Abstract: This review describes advances in the literature since 2000 in the area of reactions of vinylsulfonium and vinylsulfoxonium salts, with a particular emphasis on stereoselective examples. Although the chemistry of vinylsulfonium salts was first explored back in the 1950s, and that of vinylsulfoxonium salts in the early 1970s, there has been renewed interest in these compounds since the turn of the century. This has been largely due to an increased appreciation for the many synthetic possibilities associated with these valuable electrophiles. The development of improved routes to vinylsulfonium salts allowing for their in situ generation has played a part in accelerating their study. In general, reactions of the two sulfur salt classes follow a similar mechanistic pathway: initial conjugate addition of a nucleophile to the β-position, followed by protonation of an ylide intermediate, and cyclization of tethered anion to afford monocyclic or bicyclic product (e.g., cyclopropane, aziridine, oxazole, oxazolidinone, γ-lactam or γ-lactone). Alternatively, reactions involve formation of an ylide intermediate followed by intramolecular Johnson-Corey-Chaykovsky reaction (epoxidation or cyclopropanation), and subsequent cyclization to afford the desired bicyclic product (e.g., fused bicyclic epoxide or cyclopropane).

Keywords: vinylsulfonium; vinylsulfoxonium; sulfonium salts; sulfoxonium salts; oxosulfonium; ylides; conjugate addition; epoxide; cyclopropane; γ-lactone

1. Introduction

Ever since the independent contributions of Johnson, Corey and Chaykovsky in the 1960s, organosulfur chemistry has assumed a central position in synthetic organic chemistry [1,2]. This is mainly because sulfur ylide and sulfur salt chemistry has provided simple, efficient, and frequently highly stereoselective (diastereoselective and enantioselective) routes to important synthetic building blocks, including epoxides, cyclopropanes, aziridines, and more recently γ-lactones and alkenes. These reaction products often function as key intermediates in natural product and in pharmaceutical synthesis, and so have broad appeal to both academia and to industry. This review will center on recent contributions to the literature on chemistry of vinyl sulfonium and vinyl sulfoxonium salts since 2000, as prior to this review a number of excellent treatises describing progress in the area of sulfur ylide and sulfur salt chemistry have been presented [3–7].

2. Sulfur is Special

The sulfur atom’s ability to stabilize an adjacent (α) negatively charged carbon has long attracted attention from synthetic organic and theoretical chemists [4–7]. This stabilization was at one point attributed to the ability of empty low-lying d-orbitals to delocalize electron density from the filled orbital of the carbanion [8]. However, more recently ab initio computational studies have shed more
light on the mode of stabilization. It is now generally accepted that delocalization into d-orbitals does not play a role in stabilization of sulfur ylides [4,5,9–11]. Instead, it has been proposed that the stabilization is largely due to electrostatic attraction, and negative hyperconjugation (overlap between the carbanion lone pair orbital \(n\) with the \(\sigma^*\) orbital of sulfur-carbon bond) [9–14]. Therefore, it is not surprising that vinylsulfonium and vinylsulfoxonium salts function as effective electrophilic Michael acceptors akin to \(\alpha,\beta\)-unsaturated ketones, given the ability of the sulfur atom to stabilize ylide intermediates (sulfonium and sulfoxonium ylides) and associated transition states. In contrast, the analogous vinyl ammonium salts do not act as Michael acceptors [6,7].

3. Early Contributions

In 1966 Gosselck and co-workers demonstrated through the reaction of carbanions with vinyl(dimethyl)sulfonium salts [15–18]. Shortly after, in the early 1970s, Johnson’s group advanced the idea of vinylsulfoxonium salts as electrophilic species which could potentially provide a new arsenal of reactions that would complement those that had been developed using various nucleophilic sulfur ylides [19,20]. In 1980 Johnson’s group demonstrated that vinylsulfoxonium salts could undergo conjugate addition reactions with a range of protic nucleophiles (some ambident), including amines, ketoesters, and nitromethane to afford 3-membered and 5-membered cyclic products [21]. However, vinylsulfoxonium salt research remained largely dormant until Gais’s group carried out further work in the 1990s and 2000s [22–24]. On the other hand, vinylsulfoniums have attracted a lot of interest recently, in no small part, due to the contributions of the Aggarwal group in the period 2000 to present [25]. This review will focus on recent contributions to the literature on the chemistry of vinylsulfonium and vinylsulfoxonium salts since 2000.

4. Synthesis of Vinylsulfonium and Vinylsulfoxonium Salts

4.1. Synthesis of Diphenylvinylsulfonium Triflate (1)

Aggarwal and colleagues recently reported an efficient and practical method for the synthesis of diphenylvinylsulfonium triflate (Scheme 1) [25,26]. The reaction of 2-bromoethyl triflate 2 with diphenyl sulfide in refluxing toluene under an inert atmosphere furnished crystalline solid bromoethylidiphenylsulfonium triflate 3 in high yield. Bromoethylidiphenylsulfonium triflate 3 on treatment with potassium bicarbonate in a mixture of tetrahydrofuran and water at room temperature gave the desired diphenylvinylsulfonium triflate 1 as a light-yellow oil in excellent yield. Bromoethylidiphenylsulfonium triflate 3 is now commercially available and used as a precursor for the in-situ generation of diphenylvinylsulfonium triflate under various reaction conditions.

