to furnish compound 151 (90%, over 2 steps). The tertiary alcohol moiety of compound 151 was exposed to protection with TESCl (Triethyl-chlorosilane) and then diastereoselective epoxidation provided epoxide 152 (58%). In the next step, the -OH group of compound 152 underwent protection followed by TBAF-mediated epoxide ring opening reaction in THF with subsequent deprotection (t BuOK) to attain 153 (75%). The synthesized compound 153 was finally converted to Isodehydrothrysiferol 154 over few steps (Scheme 17).

Indole sequequiterpenenoids. Xiamycin A 163 and Dixiamycin C 167 are indole sequequiterpenenoids which were extracted by Hertweck¹³³⁻¹³⁶ and Zhang¹³⁷⁻¹³⁹ from *Streptomyces* species. Xiamycin 163 and Dixiamycin C 167 demonstrate

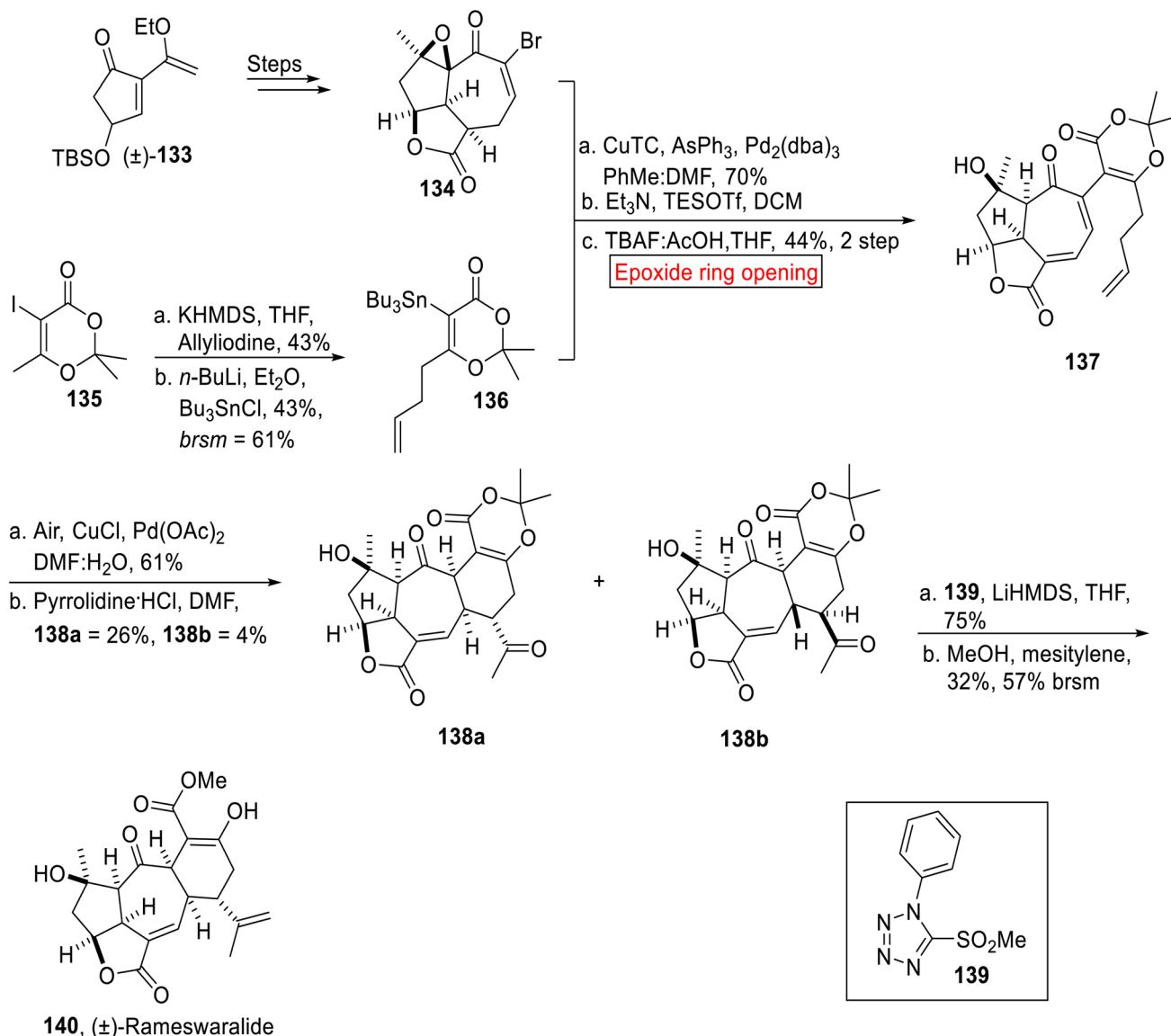
substantial inhibitory activity opposite to herpes simplex virus-1 (HSV-1). Recently, work on Xiamycin A 163 and Dixiamycin B was reported by research group of Baran¹⁴⁰ for the first. In 2015, Meng *et al.* described the total synthesis of Xiamycin 163 and Dixiamycin C 167 (for the first time) by employing epoxide ring opening reaction as one of the key steps.¹⁴¹ The synthetic route started with the preparation of α , β -epoxy ester 156 (76%, 2 steps) from optically active epoxide 155 through AZADO (2-azaadamantane *N*-oxyl)-mediated oxidation and esterification. Next, the compound 156 underwent Cp_2TiCl_2 -catalyzed epoxide ring opening reaction in the presence of i Pr₂Net, TMSCl, Mn and THF to furnish *trans*-decalin 157. In the next step, compound 158 (44%, 3 steps) was obtained from decalin 157 via TBS protection accompanied by acetyl deprotection. Then, compound 158 was subjected to oxidation (using DMP)



Scheme 14 Total syntheses of Marrubasch F **121**, Marrubiin **122**, Desertine **124b**, Marrulibacetal **125a**, Marrulibacetal A **125b**, Marrulactone **129**, Marrulanic acid **130** and Cyllenine C **132**.

followed by Grignard addition (**159** or **160**) with subsequent dehydration in the presence of $\text{MsCl}/\text{iPr}_2\text{N}^+$ to afford triene **161** or **162**. Next, triene **161** or **162** experienced thermal 6π -

electrocyclization accompanied by aromatization, desulfonation and TMSE deprotection to achieve Xiamycin A **163** in excellent yield (95%). Similarly, compounds **164** and **165** were



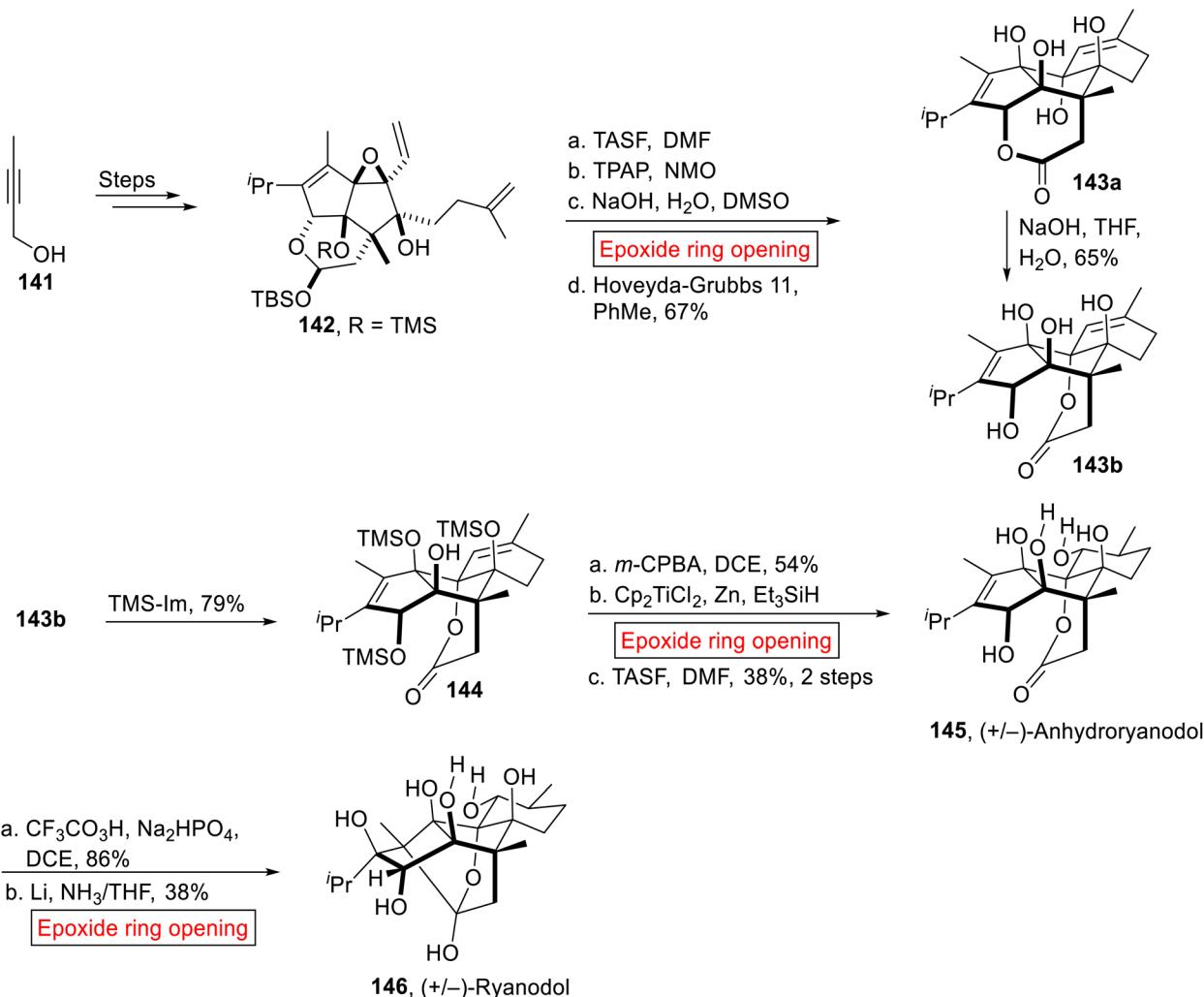
Scheme 15 First total synthesis of (±)-Rameswaralide 140.

reacted with compound 166 in the presence of CuI followed by deprotection with TSAF to render Dixiamycin C 167 (96%, over 2 steps) in a good yield (Scheme 18).