![Scheme 1. Synthesis of diphenylvinylsulfonium triflate.](image-url)

4.2. Synthesis of Vinylsulfoxonium Salts (16)

Johnson and co-workers reported the first synthesis of aminosulfoxonium salts 11 (Scheme 2) [27]. The preparation started with the alkylation of an arenethiolate, followed by a smooth oxidation of the resulting sulfide to a sulfoxide, then a conversion of the corresponding sulfoxide to a sulfoximine. It was determined that hydrazoic acid gave a high yield (92%) for the latter conversion in the case of methylphenylsulfoxide. Alkylation of free sulfoximine to dimethylaminosulfoxonium fluoroborate was completed by employing Meerwein’s salt (trimethylxonium tetrafluoroborate) as methylating agent.
Exhaustive alkylation produced the desired dimethylaminosulfoxonium salt 11, while attempted monoalkylation usually resulted in a mixture of products (9 and 11).

![Scheme 2. Preparation of dialkylaminosulfoxonium salts.]

Following their procedure for the synthesis of dialkylaminosulfoxonium salts, Johnson and co-workers were able to isolate and characterize mono-N-alkyl sulfoximines 10 [27]. Deprotonation of the sulfoximine with a strong base, and then addition to an aldehyde or ketone to afford 14, followed by dehydration under acidic conditions furnished α,β-unsaturated sulfoximine 15. Treatment of 14 with concentrated sulfuric acid at 0 °C gave excellent yield (≥96%) for the dehydration step after an examination of different reaction conditions. Alternatively, mesylation of 14 followed by DBU-mediated elimination provided 15 with high olefin isomer stereoselectivity [28]. Finally, methylation of 15 with trimethyloxonium tetrafluoroborate in dichloromethane yielded the desired vinylsulfoxonium salt 16 in high purity (Scheme 3) [19–21,27].

![Scheme 3. Synthesis of vinylsulfoxonium salts.]

5. Reactions of Vinylsulfonium Salts

Vinylsulfonium salts are generally very reactive towards conjugate addition by various nucleophiles, thereby producing sulfur ylide intermediates. There are two possible pathways through which the newly generated sulfonium ylide can react [25,26]. In the first pathway, the sulfonium ylide 19, generated by conjugate addition of a suitable nucleophile, undergoes intramolecular protonation from a neighboring acidic site to generate a new nucleophilic center. The second nucleophile facilitates ring closure with the displacement of the sulfonium leaving group (Scheme 4) [29]. The second pathway is more similar to Johnson–Corey–Chaykovsky-type reactions, where the ylide
intermediate 23 undergoes intramolecular 1,2- or 1,4-addition to a pendant electrophile (aldehyde, ketone, imine, or Michael acceptor) to generate a new zwitterionic intermediate 24. The zwitterionic intermediate 24 undergoes ring closure with the displacement of sulfide to produce fused heterocycles 25 (Scheme 5) [30–32].

5.1. Three-Membered Heterocycle Synthesis

Compounds with an activated methylene group react with vinyl sulfonium salts in the presence of base to generate ylide intermediates. The ylides on subsequent proton transfer followed by ring closure, with the displacement of sulfide, produce cyclopropane derivatives. Xie and colleagues reported the synthesis of gem-disubstituted cyclopropanes 27 from the reaction of N-alkyl malonyl amides 26 and diphenylvinylsulfonium triflate 1 in the presence of the organic base DBU under mild conditions and with good yields (Scheme 6) [33]. Similarly, reactions of primary amines and sulfonamides with vinylsulfonium salt 1 in the presence of mild base furnished aziridines [34,35].

Recently, Qian and coworkers reported for the first time a zinc triflate-mediated cyclopropanation of both N-unsubstituted and N-substituted oxindoles 28 with diphenylvinylsulfonium triflate salt 1 to afford 29 (Scheme 7) [36].

The reaction proceeded under ambient conditions and consistently provided very high yields with broad functional group tolerability. A broad reaction scope was observed, with applications employed in the late stage cyclopropanation of complex medicinally-interesting heterocycles (Scheme 7). In 2004 Mukaiyama introduced a method for the preparation of aziridines from in situ generated vinylsulfonium salts. The vinylsulfonium 1 was generated from the precursor, bromoethyl(diphenyl)sulfonium triflate 3, in the presence of excess nucleophilic base TsNHNa at room temperature, to produce the desired N-tosylaziridine 30 in very good yield (Scheme 8) [37].
Scheme 7. Cyclopropanation of oxindoles with diphenylvinylsulfonium triflate salt.

Aggarwal and coworkers reported the three-component coupling reactions of vinylsulfonium salt 1 with a variety of nucleophiles (e.g., 31) and aldehydes or imines 32 or 34 to provide easy access to epoxides 33 and aziridines 35 respectively (Scheme 9) [30].

Scheme 8. Aziridination using in situ generated vinylsulfonium salts.

Scheme 9. Epoxidation and aziridination from vinylsulfonium salt.
5.2. Four-Membered Heterocycle Synthesis

Aggarwal and colleagues reported an efficient synthesis of several 2,2-disubstituted azetidines 37 and oxetanes 39 through the reaction of in situ generated vinylsulfonium salt 1, from the precursor (2-bromoethyl)diphenylsulfonium triflate (3), with arylglycine derivatives 36 and hydroxymalonates 38 respectively (Scheme 10) [38]. These reaction procedures are simple, give moderate to high yields, and display broad substrate scope, especially with respect to the arylglycine derivative components.

![Scheme 10. Synthesis of azetidines and oxetanes from in-situ generated vinylsulfonium salt.](image)

5.3. Five-Membered Heterocycle Synthesis

The Mukaiyama group reported the synthesis of oxazoles 41 and thiooxazoles 43 with moderate yields by subjecting sodium salts of phenylamide 40 and phenylthioamide 42 to reaction with diphenylvinylsulfonium triflate 1 under mild conditions (Scheme 11) [37].

![Scheme 11. Synthesis of oxazoles and thiooxazoles from vinylsulfonium salt.](image)
They were able to improve the yields substantially (up to 65%) by replacing the vinylsulfonium salt 1 with its precursor (2-bromoethyl)diphenylsulfonium triflate 3 and a catalytic amount of potassium iodide (KI is proposed to facilitate conversion of bromide 3 to 1).

Xie and coworkers reported an efficient domino reaction of diphenylvinylsulfonium salt 1 with tert-butylcarbamates 44 leading to the synthesis of N-aryloxazolidin-2-ones 45 [39]. A range of carbamates bearing amide residues with different degrees of substitution were tested and the N-aryloxazolidin-2-one products were produced in very high yields (Scheme 12).

\[ \text{Scheme 12. Synthesis of N-aryloxazolidin-2-ones from diphenylvinylsulfonium salt.} \]

Xie and colleagues during their cyclopropane synthesis, modified the amide reactants by using alkyl substituted N-arylmalonylamides 46, possessing just two acidic protons, and subjected them to reaction with diphenylvinylsulfonium triflates 1a to produce substituted N-arylpyrrolidin-2-ones 47 in moderate to excellent yields (Scheme 13) [33]. This reaction displayed broad substrate scope with respect to both N-aryl malonylamide 46 and vinylsulfonium triflates 1a.

\[ \text{Scheme 13. Synthesis of N-arylpyrrolidin-2-one from vinylsulfonium salt.} \]

Aggarwal’s group investigated the reaction of vinylsulfonium salt 1, generated in situ from its precursor (2-bromoethyl)diphenylsulfonium triflate (3) in the presence of organic base, with formamidines 48 to synthesize various imidazolinium salts, such as 49, in high yield, with short reaction times, and in excellent yields (Scheme 14) [40]. The method is applicable to the synthesis of symmetrical and unsymmetrical imidazolinium salts bearing aromatic or aliphatic substituents.
Scheme 14. Synthesis of imidazolinium salts from in-situ generated vinylsulfonium salt.

Aggarwal and co-workers also systematically studied the effect of the \(N\)-protecting group of 1,2-amino alcohols, e.g., 50, on annulation reactions with vinylsulfonium salt 1 [41]. They observed selective formation of \(N\)-vinyl oxazolidinones 51 in excellent yield when \(N\)-Cbz protected 1,2-amino alcohols 50 were treated with vinylsulfonium salt 1 in the presence of inorganic base under mild conditions (Scheme 15).

Scheme 15. Synthesis of \(N\)-vinyl oxazolidinones using diphenylvinylsulfonium triflate.

5.4. Six-Membered Heterocycle Synthesis

In 2008 Aggarwal’s group reported the first \([4 + 2]\) annulation reactions of \(\beta\)-heteroatom-substituted amino compounds, e.g., 52, and diphenylvinylsulfonium triflate 1 for the expedient synthesis of several morpholines (53), thiomorpholines (55), and piperazines (57) (Scheme 16) [42].

Scheme 16. Synthesis of morpholines/thiomorpholines/piperazines using diphenylvinylsulfonium triflate 1.
Using this procedure, a range of sulfonamide-protected amino alcohols 52/amino thiols 54/disulfonamides 56 with different degrees of substitution and stereochemistry gave the corresponding morpholines/thiomorpholines/piperazines in very high yield (morpholines 53, 94–98%; thiomorpholines 55, 94–98%; piperazines 57, 91–99%).

The same group extended the above annihilation methodology using diphenylvinylsulfonium triflate 1, generated in situ from its precursor (2-bromoethyl)diphenylsulfonium triflate 3, to undergo reaction with several β-amino alcohols/thiols/amines 54/56/58 and produce an array of morpholines 59, piperazines 57, and thiomorpholines 55 [43,44]. Important disubstituted morpholines were synthesized with a range of nitrogen-protecting groups (59 vs. 57) in excellent yields (Scheme 17).