Meroterpenoid. (–)-Siphonodictyyl B 170 (marine sponge) and (+)-Liphagal 171 belong to the meroterpenoid family of natural products. (+)-Liphagal 171 was extracted by Andersen and colleagues from *Aka coralliphaga*¹⁴² while Siphonodictyyl B was also isolated from *Aka coralliphaga* by the research groups of Faulkner¹⁴³ and Köck.¹⁴⁴ Its structure was first reported in 1981 by Faulkner and colleagues and then was revised by Clardy and coworkers¹⁴⁵ (1986). In 2015, George *et al.* reported the correct revised structure of (–)-Siphonodictyyl B 170 which was then converted into (+)-Liphagal 171 by employing epoxide ring opening reaction as one of the key steps.¹⁴⁶ Their research work highlights the significance of biosynthetic suppositions which help in the development of innovative sequential reactions and structural reassignment of natural products. The synthetic

route commenced with the preparation of benzylic alcohol 169 from (+)-sclareolide 168 over few steps. In the next step, alcohol 169 underwent POCl₃-mediated dehydration followed by *ortho*-lithiation, then quenching by utilizing DMF with subsequent deprotection (BCl₃) of isopropyl ether to afford (–)-Siphonodictyyl B 170 (77%). Finally, synthesis of (+)-Liphagal 171 (42%) was achieved by *m*-CPBA-mediated epoxidation in the presence of NaHCO₃ and CCl₄ accompanied by TFA-catalyzed epoxide ring opening reaction (Scheme 19).

Rhodonoids C 174 and D 175 belong to the class of meroterpenoids extracted from *Rhododendron capitatum*.¹⁴⁷ Rhodonoids C 174 and D 175 have 6/6/6/5 and 6/6/5/5 ring systems respectively. In 2017, research group of Day⁶⁷ synthesized Rhodonoids C 174 and D 175 by using Chromene 172 (meroterpenoid) which was prepared according to Hsung and colleagues¹⁴⁸ from orcinol and citral. In the first step, prenyl side chain of Chromene 172 underwent *m*-CPBA-mediated

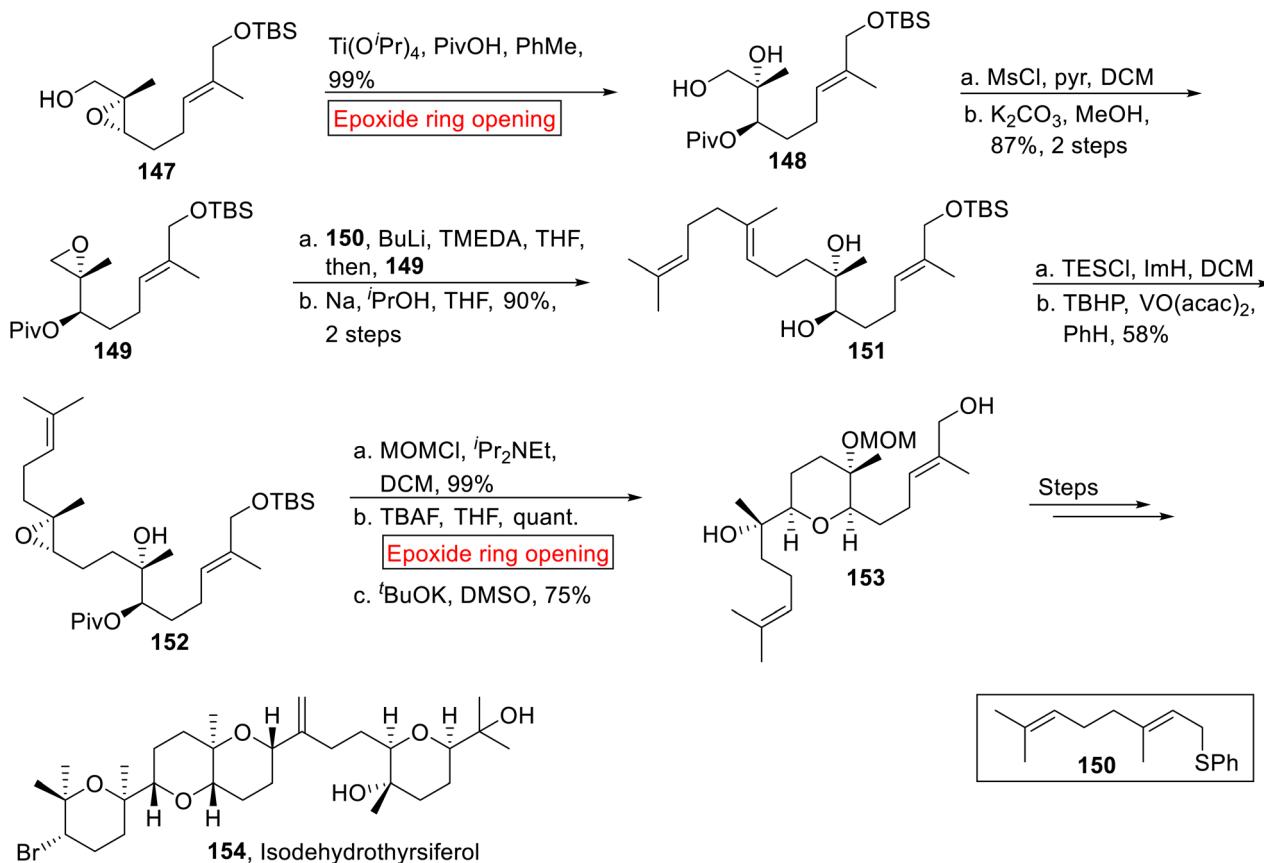


Scheme 16 Synthesis of (+/-)-Anhydroryanodol 145.

epoxidation to furnish diastereomer **173** (51%, *dr* = 1 : 1). Then, **173** experienced SnCl_4 -catalyzed epoxide ring opening reaction with subsequent cyclization in the presence of CHCl_3 to synthesize Rhodonoids C **174** (32%), D **175** (5%) and **176** (Scheme 20).

Sesquiterpenoids. Heronapyrrole C **186** belongs to a sesquiterpene (rare nitropyrrole) family of natural product which was isolated from the culture of *Streptomyces* sp. (CMB-M0423) in 2010 (Australia).¹⁴⁹ Considering the widespread microbial diseases, researchers are continuously making efforts to develop efficient anti-microbial agents.¹⁵⁰ Nitropyrrole natural products exhibit activity opposite to Gram-positive bacteria without exhibiting cytoidal activity towards mammalian cell lines. In 2012, Stark disclosed the synthesis of Heronapyrrole C with less yield.¹⁵¹ In 2014, Brimble *et al.* reported the regioselective synthesis of (+)-Heronapyrrole C **186** by employing epoxide ring opening reaction as one of the key steps.¹⁵² Their strategy was based on the synthesis of regiocontrolled 2-nitropyrrole building blocks that have received limited attention until now. The synthetic scheme towards (+)-Heronapyrrole C **186** began with the syntheses of aldehyde fragments **178a** and

178b from 2-nitropyrrole **177** over few steps. The synthesis of second fragment **184** was initiated with the preparation of epoxy mesylate **180** from geraniol **179** by Sharpless asymmetric epoxidation followed by mesylation. Then, epoxy mesylate **180** went through Sharpless asymmetric dihydroxylation accompanied by acid-catalyzed (CSA = Camphorsulfonic acid) epoxide ring opening reaction to afford **181**. In the next step, **181** went through epoxidation to render terminal epoxide **182** (85%). Then, compound **182** was subjected to protection (TESCl) of tertiary alcohol moiety followed by copper(i) chloride-catalyzed epoxide ring opening reaction with allyl magnesium bromide in Et_2O and again protection with TESCl to furnish alkene **183** (85%). Next, alkene **183** upon Markovnikov oxymercuration reduction followed by Mitsunobu inversion (*p*-TsOH) with *m*-CPBA-mediated oxidation rendered olefination partner **184** (75%). Then, the coupling partner **178b** and **184** were coupled through Julia-Kocienski olefination followed by (-)-Shi ketone-mediated asymmetric epoxidation to give epoxides **185a** (81%) and **185b** (82%). Finally, **185b** was converted into (+)-Heronapyrrole C **186** via TBAF-mediated deprotection accompanied



Scheme 17 Synthesis of Isodehydrothrysiferol 154.

by acid (CSA)-catalyzed epoxide ring opening reaction in toluene with subsequent heating at 50 °C (Scheme 21).

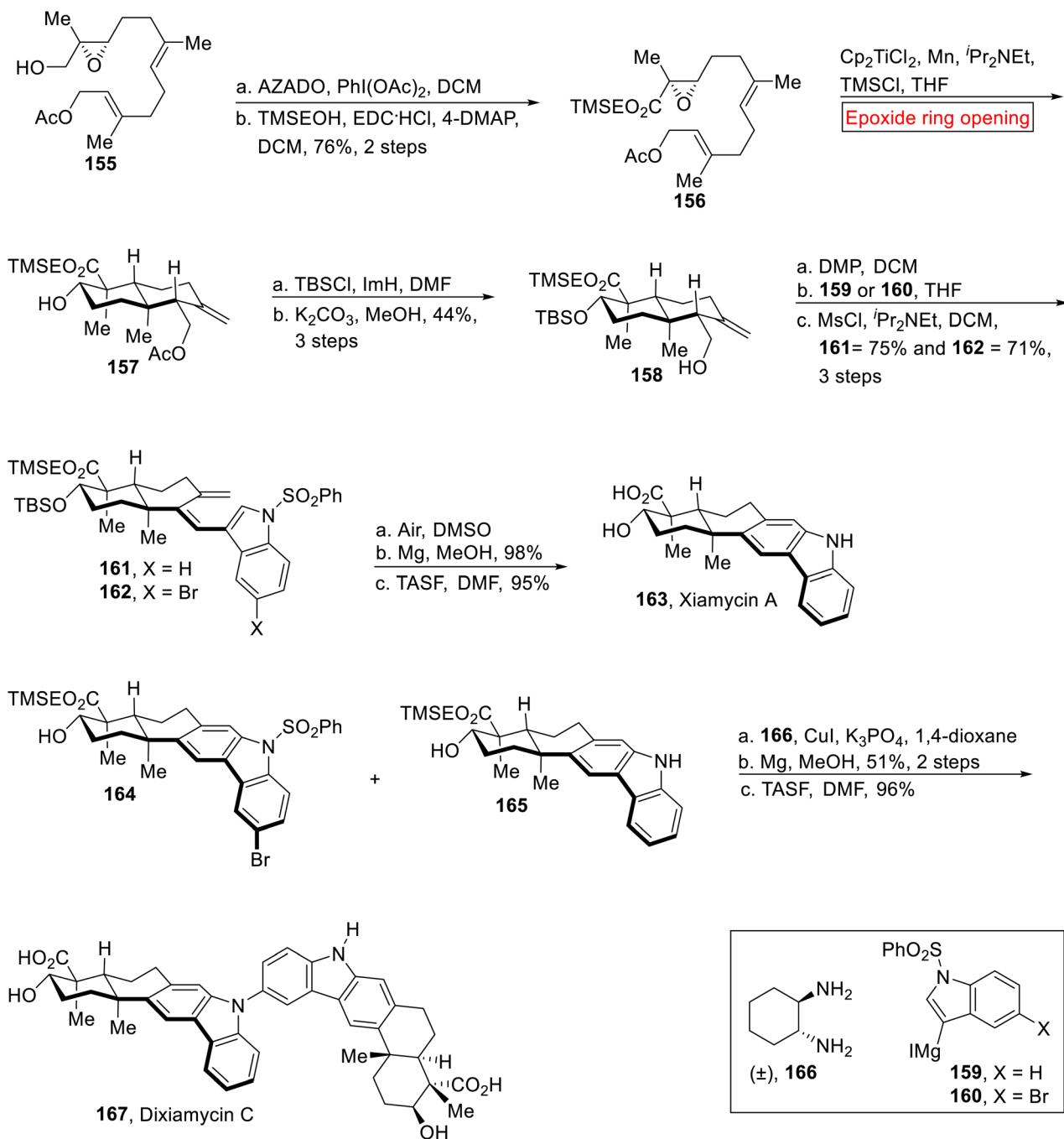
Guaiane-type sesquiterpenoids (Guaia-4(5)-en-11-ol **191**, Aciphylene **192**, 1-*epi*-Melicodenones C **193**, 1-*epi*-Melicodenones E **194**, Guaia-5(6)-en-11-ol **195**, 1-*epi*-Aciphylene **198**, 1-*epi*-Guaia-4(5)-en-11-ol **200**) were isolated from fungi plants and marine life.^{153,154} Previously synthesized Guaiane-type sesquiterpenoids have low overall yield^{155,156} and experienced difficulties in installing the required stereochemistry while synthesizing the [5.3.0]-bicyclic ring cores. The problem was then solved by Taylor and coworkers by using inexpensive naturally occurring Guaiol **187** as a starting material for the synthesis of Guaiane-type sesquiterpenoids. In 2014, research group of Taylor¹⁵⁷ reported the synthesis of these sesquiterpenoids *via* epoxide ring opening reaction as one of the key steps. The synthetic route initiated with the formation of β -epoxyguaiol **188** from **187** over few steps. Then, **188** was subjected to $LiAlH_4$ -catalyzed epoxide ring opening reaction in the presence of $AlCl_3$ in THF to render **189** (79%). Then, compound **189** was exposed to selective benzylation under Ogawa's method in the presence of *in situ* generated benzyl iodide to afford compound **190** (73%). Treatment of compound **190** with $TsOH \cdot H_2O$ ($MeCN$) followed by reduction ($LiAlH_4$) yielded Guaia-4(5)-en-11-ol **191** with 26% overall yield (91%). In the next step, alcohol moiety of **191** experienced dehydration ($SOCl_2$) followed by SNIS (silver nitrate impregnated upon silica gel) chromatography