Scheme 17. Synthesis of morpholines/thiomorpholines/piperazines using in situ generated diphenylvinylsulfonium triflate.

Kristensen and colleagues reported the microwave-assisted annihilation of enantiopure N-2-benzo-thiazolesulfonyl (Bts) protected 1,2-amino alcohols, e.g., 60, with diphenylvinylsulfonium triflate 1 in the presence of triethylamine to furnish Bts-protected morpholines, e.g., 61, in high yields (Scheme 18) [45].

Scheme 18. Synthesis of morpholines from 1,2-amino alcohols using diphenylvinylsulfonium triflate.

An et al. reported annulation of (1H-indol-2-yl)methanols 62 with vinylsulfonium salt 1 for the efficient and general synthesis of oxazino[4,3-a]indole architectures 63 in very high yields (Scheme 19) [46].
Aggarwal and colleagues reported the concise synthesis of more complex stereodefined C-substituted morpholines (e.g., 66) and piperazines (e.g., 68) in high yields through reaction of 1,2-amino alcohols 64/disulfonamides 67 with an α-phenylvinylsulfonium salt 65 (Scheme 20) [47]. They also achieved excellent regio- and diastereoselectivity by choosing a suitable combination of base and solvent (Scheme 20).

Scheme 20. Diastereoselective synthesis of morpholines and piperazines using α-phenylvinylsulfonium salt.

5.5. Seven-Membered Heterocycle Synthesis

Aggarwal and co-workers reported the cyclization reaction of 1,3-aminoalcohols 69/diamines 71 with vinylsulfonium salt 1, generated in situ from its precursor (2-bromoethyl)diphenylsulfonium triflate 3 in the presence of base, to produce 1,4-oxazepines 70 and 1,4-diazepines 72 in excellent yields (Scheme 21) [43].
The same group also extended the prior annulation reaction scope by subjecting α-phenylvinylsulfonium salt 65 to reaction with 1,3-aminoalcohols 69/disulfonamides 74, thereby producing the corresponding phenyl-substituted 1,4-oxazepines 73 and 1,4-diazepines 75 in moderate yields (Scheme 22) [47].

![Scheme 22. Synthesis of 1,4-oxazepines and 1,4-diazepines using α-phenylvinylsulfonium salt.](image)

Tanyeli and colleagues recently reported an efficient synthesis of a 1,4-naphthoxazepine derivative 77 using the reaction between enantioenriched 1,3-aminonaphthol 76 and diphenylvinylsulfonium salt 1, generated in situ from its precursor (2-bromoethyl)diphenylsulfonium triflate 3 in the presence of inorganic base under mild conditions, without any loss in enantiopurity (Scheme 23) [48]. Naphthoxazepines and their derivatives have very high medicinal importance for the central nervous system as antipsychotics, antidepressants, and enzyme inhibitors.

![Scheme 23. Synthesis of 1,4-naphthoxazepine using in-situ generated diphenylvinylsulfonium salt.](image)

5.6. Johnson–Corey–Chaykovsky-Type Reactions for Fused Heterocycle Synthesis

Jimenez and co-workers introduced a camphor-derived vinylsulfonium salt 79 as a reagent for enantioselective cycloannulation reactions [49]. This chiral vinylsulfonium salt 79 underwent reaction with indole-2-carboxaldehyde 78 to afford an oxirane intermediate which upon ring opening with azide produced tricyclic azidoalcohol 80 in moderate yield and in moderate enantiomeric excess (Scheme 24).

![Scheme 24. Johnson–Corey–Chaykovsky-Type Reactions for Fused Heterocycle Synthesis](image)

Along similar lines, the synthesis of fused bicyclic epoxide heterocycles 82 was reported by Aggarwal and co-workers, whereby tandem Michael addition/Johnson–Corey–Chaykovsky-type reactions were employed [50]. The reaction of vinylsulfonium salt 1, generated in situ from its precursor (2-bromoethyl)diphenylsulfonium triflate 3 in the presence of base (DBU) under mild conditions, with α-amino ketones 81 afforded bicyclic epoxides 82 in good to excellent yields. When a chiral (2-bromoethyl)sulfonium reagent 83 was employed, the desired bicyclic epoxides were obtained in moderate to excellent yields and with very good enantioselectivities observed (Scheme 25).
A diastereoselective variant of this reaction was also reported, starting from enantiopure $\alpha$-substituted $\alpha$-amino ketones 84 [50]. Employing the achiral (2-bromoethyl)diphenylsulfonium triflate 3, good to excellent yields and good levels of diastereoselectivity were observed for the synthesis of the fused bicyclic epoxide $N$-heterocycle 85. In addition, enhanced levels of diastereoccontrol were observed when using the chiral bromoethylsulfonium triflate 83 (Scheme 26).

$\alpha$-Hydroxyketone 86 underwent epoxy annulation reactions with vinylsulfonium salt 1, generated in situ from (2-bromoethyl)diphenylsulfonium triflate 3 with base, to produce bicyclic epoxide 87.
in excellent yield but with moderate diastereoselectivity. On the other hand, β-hydroxy aldehyde 88 underwent the same epoxy annulation reaction in good yield and with good diastereoselectivity (Scheme 27) [50].

\[
\begin{align*}
&\text{O} \quad \text{O} \\
&\text{Ph} \quad \text{Ph} \\
&\text{Br} \quad \text{Br} \\
&\text{H} \quad \text{H} \\
&\text{O} \quad \text{O} \\
&\text{Me} \quad \text{Me} \\
&\text{Ar} = 4-\text{NO}_2\text{Ph} \\
&\text{3 (1.25 equiv)} \quad \text{DBU (3.5 equiv)} \quad \text{CH}_2\text{Cl}_2 (0.1 \text{ M}) \quad 0 \degree \text{C}, 2-4 \text{ h}
\end{align*}
\]

\[
\begin{align*}
&\text{O} \quad \text{O} \\
&\text{Ph} \quad \text{Ph} \\
&\text{Ph} \quad \text{Ph} \\
&\text{H} \quad \text{H} \\
&\text{O} \quad \text{O} \\
&\text{Me} \quad \text{Me} \\
&\text{Ar} = 4-\text{NO}_2\text{Ph} \\
&\text{3 (1.25 equiv)} \quad \text{DBU (3.5 equiv)} \quad \text{CH}_2\text{Cl}_2 (0.1 \text{ M}) \quad 0 \degree \text{C}, 2-4 \text{ h}
\end{align*}
\]

\[
\begin{align*}
&\text{Ph} \\
&\text{H} \\
&\text{O} \\
&\text{Me} \\
&\text{Ar} = 4-\text{NO}_2\text{Ph} \\
&87 \quad \text{99%} \quad \text{dr 3:2:1} \\
&88 \quad \text{56%} \quad \text{dr 10:1}
\end{align*}
\]

Scheme 27. Diastereoselective synthesis of bicyclic epoxides using in-situ generated vinylsulfonium salt.

Aggarwal and co-workers also developed a new epoxy-annulation method for converting α-, β-, and γ-amino aldehydes and -ketones 90 into racemic five-, six-, and seven-membered epoxide-fused heterocycles 91 through reaction with diphenylvinylsulfonium triflate 1 under mild reaction conditions [31]. An asymmetric variant for the synthesis of five- and six-membered heterocycles was developed through the use of chiral vinylsulfonium salt 92 and excellent levels of asymmetric induction were achieved (Scheme 28).

\[
\begin{align*}
&\text{O} \quad \text{N} \\
&R \quad \text{Ts} \\
&\text{R} = \text{H, Me, Et, Ph} \\
&n = 1, 2, 3 \\
&90 \quad \text{DBU (2 equiv)} \quad \text{CH}_2\text{Cl}_2 (0.09 \text{ M}) \quad 0 \degree \text{C}, 2-4 \text{ h}
\end{align*}
\]

\[
\begin{align*}
&\text{O} \quad \text{N} \\
&R \quad \text{Ts} \\
&\text{R} = \text{H, Me, Et, Ph} \\
&n = 1, 2 \\
&90 \quad \text{DBU (2 equiv)} \quad \text{CH}_2\text{Cl}_2 (0.015 \text{ M}) \quad -25 \degree \text{C}, 2-5 \text{ days}
\end{align*}
\]

\[
\begin{align*}
&\text{O} \quad \text{N} \\
&R \quad \text{Ts} \\
&\text{R} = \text{H, Me, Et, Ph} \\
&n = 1, 2 \\
&90 \quad \text{91} \quad 67-96\% \\
&90 \quad \text{92 (1 equiv)} \quad \text{DBU (2 equiv)} \quad \text{CH}_2\text{Cl}_2 (0.09 \text{ M}) \quad 0 \degree \text{C}, 2-4 \text{ h}
\end{align*}
\]

\[
\begin{align*}
&\text{O} \quad \text{N} \\
&R \quad \text{Ts} \\
&\text{R} = \text{H, Me, Et, Ph} \\
&n = 1, 2 \\
&90 \quad \text{91} \quad 30-80\% \quad \text{up to 99\% ee}
\end{align*}
\]

Scheme 28. Synthesis of bicyclic epoxides using vinylsulfonium salts.

The same group also reported diastereoselective diphenylvinylsulfonium salt 1-mediated epoxy annulation reactions with enantiopure α-amino ketone 93 giving syn-bicyclic epoxides 94 predominantly [51]. The observed diastereoselectivity of these epoxy annulation reactions depended upon the steric properties of the ketones as well as that of the vinylsulfonium salt employed. With the larger phenyl ketone 93 (R^1 = Ph), highest diastereoselectivity (>50:1) was achieved with both achiral and chiral vinylsulfonium salts, while the intermediate-size dialkylketones (R^1 = Et or Me) gave moderate levels of diastereoselectivity in the presence of the achiral vinylsulfonium salt. However, intermediate-size dialkylketones underwent reaction with chiral vinylsulfonium salt with excellent...
diastereoselectivity. The reaction of aldehydes with achiral vinylsulfonium salt 1 displayed almost no stereocontrol (Scheme 29).