purification to synthesize Aciphylene **192** in 18% overall yield (72%). Then, Aciphylene **192** upon sequential allylic and Dess-Martin periodinane oxidation provided 1-*epi*-Melicodenones C **193** (72%) which was further treated with base ($NaOMe$) followed by CrO_3 -mediated oxidation to generate the 1-*epi*-Melicodenones E **194** (32%).

Guaia-5(6)-en-11-ol **195** (31%, overall yield) was obtained by the dehydration ($SOCl_2$) of **190** accompanied by treatment with Li wire and naphthalene in THF . Similarly, compound **196** went through *m*-CPBA-mediated epoxidation accompanied by $LiAlH_4$ -mediated epoxide ring opening reaction in the presence of $AlCl_3$ in THF to afford alcohol **197** (43%) which was subjected to dehydration to afford 1-*epi*-Aciphylene **198** (87%). Then, alcohol **197** was subjected to sequential epoxidation and dehydration to generate epoxide **199**. In the next step, compound **199** went through $LiAlH_4$ -catalyzed epoxide ring opening reaction reductively by using $AlCl_3$ and THF to accomplish 1-*epi*-Guaia-4(5)-en-11-ol **200** in 73% yield over 3 steps (Scheme 22).

Arglabin **203** (guaianolide) belongs to the family of sesquiterpene lactones which was isolated from *Artemisia glabella*¹⁵⁸ specie. The dimethyl amino adduct of Arglabin exhibits anti-tumor activity against lung, breast, colon and ovarian cancer.¹⁵⁹ Total synthesis and hemisynthesis of Arglabin **203** from parthenolide have been reported by the research groups of Reiser¹⁶⁰ and Chen¹⁶¹ respectively. In 2015, Lone and Bhat have accomplished the hemisynthesis of Arglabin **203** (51%, overall yield)

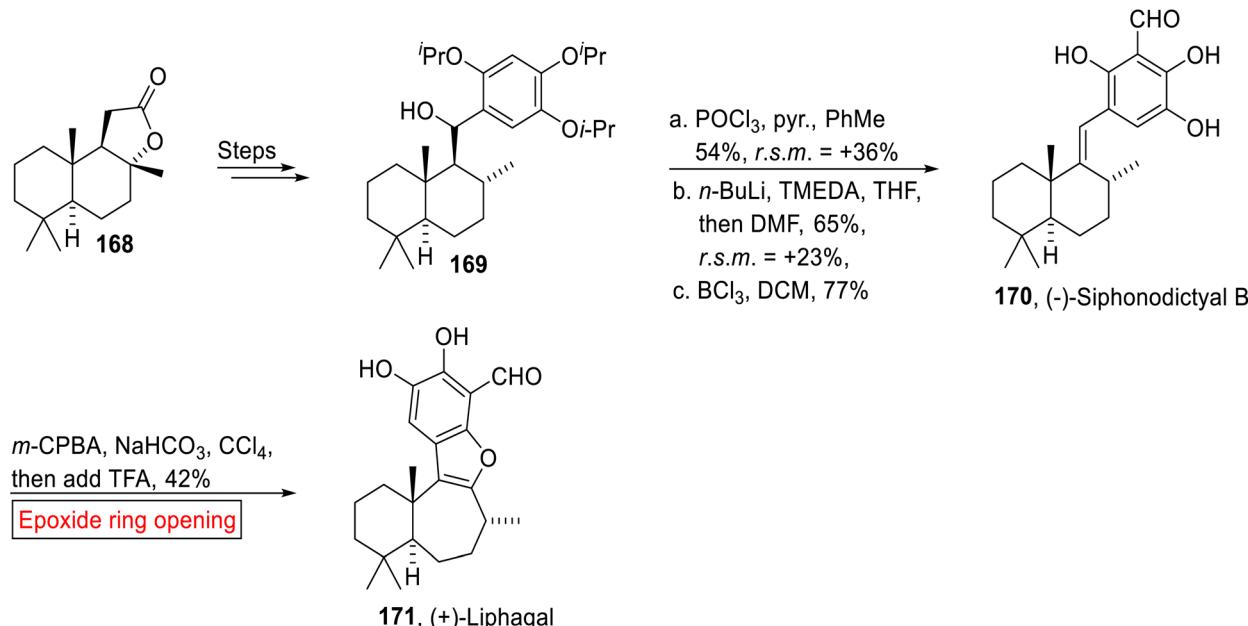




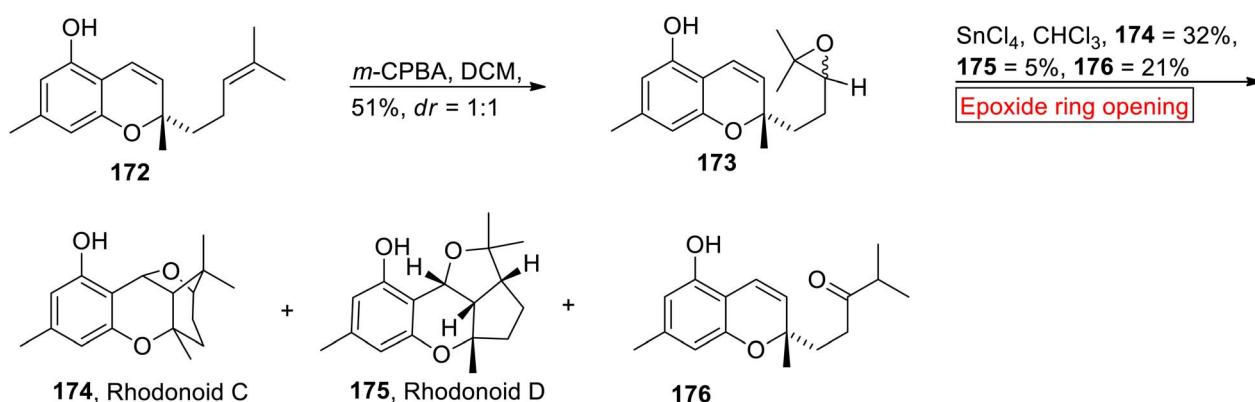
Scheme 18 Total synthesis of Xiamycin 163 and Dixiamycin C 167.

from ludartin 201 (ref. 162) *via* short and efficient reaction process, by taking into account the less side effects of Arglabin as compared to other chemotherapeutics. They utilized epoxide ring opening reaction as one of the key steps in their strategy for the synthesis of Arglabin. In the first step, ludartin 201 underwent Lewis acid ($\text{BF}_3 \cdot \text{Et}_2\text{O}$)-catalyzed regioselective ring opening of epoxide using NaBH_4 , which resulted in compound 202 (90%). Stereoselective epoxidation of compound 202 in DCM followed by selective reduction synthesized Arglabin 203 in excellent yield (Scheme 23).

In 1964, Chetty and Dev¹⁶³ extracted α -Cuparenones 208 and β -Cuparenones 210, sesquiterpenes from the oil of *Thuja orientalis* leaves (Family – Cupressaceae) which display a number of biological activities. Then in 1976, Benesova¹⁶⁴ and co-workers isolated α and β -Cuparenones from *Mania fragrans* (liverworts). Similarly, (*S*)-Cuparene 209, a sesquiterpene was isolated in 1958 by Erdtman and colleagues.¹⁶⁵ Nanda and allies reported the optically pure synthesis of (*R*)- α -Cuparenone 208, (*R*)- β -Cuparenone 210 and (*S*)-Cuparene 209 by employing epoxide ring opening reaction as one of the key steps.¹⁶⁶ In the



Scheme 19 Synthesis of (-)-Siphonodictyal B 170 and (+)-Liphagal 171.



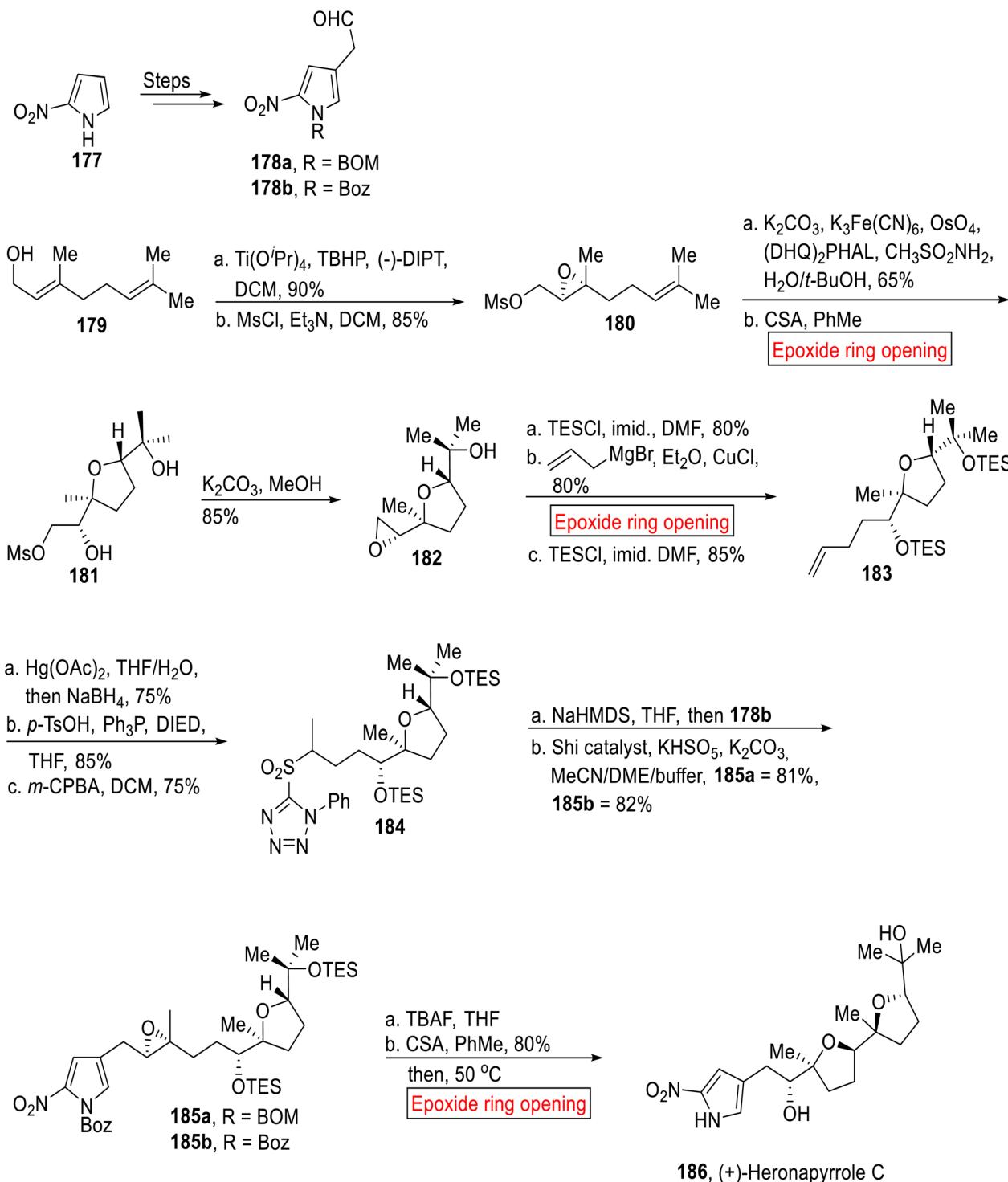
Scheme 20 Synthesis of Rhodonoids C 174, D 175 and 176.

first step, 4-methylbenzyl cyanide **204** went through aldol reaction (Me-CHO) followed by DIBAL-H-mediated reduction, acid-catalyzed hydrolysis with subsequent reduction (NaBH_4) to furnish *E*-allylic alcohol **205** (85%, 3 steps). Then, *E*-allylic alcohol **205** was subjected to asymmetric epoxidation followed by *tert*-butyldiphenyl chlorosilane (TBDPS*Cl*)-mediated protection to provide protected epoxide **206** (90%). In the next step, compound **206** experienced Lewis acid-mediated epoxide ring opening reaction which caused Meinwald rearrangement to forge aldehyde intermediate **207** (95%). The compound **207** was converted to (*R*)- α -Cuparenone **208** and (*R*)- β -Cuparenone **210** *via* several steps. In the next step, (*S*)-cuparene **209** was obtained (7.5%, overall yield) from (*R*)- α -Cuparenone **208** (9.4%, overall yield) *via* reductive deoxygenation under Huang-Minlon conditions (Scheme 24).

(\pm)-Isoclavukerin A **216** belongs to sesquiterpene (tri-*nor*-guaiane) family of natural products. It was isolated by research

groups of Kitagawa^{167,168} and Bowden¹⁶⁹ from *Clavularia koellikeri* (Okinawan soft coral) and *Cespitularia* sp. (Australian soft coral) respectively. In 2023, Chakraborty¹⁷⁰ *et al.* reported the synthesis of (\pm)-Isoclavukerin A **216** by employing epoxide ring opening reaction as one of the key steps. The method used by research group of Chakraborty is an attractive approach for the synthesis of sesquiterpenoids owing to high diastereoselective route, simple pathway focusing on step economy and mild reaction conditions. The synthetic endeavor started with the preparation of epoxides **213a** (75%) and **213b** (91%) from cyclopentenone **211** and hex-6-enal **212** in the presence of PBU_3 followed by treatment with AcCl with subsequent epoxidation (*m*-CPBA). In the next step, compound **213a** and **213b** were subjected to Cp_2TiCl -catalyzed epoxide ring opening reaction in THF to afford corresponding cyclized products **214a** and **214b**. Then, the mixture of **214a** and **214b** experienced sequential bromination and debromination to afford enones **215a** and



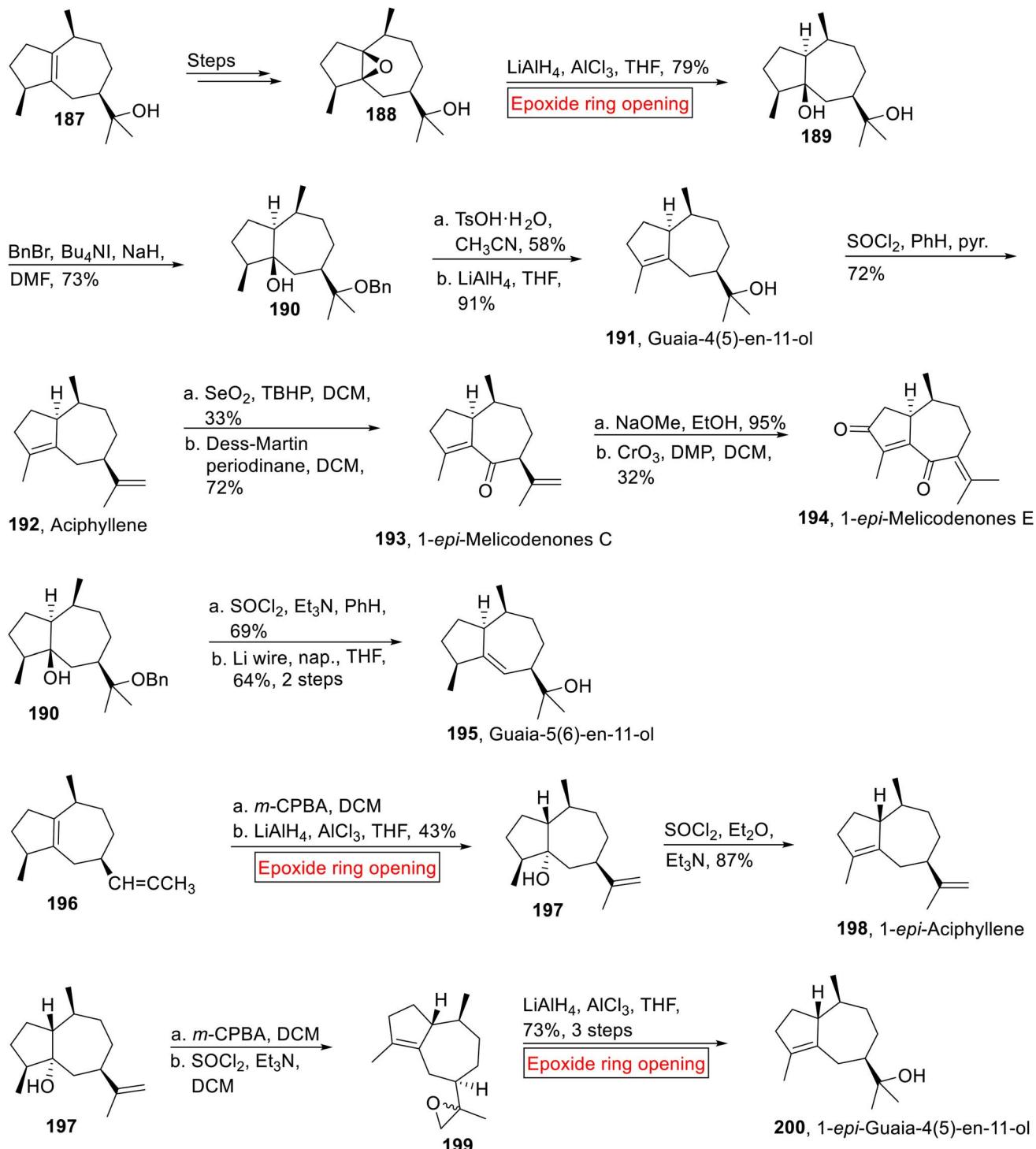


Scheme 21 Regioselective synthesis of (+)-Heronapyrrole C 186.

215b ($\text{dr} = 7:1$). In the last step, mixture of enones **215a** and **215b** upon treatment with MeLi and additive $\text{LaCl}_3 \cdot 2\text{LiCl}$ accompanied by 1,4-conjugate elimination in the presence of 2,4-dinitrobenzenesulfonylchloride and Et_3N forged (\pm) -Iso-clavukerin A **216** in 72% yield (Scheme 25).