\[
\begin{align*}
\text{O} & \text{R}^1 \\
\text{R}^2 & \text{NH} \\
\text{Ts} & \\
\text{Ph} & \text{S} \\
\text{OTf} & 1 \ (1.2 \text{ equiv}) \\
\text{DBU or NaOH} & \\
\text{CH}_2\text{Cl}_2, 0 \ ^\circ\text{C} & \to \\
\text{R}^1 & \text{O} \\
\text{Ts} & \\
\text{R}^2 & \text{N(Ts)} \\
\text{NTs} & \\
\text{syn} \ (\text{major}) & \\
\text{anti} \ (\text{minor}) & \\
\end{align*}
\]

\[R^1 = \text{H, Me, Et, Ph} \]
\[R^2 = \text{Me, Ph} \]

Scheme 29. Diastereoselective synthesis of bicyclic epoxide using vinylsulfonium salt.

\[\beta\text{-Trifluoromethyl-substituted diphenylvinylsulfonium triflate } 96 \text{ was introduced by Aggarwal and colleagues for epoxy annulation reactions with } \alpha\text{- or } \beta\text{-amino ketones/hydroxyketones } 95 \text{ to produce } \alpha\text{-trifluoromethyl-substituted bicyclic epoxy-fused heterocycles } 97 \text{ (pyrrolidines, piperidines and tetrahydrofurans) in high yield and with high diastereoselectivity (Scheme 30) [52].} \]

\[
\begin{align*}
\text{O} & \text{R}^2 \\
\text{Ph} & \text{S} \\
\text{OTf} & 96 \ (1.2 \text{ equiv}) \\
\text{Et}_3\text{N} (2 \text{ equiv}) & \\
\text{CH}_2\text{Cl}_2 (0.1 \text{ M}) & \to \\
\text{rt, 24 h} & \\
\text{O} & \text{R}^1 \\
\text{CF}_3 & \\
\text{syn} & \\
\text{anti} & \\
\text{45-90\%} & \\ \\
\text{dr } \geq 20:1 & \\
\end{align*}
\]

Scheme 30. Synthesis of bicyclic epoxide heterocycles using \(\beta\text{-trifluoromethyl-substituted diphenylvinylsulfonium triflate.} \)

Aggarwal and co-workers later introduced \(\alpha\text{-substituted vinylsulfonium tetraphenylborates } 98 \text{ as stable isolable salts [53]. Epoxy annulation reactions of the } \alpha\text{-substituted vinylsulfonium tetraphenylborates } 98 \text{ with } \alpha\text{-amino ketones } 81 \text{ gave bicyclic epoxy-fused heterocycles } 99 \text{ in good yields and with high diastereoselectivity (Scheme 31).} \]

\[
\begin{align*}
\text{O} & \text{R}^2 \\
\text{Me} & \text{Me} \\
\text{BPh}_4 & \text{B} \\
\text{Me} & \text{Me} \\
\text{98} & \ (1.2 \text{ equiv}) \\
\text{DBU (2 equiv)} & \\
\text{MeCN (0.1 M)} & \to \\
\text{rt, 1 h} & \\
\text{O} & \text{R}^1 \\
\text{Ar} & \\
\text{Ts} & \\
\text{30-83\%} & \\
\text{dr } \geq 20:1 & \\
\end{align*}
\]

Scheme 31. Synthesis of bicyclic epoxide heterocycles using \(\alpha\text{-substituted vinylsulfonium salt.} \)

The same reaction starting from an enantioenriched \(\alpha\text{-amino ketone } 93a \text{ gave a bicyclic epoxy-fused heterocycle } 100 \text{ with high yield and high diastereoselectivity (Scheme 32) [53].} \)
Frazier et al. reported an excellent diastereoselective annulation reaction of α-aminooxy-carbonyl compound 101 with diphenylvinylsulfonium triflate 1 in the presence of organic base (DBU) to furnish a highly substituted epoxy-oxazine 102 as a single diastereomer in good yield (Scheme 33) [54].

The γ-amino-aldehyde 104 underwent epoxy annulation reactions with diphenylvinylsulfonium triflate 1 to access challenging seven-membered heterocyclic fused epoxides 105 in good yield (Scheme 34) [31]. The γ-amino-aldehyde 104 exists predominantly in the ring-closed hemiaminal form 103, which leads to a low concentration of the required nucleophile in the reaction mixture, and ring closure to form the seven-membered ring is much more difficult to accomplish due to the large ring size. However, after optimization this substrate provided a new route to functionalized bicyclic epoxy azepines 105 (Scheme 34).

Later, the same group further extended this reaction to the diastereoselective synthesis of perhydroazepines 108 (Scheme 35) [29]. Starting from chiral 5-substituted hemiaminal 106, epoxy annulation reactions with diphenylvinylsulfonium triflate 1 gave cis-epoxides 108 in good yield and with good to excellent diastereoselectivity. The steric size and position of the substituents were found to play an important role in controlling diastereoselectivity.
The same idea was extended to the synthesis of bicyclic aziridine fused-heterocycles 111 [31]. Aziridine-annulation reaction of chiral aminal 109 with diphenylvinylsulfonium salt furnished the desired hexahydroazepine 111 in good yield and with moderate diastereoselectivity (Scheme 36).