Taking into account the deadly aspects of cancer, several research groups have focused their attention towards the

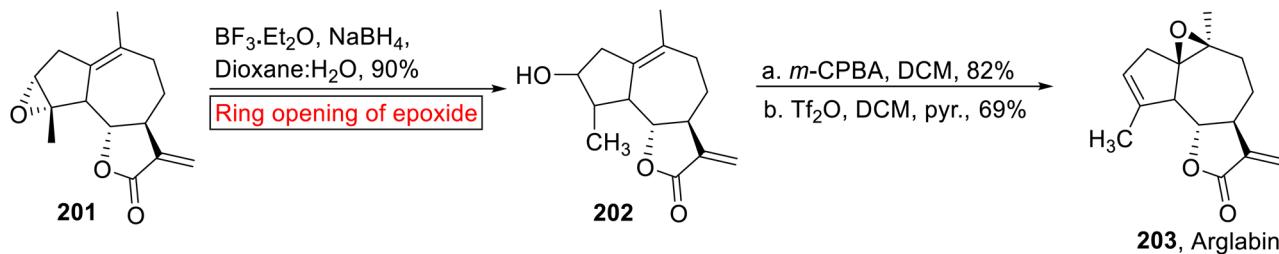
synthesis of efficacious anti-proliferative agents.^{171–173} (–)-Artatrovirenl A **226** was isolated from *Artemisia atrovirens* in 2020 (ref. 174) which exhibits cytoidal activity opposite to hepatocellular carcinoma (SMMC-7721, HepG2, and Huh7). Bridged, fused, and spirocyclic ring systems make a cage-like structure of (–)-Artatrovirenl A **226**. In 2023,¹⁷⁵ Zhu *et al.* disclosed the first total synthesis of (–)-Artatrovirenl A **226** by employing epoxide



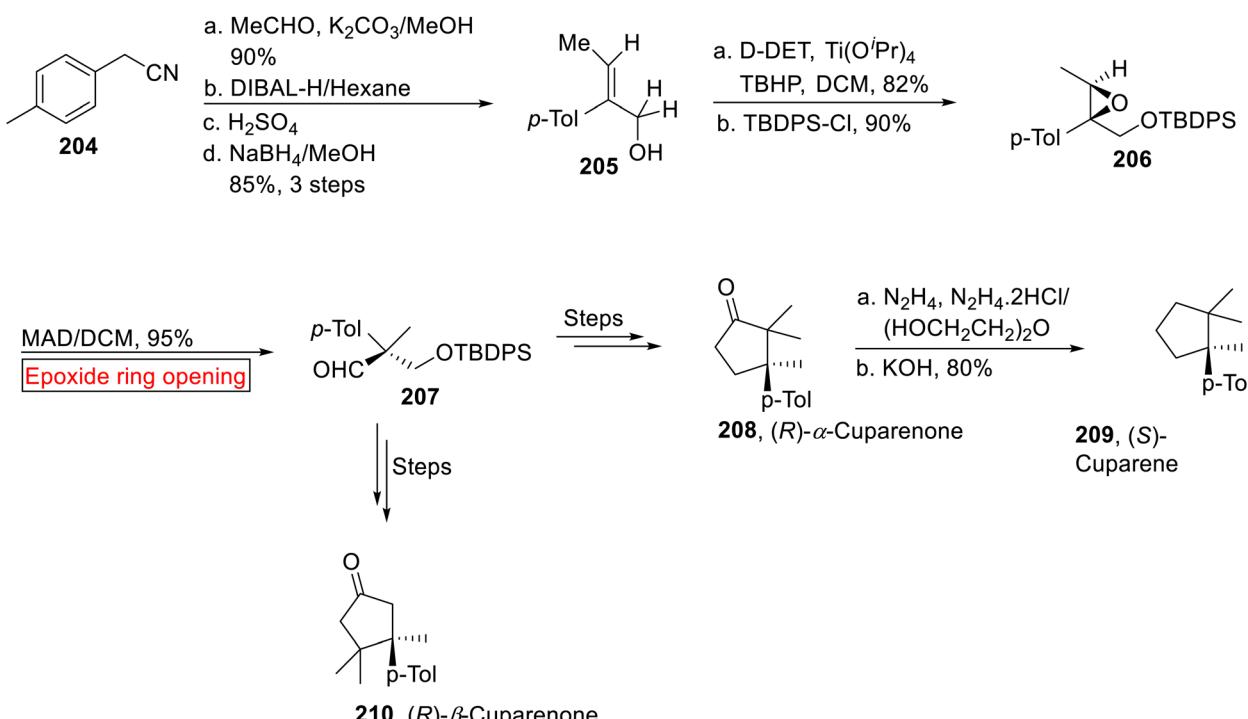
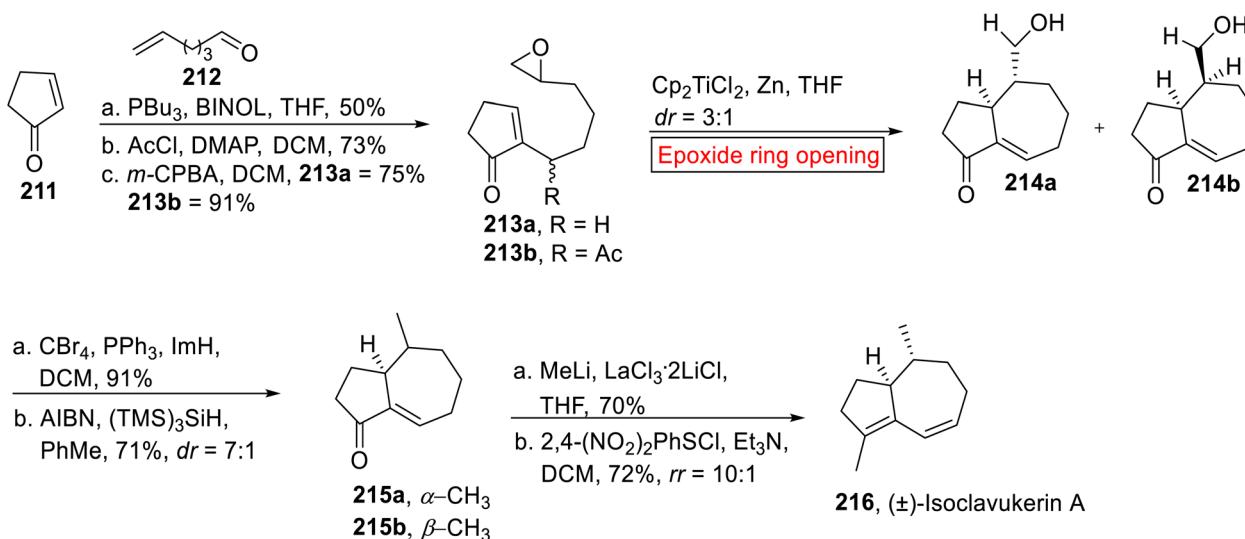
Scheme 22 Syntheses of Guaiane-type sesquiterpenoids (Guaiia-4(5)-en-11-ol **191**, Aciphylene **192**, 1-*epi*-Melicodenones C **193**, 1-*epi*-Melicodenones E **194**, Guaiia-5(6)-en-11-ol **195**, 1-*epi*-Aciphylene **198**, 1-*epi*-Guaiia-4(5)-en-11-ol **200**).

ring opening reaction as one of the significant steps. The enantioselective synthesis of (–)-Artatrovirenil A **226** initiated with the formation of TBS silyl ketene acetal **221**. In the first step, iso-prene **217** was reacted with enolate **218** using oxaza-borolidine **219** and bis triflimide (Tf_2NH) followed by chemoselective reduction (NaBH_4), acid-mediated lactonization

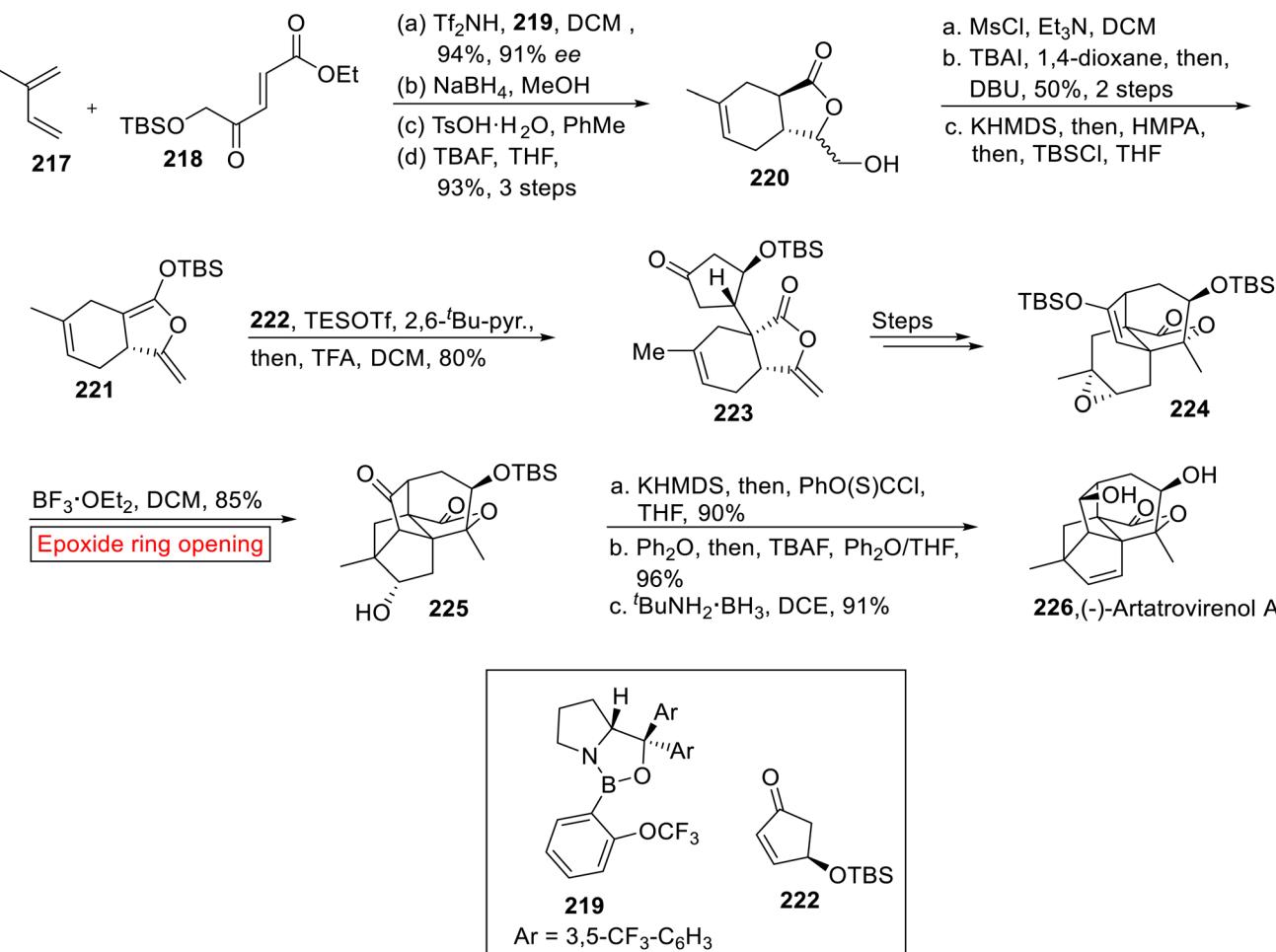
(TsOH) and deprotection (TBAF) of silyl ether to provide γ -lactone **220** (93%, 3 steps). In the next step, –OH group of lactone **220** was protected with MsCl accompanied by TBAI-mediated Finkelstein iodination and elimination with subsequent deprotection reaction (by using KHMDS = potassium bis(trimethylsilyl)amide). The deprotection strategy was then



Scheme 23 Hemisynthesis of Argabin 203.

Scheme 24 Synthesis of (R)- α -Cuparenone 208, (R)- β -Cuparenone 210 and (S)-Cuparene 209.

Scheme 25 Synthesis of (±)-Isoclavukerin A 216.



Scheme 26 Total synthesis of (-)-Artatrovirenil A 226.

followed by HMPA (hexamethylphosphoramide) and TBSCl (*tert*-butyldimethylsilyl chloride) addition to furnish silyl ketene acetal **221**. Then, acetal **221** and enone **222** were reacted in the presence of TESOTf (trimethylsilyl trifluoromethanesulfonate) followed by TFA-mediated hydrolysis to render 5,6-*cis*-fused bicyclic lactone **223** (80%) which was further converted into **224** over several steps. In the next step, compound **224** experienced $\text{BF}_3\cdot\text{OEt}_2$ -catalyzed epoxide ring opening reaction in DCM to afford the product **225** (85%). In the next step, the compound **225** went through sequential thioacetylation of alcohol, TBS deprotection (TBAF) and treatment with ${}^t\text{BuNH}_2\cdot\text{BH}_3$ to furnish (-)-Artatrovirenil **226** in 91% yield (Scheme 26).

Conclusion

This article provides an overview of the previous ten years of research on the epoxide ring opening reactions that have been employed towards the synthesis of natural products. Epoxides are frequently used as building blocks in synthetic organic chemistry by undergoing epoxide ring opening reaction. A number of reagents, catalysts, and solvents are used in an epoxide ring opening process which determine its outcome. Moreover, the total synthesis of various natural products also

utilizes epoxide ring opening reaction as one of the key steps. An updated summation of synthetic methods involving the utilization of epoxide ring opening for the production of interesting natural products with important biological activities is presented in this review article. These natural products include alkaloids and terpenoids. This review will motivate organic chemists to focus their efforts on epoxide ring opening reactions and their chemistry to devise more effective pathways for further advancements towards the synthesis of natural products in the future.

Conflicts of interest

There are no conflicts to declare.

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References

- 1 G. Sabitha, R. S. Babu, M. Rajkumar, C. S. Reddy and J. Yadav, *Tetrahedron Lett.*, 2001, **42**, 3955–3958.
- 2 R. Munir, A. F. Zahoor, U. Nazeer, M. A. Saeed, A. Mansha, A. Irfan and M. U. Tariq, *RSC Adv.*, 2023, **13**, 35172–35208.
- 3 S. E. Schaus and E. N. Jacobsen, *Org. Lett.*, 2000, **2**, 1001–1004.
- 4 U. Nazeer, A. Mushtaq, A. F. Zahoor, F. Hafeez, I. Shahzadi and R. Akhtar, *RSC Adv.*, 2023, **13**, 35695–35732.
- 5 B. M. Cole, K. D. Shimizu, C. A. Krueger, J. P. Harrity, M. L. Snapper and A. H. Hoveyda, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 1668–1671.
- 6 S. Mori, E. Nakamura and K. Morokuma, *J. Am. Chem. Soc.*, 2000, **122**, 7294–7307.
- 7 W. A. Nugent, *J. Am. Chem. Soc.*, 1998, **120**, 7139–7140.
- 8 S. Sagawa, H. Abe, Y. Hase and T. Inaba, *J. Org. Chem.*, 1999, **64**, 4962–4965.
- 9 Z. Yan, Z. Ma, J. Deng and G. Luo, *Chem. Eng. Sci.*, 2021, **242**, 116746.
- 10 S. Matsunaga, J. Das, J. Roels, E. M. Vogl, N. Yamamoto, T. Iida, K. Yamaguchi and M. Shibasaki, *J. Am. Chem. Soc.*, 2000, **122**, 2252–2260.
- 11 R.-E. Parker and N. Isaacs, *Chem. Rev.*, 1959, **59**, 737–799.
- 12 D. J. Goldsmith, *J. Am. Chem. Soc.*, 1962, **84**, 3913–3918.
- 13 R. A. Smith and S. Natelson, *J. Am. Chem. Soc.*, 1931, **53**, 3476–3479.
- 14 S. Ahmad, A. F. Zahoor, S. A. R. Naqvi and M. Akash, *Mol. Diversity*, 2018, **22**, 191–205.
- 15 Z. Li, Z. Zhou, K. Li, L. Wang, Q. Zhou and C. Tang, *Tetrahedron Lett.*, 2002, **43**, 7609–7611.
- 16 S. Faiz, A. F. Zahoor, N. Rasool, M. Yousaf, A. Mansha, M. Zia-Ul-Haq and H. Z. Jaafar, *Molecules*, 2015, **20**, 14699–14745.
- 17 M. S. Von Wittenau and H. Els, *J. Am. Chem. Soc.*, 1963, **85**, 3425–3431.
- 18 K. Fagnou and M. Lautens, *Org. Lett.*, 2000, **2**, 2319–2321.
- 19 C. Baylon, G. Prestat, M.-P. Heck and C. Mioskowski, *Tetrahedron Lett.*, 2000, **41**, 3833–3835.
- 20 M. Inai, T. Asakawa and T. Kan, *Tetrahedron Lett.*, 2018, **59**, 1343–1347.
- 21 J. T. Bagdanoff, D. C. Behenna, J. L. Stockdill and B. M. Stoltz, *Eur. J. Org. Chem.*, 2016, **12**, 2101–2104.
- 22 F. X. Li, S. J. Ren, P. F. Li, P. Yang and J. Qu, *Angew. Chem.*, 2020, **132**, 18631–18636.
- 23 C. P. Bold, M. Gut, J. Schürmann, D. Lucena-Agell, J. Gertsch, J. F. Diaz and K. H. Altmann, *Chem.-Eur. J.*, 2021, **27**, 5936–5943.
- 24 A. Gehlawat, R. Prakash and S. Kumar Pandey, *ChemistrySelect*, 2020, **5**, 6373–6375.
- 25 O. Hoff, N. Kratena, D. Aynedtinova, K. E. Christensen and T. J. Donohoe, *Chem.-Eur. J.*, 2022, **28**, e202202464.
- 26 P. Thesmar, S. Coomar, A. Prescimone, D. Häussinger, D. Gillingham and O. Baudoin, *Chem.-Eur. J.*, 2020, **26**, 15298–15312.
- 27 S. Meninno, L. Zullo, J. Overgaard and A. Lattanzi, *Adv. Synth. Catal.*, 2017, **359**, 913–918.
- 28 W. Hofer, E. Oueis, A. A. Fayad, F. Deschner, A. Andreas, L. P. de Carvalho, S. Hüttel, S. Bernecker, L. Pätzold and B. Morgenstern, *Angew. Chem., Int. Ed.*, 2022, **61**, e202202816.
- 29 R. Rengarasu and M. E. Maier, *Asian J. Org. Chem.*, 2017, **6**, 108–117.
- 30 X. Wang, G. Huang, Y. Wang and J. Gui, *J. Am. Chem. Soc.*, 2023, **145**, 9354–9363.
- 31 T. Kasemsuk, P. Piyachaturawat, R. Bunthawong, U. Sirion, K. Suksamrarn and R. Saeeng, *Eur. J. Med. Chem.*, 2017, **138**, 952–963.
- 32 Z. Liu, F. Zhao, B. Zhao, J. Yang, J. Ferrara, B. Sankaran, B. Venkataram Prasad, B. B. Kundu, G. N. Phillips Jr and Y. Gao, *Nat. Commun.*, 2021, **12**, 4158.
- 33 B. R. McDonald and K. A. Scheidt, *Acc. Chem. Res.*, 2015, **48**, 1172–1183.
- 34 F. Isnard, M. Lamberti, C. Pellecchia and M. Mazzeo, *ChemCatChem*, 2017, **9**, 2972–2979.
- 35 L. Wang, A. Parnell, C. Williams, N. A. Bakar, M. R. Challand, M. W. van der Kamp, T. J. Simpson, P. R. Race, M. P. Crump and C. L. Willis, *Nat. Catal.*, 2018, **1**, 968–976.
- 36 A. Rivas, M. Castiñeira, R. Álvarez, B. Vaz and A. R. de Lera, *J. Nat. Prod.*, 2022, **85**, 2302–2311.
- 37 Z. Y. Liu, Z. C. Chen, C. Z. Yu, R. F. Wang, R. Z. Zhang, C. S. Huang, Z. Yan, D. R. Cao, J. B. Sun and G. Li, *Chem.-Eur. J.*, 2002, **8**, 3747–3756.
- 38 H. Huang and J. S. Panek, *Org. Lett.*, 2003, **5**, 1991–1993.
- 39 T. R. Hoye and M. Hu, *J. Am. Chem. Soc.*, 2003, **125**, 9576–9577.
- 40 J. A. Faraldo and J.-L. Giner, *J. Org. Chem.*, 2002, **67**, 4659–4666.
- 41 L. Shi, K. Meyer and M. F. Greaney, *Angew. Chem.*, 2010, **122**, 9436–9439.
- 42 K. Miyashita and T. Imanishi, *Chem. Rev.*, 2005, **105**, 4515–4536.
- 43 A. F. Barrero, J. E. Oltra, M. Alvarez and A. Rosales, *J. Org. Chem.*, 2002, **67**, 5461–5469.
- 44 D. J. Aldous, A. J. Dalençon and P. G. Steel, *Org. Lett.*, 2002, **4**, 1159–1162.
- 45 A. Ahmed, E. K. Hoegenauer, V. S. Enev, M. Hanbauer, H. Kaehlig, E. Öhler and J. Mulzer, *J. Org. Chem.*, 2003, **68**, 3026–3042.
- 46 S. Diaz, J. Cuesta, A. González and J. Bonjoch, *J. Org. Chem.*, 2003, **68**, 7400–7406.
- 47 O. Smitt and H.-E. Höglberg, *Tetrahedron*, 2002, **58**, 7691–7700.
- 48 J. Cuerva, J. Justicia, J. Oller-López, B. Bazdi and J. Oltra, *Mini-Rev. Org. Chem.*, 2006, **3**, 23–35.
- 49 I. Vilotijevic and T. F. Jamison, *Angew. Chem., Int. Ed.*, 2009, **48**, 5250–5281.



50 I. Vilotijevic and T. F. Jamison, *Mar. Drugs*, 2010, **8**, 763–809.

51 R. R. Rodríguez-Berriós, S. R. Isbel and A. Bugarin, *Int. J. Mol. Sci.*, 2023, **24**, 6195.

52 M. Tsuda, Y. Kasai, K. Komatsu, T. Sone, M. Tanaka, Y. Mikami and J. I. Kobayashi, *Org. Lett.*, 2004, **6**, 3087–3089.