Scheme 36. Synthesis of hexahydroazepine using diphenylvinylsulfonium salt.

Aggarwal and colleagues reported an efficient and versatile method for the formation of bicyclic cyclopropane-fused heterocycles 113 by subjecting β,γ-unsaturated amine derivatives 112 to reaction with diphenylvinylsulfonium triflate 1, generated in situ from the precursor (2-bromoethyl)diphenylsulfonium triflate 3 [55]. Allylic amine derivatives 112 bearing Michael acceptors with various electron-withdrawing groups were successfully converted to the desired bicyclic 3-azabicyclo[3.1.0]hexanes 113 in moderate to good yields and with moderate to excellent diastereoselectivity (Scheme 37).

Scheme 37. Synthesis of bicyclic cyclopropane-fused heterocycles using in situ generated vinylsulfonium salt.

This methodology was further explored by using chiral aza-Morita–Baylis–Hillman adducts 114 as reactants [55]. The annulation reaction with in situ generated diphenylvinylsulfonium triflate 1 gave the desired products 115 in moderate to good yields, and with excellent diastereoselectivity (Scheme 38).
While the reaction of aza-Morita–Baylis–Hillman adducts 114 possessing an ester group as electron withdrawing group worked very well, unsaturated ketone 114a was less effective, giving the product 115a in low yield, albeit with excellent diastereoselectivity. In this case, a competing epoxy-annulation reaction, resulting from 1,2-addition of the sulfur ylide intermediate onto the methyl ketone (6-exo-trig cyclization to give 116) dominated, instead of the desired 1,4-addition onto the Michael acceptor (6-endo-trig cyclization to give 115a) (Scheme 39) [55].

6. Reactions of Vinylsulfoxonium Salts

6.1. Asymmetric Synthesis of Anti-Homopropargylic Alcohols

Enantiomerically pure homopropargylic alcohols have frequently been used as precursors in natural product synthesis [56]. Gais and co-workers approached the asymmetric synthesis of anti-homopropargylic alcohols 120 through utilization of their sulfonimidoyl-substituted homoallylic alcohols 117 (Scheme 40).

The latter compounds were prepared through the addition of chiral sulfonimidoyl substituted bis(allyl)titanium complexes to unsaturated or highly branched aldehydes [57]. Methylation at the N-atom converted the sulfonimidoyl group on the alkynylsulfoximines 117 into a (dimethylamino)sulfoxonium group (in 118), which would act as a better leaving group. The synthesis of the desired homopropargylic alcohols 120 was then completed by LiN(H)Bu-mediated elimination of the alkenyl(dimethylamino)sulfoxonium salt 118, followed by deprotection of the resulting silyl ether 119 [57].

Facile lithiation of the alkynylsulfoximine 117a at the α-position opened up access to nonterminal homopropargylic alcohols 124. Introduction of a substituent to the α-position of 117a afforded 121. Elimination of the corresponding α-methylated alkenyl(dimethylamino)sulfoxonium salt 122 at different temperatures led to either enantiomerically pure anti-configured homoallylic alcohol derivative 123 or nonterminal homopropargylic alcohol derivative 124, both of which are synthetically useful motifs (Scheme 41) [57].
6.2. Asymmetric Synthesis of Unsaturated, Fused Bicyclic Proline Analogues

Gais et al. were also interested in the asymmetric synthesis of fused bicyclic proline analogues 129 due to their application as starting materials for the preparation of biologically active amino acids and peptidomimetics (Scheme 42) [22].

The required 4-amino 1-alkenyl sulfoximine 125 for methylation was prepared through alkylation of the enantiomerically pure cyclic bis(allylsulfoximine)titanium complex with N-tert-butylsulfonyl imino ethyl ester, proceeding with high regioselectivity and diastereoselectivity [22].

Methylation of N-methyl sulfoximine 125 with Meerwein’s salt, to convert the sulfoximine into a good leaving group, provided the corresponding (dimethylamino)sulfoxonium salt 126 in excellent yield (≥95%). The novel migratory cyclization of the δ-amino alkenylsulfoxonium salt 126 was initiated by DBU. Isomerization of 126 to the corresponding allylic (dimethylamino)sulfoxonium salt 127, followed by intramolecular substitution of the (dimethylamino)sulfoxonium group by the pendant sulfonamide group provided the pyrrolidine ring in 128. Deprotection completed the synthesis of the enantiomerically and diastereomerically pure, unsaturated, fused bicyclic proline analogue 129. The cyclization was not affected by the geometry of the alkenyl group in the vinylsulfoxonium salt...
126, and this method was also effective with an eight-membered carbocyclic ring 130 starting material (Scheme 43) [22].