53 Z. Bian, C. C. Marvin, M. Pettersson and S. F. Martin, *J. Am. Chem. Soc.*, 2014, **136**, 14184–14192.

54 M. Chen, L. Gan, S. Lin, X. Wang, L. Li, Y. Li, C. Zhu, Y. Wang, B. Jiang, J. Jiang, J. Yang and J. Shi, *J. Nat. Prod.*, 2012, **75**, 1167–1176.

55 D. Gahtory, M. Chouhan, R. Sharma and V. A. Nair, *Org. Lett.*, 2013, **15**, 3942–3945.

56 S. D. Vaidya and N. P. Argade, *Org. Lett.*, 2013, **15**, 4006–4009.

57 Z.-J. Cai, S.-Y. Wang and S.-J. Ji, *Org. Lett.*, 2013, **15**, 5226–5229.

58 S. K. Ghosh and R. Nagarajan, *RSC Adv.*, 2014, **4**, 63147–63149.

59 R. H. Jiao, S. Xu, J. Y. Liu, H. M. Ge, H. Ding, C. Xu, H. L. Zhu and R. X. Tan, *Org. Lett.*, 2006, **8**, 5709–5712.

60 B. B. Snider and X. Wu, *Org. Lett.*, 2007, **9**, 4913–4915.

61 A. Coste, M. Toumi, K. Wright, V. Raza, F. Couty, J. Marrot and G. Evano, *Org. Lett.*, 2008, **10**, 3841.

62 B. Malgesini, B. Forte, D. Borghi, F. Quartieri, C. Gennari and G. Papeo, *Chem.-Eur. J.*, 2009, **15**, 7922–7929.

63 A. Coste, G. Karthikeyan, F. Couty and G. Evano, *Synthesis*, 2009, 2927–2934.

64 Q.-L. Peng, S.-P. Luo, X.-E. Xia, L.-X. Liu and P.-Q. Huang, *Chem. Commun.*, 2014, **50**, 1986–1988.

65 S. Tabassum, A. F. Zahoor, S. Ahmad, R. Noreen, S. G. Khan and H. Ahmad, *Mol. Diversity*, 2021, 1–43.

66 Y. Nalli, V. Khajuria, S. Gupta, P. Arora, S. Riyaz-Ul-Hassan, Z. Ahmed and A. Ali, *Org. Biomol. Chem.*, 2016, **14**, 3322–3332.

67 A. J. Day, H. C. Lam, C. J. Sumby and J. H. George, *Org. Lett.*, 2017, **19**, 2463–2465.

68 R. Hesse, K. K. Gruner, O. Kataeva, A. W. Schmidt and H. J. Knölker, *Chem.-Eur. J.*, 2013, **19**, 14098–14111.

69 M. Áiqbal Choudhary, *Nat. Prod. Rep.*, 1999, **16**, 619–635.

70 F.-P. Wang, Q.-H. Chen and X.-Y. Liu, *Nat. Prod. Rep.*, 2010, **27**, 529–570.

71 X.-W. Wang and H. Xie, *Drugs Future*, 1999, **24**, 877–882.

72 K. G. Kou, S. Kulyk, C. J. Marth, J. C. Lee, N. A. Doering, B. X. Li, G. M. Gallego, T. P. Lebold and R. Sarpong, *J. Am. Chem. Soc.*, 2017, **139**, 13882–13896.

73 L. M. Liao, *Alkaloids*, Academic Press, New York, 2003, vol. 60, pp. 287–344.

74 T.-J. Hsieh, F.-R. Chang, Y.-C. Chia, C.-Y. Chen, H.-F. Chiu and Y.-C. Wu, *J. Nat. Prod.*, 2001, **64**, 616–619.

75 R. A. Clery, J. R. Cason and V. Zelenay, *J. Agric. Food Chem.*, 2016, **64**, 4566–4573.

76 L. Liu, Y. Cao, C. Chen, X. Zhang, A. McNabola, D. Wilkie, S. Wilhelm, M. Lynch and C. Carter, *Cancer Res.*, 2006, **66**, 11851–11858.

77 K. Zhao, L. Shen, Z. L. Shen and T. P. Loh, *Chem. Soc. Rev.*, 2017, **46**, 586–602.

78 R. Akhtar and A. F. Zahoor, *Synth. Commun.*, 2020, **50**, 3337–3368.

79 P. Shelton, T. J. Ligon, J. M. Dell, L. Yarbrough and J. R. Vyvyan, *Tetrahedron Lett.*, 2017, **58**, 3478–3481.

80 X.-W. Yang, X.-D. Luo, P. K. Lunga, Y.-L. Zhao, X.-J. Qin, Y.-Y. Chen, L. Liu, X.-N. Li and Y.-P. Liu, *Tetrahedron*, 2015, **71**, 3694–3698.

81 X.-W. Yang, X.-J. Qin, Y.-L. Zhao, P. K. Lunga, X.-N. Li, S.-Z. Jiang, G.-G. Cheng, Y.-P. Liu and X.-D. Luo, *Tetrahedron Lett.*, 2014, **55**, 4593–4596.

82 D. Wang, M. Hou, Y. Ji and S. Gao, *Org. Lett.*, 2017, **19**, 1922–1925.

83 T. Feng, Y. Li, Y.-Y. Wang, X.-H. Cai, Y.-P. Liu and X.-D. Luo, *J. Nat. Prod.*, 2010, **73**, 1075–1079.

84 M. Walia, C. N. Teijaro, A. Gardner, T. Tran, J. Kang, S. Zhao, S. E. O'Connor, V. Courdavault and R. B. Andrade, *J. Nat. Prod.*, 2020, **83**, 2425–2433.

85 N. Mizutani, Y. Aoki, T. Nabe, M. Ishiwara, S. Yoshino, H. Takagaki and S. Kohno, *Eur. J. Pharmacol.*, 2009, **602**, 138–142.

86 A. J. Duplantier, S. L. Becker, M. J. Bohanon, K. A. Borzilleri, B. A. Chrunyk, J. T. Downs, L.-Y. Hu, A. El-Kattan, L. C. James and S. Liu, *J. Med. Chem.*, 2009, **52**, 3576–3585.

87 J. Ramnauth, J. Speed, S. P. Maddaford, P. Dove, S. C. Annedi, P. Renton, S. Rakshit, J. Andrews, S. Silverman and G. Mladenova, *J. Med. Chem.*, 2011, **54**, 5562–5575.

88 H. Tang, Y. Tang, I. V. Kurnikov, H.-J. Liao, N.-L. Chan, M. G. Kurnikova, Y. Guo and W.-C. Chang, *ACS Catal.*, 2021, **11**, 7186–7192.

89 D. G. Yu, F. de Azambuja and F. Glorius, *Angew. Chem., Int. Ed.*, 2014, **53**, 2754–2758.

90 G.-D. Xu and Z.-Z. Huang, *Org. Lett.*, 2017, **19**, 6265–6267.

91 X. Kou and K. G. Kou, *ACS Catal.*, 2020, **10**, 3103–3109.

92 H. Wang, F. Cao, W. Gao, X. Wang, Y. Yang, T. Shi and Z. Wang, *Org. Lett.*, 2021, **23**, 863–868.

93 D. P. A. Gossan, A. A. Magid, P. A. Kouassi-Yao, J.-B. Behr, A. C. Ahibo, L. A. Djakouré, D. Harakat and L. Voutquenne-Nazabadioko, *Phytochemistry*, 2015, **109**, 76–83.

94 B. J. Byatt, A. Kato and S. G. Pyne, *Org. Lett.*, 2021, **23**, 4029–4033.

95 J.-X. Zhao, C.-P. Liu, W.-Y. Qi, M.-L. Han, Y.-S. Han, M. A. Wainberg and J.-M. Yue, *J. Nat. Prod.*, 2014, **77**, 2224–2233.

96 C. M. Hasler, G. Acs and P. M. Blumberg, *Cancer Res.*, 1992, **52**, 202–208.

97 E. Hecker, *Pure Appl. Chem.*, 1977, **49**, 1423–1431.

98 X. Liu, J. Liu, J. Zhao, S. Li and C.-C. Li, *Org. Lett.*, 2017, **19**, 2742–2745.

99 E. M. Simmons, J. R. Yen and R. Sarpong, *Org. Lett.*, 2007, **9**, 2705–2708.

100 Z.-W. Jiao, Y.-Q. Tu, Q. Zhang, W.-X. Liu, S.-Y. Zhang, S.-H. Wang, F.-M. Zhang and S. Jiang, *Nat. Commun.*, 2015, **6**, 7332.



101 D. Martinez-Solorio and M. P. Jennings, *Org. Lett.*, 2009, **11**, 189–192.

102 S. Sengupta, M. G. Drew, R. Mukhopadhyay, B. Achari and A. K. Banerjee, *J. Org. Chem.*, 2005, **70**, 7694–7700.

103 Y. Suto, K. Kaneko, N. Yamagiwa and G. Iwasaki, *Tetrahedron Lett.*, 2010, **51**, 6329–6330.

104 C. Thommen, M. Neuburger and K. Gademann, *Chem.-Eur. J.*, 2017, **23**, 120–127.

105 G. Majetich, Y. Li and G. Zou, *Heterocycles*, 2007, **73**, 217–225.

106 G. Majetich, Y. Li and G. Zou, *Heterocycles: an International Journal for Reviews and Communications in Heterocyclic Chemistry*, 2007, vol. 73, pp. 217–225.

107 C. H. Oh, L. Piao, J. Jung and J. Kim, *Asian J. Org. Chem.*, 2016, **5**, 1237–1241.

108 A. Ahmad and A. C. Burtoloso, *Org. Lett.*, 2019, **21**, 6079–6083.

109 Y. Li and G. Pattenden, *Nat. Prod. Rep.*, 2011, **28**, 429–440.

110 J.-H. Sheu, A. F. Ahmed, R.-T. Shiue, C.-F. Dai and Y.-H. Kuo, *J. Nat. Prod.*, 2002, **65**, 1904–1908.

111 N. P. Thao, N. H. Nam, N. X. Cuong, T. H. Quang, P. T. Tung, D. Chae, S. Kim, Y.-S. Koh, P. Van Kiem and C. Van Minh, *Bioorg. Med. Chem. Lett.*, 2013, **23**, 228–231.

112 N. J. Hafeman, S. A. Loskot, C. E. Reimann, B. P. Pritchett, S. C. Virgil and B. M. Stoltz, *J. Am. Chem. Soc.*, 2020, **142**, 8585–8590.

113 C. Meyre-Silva and V. Cechinel-Filho, *Curr. Pharm. Des.*, 2010, **16**, 3503–3518.

114 O. K. Popoola, A. M. Elbagory, F. Ameer and A. A. Hussein, *Molecules*, 2013, **18**, 9049–9060.

115 S. El Bardai, N. Morel, M. Wibo, N. Fabre, G. Llabres, B. Lyoussi and J. Quetin-Leclercq, *Planta Med.*, 2003, **69**, 75–77.

116 F. Piozzi, M. Bruno, S. Rosselli and A. Maggio, *Nat. Prod. Commun.*, 2006, **1**, 1934578X0600100713.

117 G. Laonigro, R. Lanzetta, M. Parrilli, M. Adinolfi and L. Mangoni, *Gazz. Chim. Ital.*, 1979, **109**, 145–150.

118 Y. Sakagami, N. Kondo, Y. Sawayama, H. Yamakoshi and S. Nakamura, *Molecules*, 2020, **25**, 1610.

119 R. A. Craig and B. M. Stoltz, *Chem. Rev.*, 2017, **117**, 7878–7909.

120 P. Ramesh, N. S. Reddy, Y. Venkateswarlu, M. V. R. Reddy and D. J. Faulkner, *Tetrahedron Lett.*, 1998, **39**, 8217–8220.

121 B. R. Chitturi, V. B. Tatipamula, C. B. Dokuburra, U. K. Mangamuri, V. R. Tuniki, S. V. Kalivendi, R. A. Bunce and V. Yenamandra, *Tetrahedron*, 2016, **72**, 1933–1940.

122 I. Shahzadi, A. F. Zahoor, A. Rasul, N. Rasool, Z. Raza, S. Faisal, B. Parveen, S. Kamal, M. Zia-ur-Rehman and F. M. Zahid, *J. Heterocycl. Chem.*, 2020, **57**, 2782–2794.

123 N. J. Truax, S. Ayinde, J. O. Liu and D. Romo, *J. Am. Chem. Soc.*, 2022, **144**, 18575–18585.

124 E. F. Rogers, F. R. Koniuszy, J. Shavel Jr and K. Folkers, *J. Am. Chem. Soc.*, 1948, **70**, 3086–3088.

125 K. Wiesner, *Pure Appl. Chem.*, 1963, **7**, 285–296.

126 A. Bélanger, D. J. Berney, H.-J. Borschberg, R. Brousseau, A. Douthneau, R. Durand, H. Katayama, R. Lapalme, D. M. Leturc, C.-C. Liao, F. N. MacLachlan, J.-P. Maffrand, F. Marazza, R. Martino, C. Moreau, L. Saint-Laurent, R. Saintonge, P. Soucy, L. Ruest and P. Deslongchamps, *Can. J. Chem.*, 1979, **57**, 3348–3354.

127 M. Nagatomo, M. Koshimizu, K. Masuda, T. Tabuchi, D. Urabe and M. Inoue, *J. Am. Chem. Soc.*, 2014, **136**, 5916–5919.

128 K. V. Chuang, C. Xu and S. E. Reisman, *Science*, 2016, **353**, 912–915.

129 K. Du, M. J. Kier, Z. D. Stempel, V. Jeso, A. L. Rheingold and G. C. Micalizio, *J. Am. Chem. Soc.*, 2020, **142**, 12937–12941.

130 J. J. Fernández, M. L. Souto and M. Norte, *Nat. Prod. Rep.*, 2000, **17**, 235–246.

131 J. Blunt, M. Hartshorn, T. McLennan, M. Munro, W. T. Robinson and S. Yorke, *Tetrahedron Lett.*, 1978, **19**, 69–72.

132 A. Hoshino, H. Nakai, M. Morino, K. Nishikawa, T. Kodama, K. Nishikibe and Y. Morimoto, *Angew. Chem.*, 2017, **129**, 3110–3114.

133 L. Ding, J. Münch, H. Goerls, A. Maier, H.-H. Fiebig, W.-H. Lin and C. Hertweck, *Bioorg. Med. Chem. Lett.*, 2010, **20**, 6685–6687.

134 L. Ding, A. Maier, H.-H. Fiebig, W.-H. Lin and C. Hertweck, *Org. Biomol. Chem.*, 2011, **9**, 4029–4031.

135 Z. Xu, M. Baunach, L. Ding and C. Hertweck, *Angew. Chem.*, 2012, **41**, 10439–10443.

136 M. Baunach, L. Ding, T. Bruhn, G. Bringmann and C. Hertweck, *Angew. Chem., Int. Ed.*, 2013, **52**, 9040–9043.

137 H. Li, Q. Zhang, S. Li, Y. Zhu, G. Zhang, H. Zhang, X. Tian, S. Zhang, J. Ju and C. Zhang, *J. Am. Chem. Soc.*, 2012, **134**, 8996–9005.

138 Q. Zhang, H. Li, S. Li, Y. Zhu, G. Zhang, H. Zhang, W. Zhang, R. Shi and C. Zhang, *Org. Lett.*, 2012, **14**, 6142–6145.

139 Q. Zhang, A. Mándi, S. Li, Y. Chen, W. Zhang, X. Tian, H. Zhang, H. Li, W. Zhang and S. Zhang, *Eur. J. Org. Chem.*, 2012, **2012**, 5256–5262.

140 B. R. Rosen, E. W. Werner, A. G. O'Brien and P. S. Baran, *J. Am. Chem. Soc.*, 2014, **136**, 5571–5574.

141 Z. Meng, H. Yu, L. Li, W. Tao, H. Chen, M. Wan, P. Yang, D. J. Edmonds, J. Zhong and A. Li, *Nat. Commun.*, 2015, **6**, 6096.

142 F. Marion, D. E. Williams, B. O. Patrick, I. Hollander, R. Mallon, S. C. Kim, D. M. Roll, L. Feldberg, R. Van Soest and R. J. Andersen, *Org. Lett.*, 2006, **8**, 321–324.

143 B. Sullivan, P. Djura, D. E. McIntyre and D. J. Faulkner, *Tetrahedron*, 1981, **37**, 979–982.

144 A. Grube, M. Assmann, E. Lichte, F. Sasse, J. R. Pawlik and M. Köck, *J. Nat. Prod.*, 2007, **70**, 504–509.

145 B. W. Sullivan, D. J. Faulkner, G. K. Matsumoto, C. H. He and J. Clardy, *J. Org. Chem.*, 1986, **51**, 4568–4573.

146 A. W. Markwell-Heys, K. K. Kuan and J. H. George, *Org. Lett.*, 2015, **17**, 4228–4231.

147 H.-B. Liao, G.-H. Huang, M.-H. Yu, C. Lei and A.-J. Hou, *J. Org. Chem.*, 2017, **82**, 1632–1637.

148 G.-Y. Luo, H. Wu, Y. Tang, H. Li, H.-S. Yeom, K. Yang and R. P. Hsung, *Synthesis*, 2015, **47**, 2713–2720.



149 R. Raju, A. M. Piggott, L. X. Barrientos Diaz, Z. Khalil and R. J. Capon, *Org. Lett.*, 2010, **12**, 5158–5161.

150 S. Faiz, A. F. Zahoor, M. Ajmal, S. Kamal, S. Ahmad, A. M. Abdelgawad and M. E. Elnagggar, *J. Heterocycl. Chem.*, 2019, **56**, 2839–2852.

151 J. Schmidt and C. B. Stark, *Org. Lett.*, 2012, **14**, 4042–4045.

152 X.-B. Ding, D. P. Furkert, R. J. Capon and M. A. Brimble, *Org. Lett.*, 2014, **16**, 378–381.

153 B. M. Fraga, *Nat. Prod. Rep.*, 2012, **29**, 1334–1366.

154 B. Fraga, *Nat. Prod. Rep.*, 2013, **30**, 1226.

155 J. A. Marshall and A. E. Greene, *J. Org. Chem.*, 1972, **37**, 982–985.

156 A. Srikrishna and V. H. Pardeshi, *Tetrahedron*, 2010, **66**, 8160–8168.

157 A.-C. Huang, C. J. Sumby, E. R. Tiekkink and D. K. Taylor, *J. Nat. Prod.*, 2014, **77**, 2522–2536.

158 S. Adekenov, M. Mukhametzhanov, A. Kagarlitskii and A. Kupriyanov, *Chem. Nat. Compd.*, 1982, **18**, 623–624.

159 N. Zhangabylov, L. Y. Dederer, L. Gorbacheva, S. Vasil'eva, A. Terekhov and S. Adekenov, *Pharm. Chem. J.*, 2004, **38**, 651–653.

160 S. Kalidindi, W. B. Jeong, A. Schall, R. Bandichhor, B. Nosse and O. Reiser, *Angew. Chem., Int. Ed.*, 2007, **46**, 6361–6363.

161 J.-D. Zhai, D. Li, J. Long, H.-L. Zhang, J.-P. Lin, C.-J. Qiu, Q. Zhang and Y. Chen, *J. Org. Chem.*, 2012, **77**, 7103–7107.

162 S. H. Lone and K. A. Bhat, *Tetrahedron Lett.*, 2015, **56**, 1908–1910.

163 G. L. Chetty and S. Dev, *Tetrahedron Lett.*, 1964, **5**, 73–77.

164 V. Benesova, *Collect. Czech. Chem. Commun.*, 1976, **41**, 3812–3814.

165 H. Erdtman, B. Thomas, E. Stenhagen, L. G. Sillén, B. Zaar and E. Diczfalussy, *Acta Chem. Scand.*, 1958, **12**, 267–273.

166 R. Kumar, J. Halder and S. Nanda, *Tetrahedron*, 2017, **73**, 809–818.

167 M. Kobayashi, B. Son, M. Kido, Y. Kyogoku and I. Kitagawa, *Chem. Pharm. Bull.*, 1983, **31**, 2160–2163.

168 M. Kobayashi, B. W. Son, Y. Kyogoku and I. Kitagawa, *Chem. Pharm. Bull.*, 1984, **32**, 1667–1670.

169 B. F. Bowden, J. C. Coll and D. M. Tapiolas, *Aust. J. Chem.*, 1983, **36**, 211–214.

170 S. Begum, R. Bhattacharya, S. Paul and T. K. Chakraborty, *J. Org. Chem.*, 2023, **88**, 12677–12697.

171 Z. Ma, G. Gao, K. Fang and H. Sun, *ACS Med. Chem. Lett.*, 2019, **10**, 191–195.

172 I. Shahzadi, A. F. Zahoor, A. Rasul, A. Mansha, S. Ahmad and Z. Raza, *ACS Omega*, 2021, **6**, 11943–11953.

173 R. Akhtar, A. F. Zahoor, A. Rasul, M. Ahmad, M. N. Anjum, M. Ajmal, Z. Raza and Z. Pak, *J. Pharm. Sci.*, 2019, **32**, 2215–2222.

174 L.-H. Su, C.-A. Geng, T.-Z. Li, Y.-B. Ma, X.-Y. Huang, X.-M. Zhang and J.-J. Chen, *J. Org. Chem.*, 2020, **85**, 13466–13471.

175 R. Lavernhe, P. Domke, Q. Wang and J. Zhu, *J. Am. Chem. Soc.*, 2023, **145**, 24408–24415.