![Scheme 42. Synthesis of bicyclic proline analogues.](image)

6.3. Asymmetric Synthesis of 2,3-Dihydrofurans and Unsaturated Bicyclic Tetrahydrofurans.

During their study of asymmetric synthesis of disubstituted homopropargylic alcohols 124, Gais et al. observed that the β-Me-substituted alkenyl sulfoxonium salt 135 would give the 2,3-dihydrofuran as the product under the basic reaction conditions employed [57]. They pursued this line of enquiry and examined the reaction with different aryl and sterically bulky alkyl substituents at the 3-position [23]. Methylation of the acyclic δ-silyloxy substituted alkenyl sulfoximines 134 and subsequent treatment with one equivalent of LiN(H)₄-Bu smoothly gave the silyl-substituted monocyclic 2,3-dihydrofurans 136 in near quantitative yields (Scheme 44).

![Scheme 43. Synthesis of eight-membered bicyclic proline analogues.](image)

![Scheme 44. Asymmetric synthesis of monocyclic 2,3-dihydrofurans.](image)

Similarly, cyclic allylic sulfoximines were transformed to the corresponding enantiomerically pure bicyclic 2,3-dihydrofurans containing a six-, seven-, or eight-membered carbocyclic ring in high yields [23]. The authors proposed that the base effected α-elimination of the 1-alkenyl
aminosulfoxonium salts 135 at higher temperatures, and that the resulting β-silyloxy alkylidene carbenes 138 underwent a 1,5-O,Si bond insertion followed by a 1,2-silyl migration to access the desired products 136 (Scheme 45) [23].

Inspired by their previous results whereby treatment of (sulfonylamino)alkyl-substituted 1-alkenyl aminosulfoxonium salts 126 with DBU furnished unsaturated fused bicyclic proline derivatives 129 via a novel migratory cyclization, Gais and his colleagues applied the same strategy to the asymmetric synthesis of unsaturated fused bicyclic tetrahydrofurans 143. The latter compounds represent synthetically interesting skeletons found in many natural products [22,23]. Instead of an α-elimination, the weak base DBU facilitated the isomerization of the 1-alkenyl aminosulfoxonium salts 140 to the allylic aminosulfoxonium salts 141. The allylic aminosulfoxonium salts 141 proceeded to undergo intramolecular substitution and desilylation to produce enantioenriched bicyclic tetrahydrofurans 143 of various ring sizes in good yields (Scheme 46) [23].

6.4. Asymmetric Synthesis of Unsaturated Prolines, β,γ-Dehydro Amino Acids, and Cyclopentanoid Keto Aminosulfoxonium Ylides

Gais and co-workers extended their study on the asymmetric synthesis of proline derivatives 146 after they reported the formation of unsaturated bicyclic prolines 129 [22]. They applied a
similar strategy but this time employing a F\(^-\) ion-mediated migratory cyclization rather than DBU, to deliver the desired monocyclic 3,4-unsaturated prolines 146 with \(\geq 98\%\) ee and in moderate to excellent yields (Scheme 47) [24]. The vinyl aminosulfoxonium salts 145 subjected to cyclization in the three-phase system were prepared by activation of the corresponding chiral vinylsulfoximines 144 through methylation with Meerwein’s salt. This procedure was successful with a sterically bulky substituent at the 3-position of the proline products 146 [24].

![Scheme 47. Asymmetric synthesis of 3,4-dehydro prolines.](image)

As reported earlier, DBU-initiated migratory cyclization of the chiral vinyl aminosulfoxonium salts 126 would lead to bicyclic prolines 129 [22]. An accidental experiment involving treatment of the salts with NH\(_4\)Cl, instead of DBU or KF in THF/water, resulted in an unexpected substitution product. The allyl chloride 148 was obtained in 64\% yield (Scheme 48) [24]. Comparable yields of corresponding products were obtained in the case of treatment of acyclic vinyl aminosulfoxonium salts with NaCl or NH\(_4\)Cl. The preference for migratory substitution over migratory cyclization of salts could be explained by the differences in nucleophilicity and basicity of the Cl\(^-\) and the F\(^-\) anions [24].

![Scheme 48. Asymmetric synthesis of cyclic \(\delta\)-chloro-\(\beta,\gamma\)-dehydro amino acid.](image)

When the vinyl aminosulfoxonium salt 145a was treated with strong base LiN(H)\(_t\)-Bu in THF at low temperature, the tricyclic keto aminosulfoxonium ylide 152 was observed and isolated (Scheme 49) [24]. The vinyl aminosulfoxonium salt 145a was most likely deprotonated by lithium amide to form the corresponding vinyl aminosulfoxonium ylide 149 initially. Subsequent cyclization of the ylide through the attack of the ylidic carbon atom on the ester group provided access to the cyclopentenone derivative 150. Ortho-lithiation followed by a stereoselective intramolecular conjugate addition of the aryl group furnished novel tricyclic ylide 152 [24].

6.5. Diastereoselective Synthesis of \(\gamma\)-Lactones through Reaction of Enediolates with \(\alpha,\beta\)-Unsaturated Sulfoxonium Salts

\(\gamma\)-Lactones are structural elements that are found in 10\% of all natural products, including the paraconic acids, and an array of bicyclic and tricyclic ring systems (e.g., xanthatin) [58]. \(\gamma\)-Lactones possess interesting biological activity including strong antifungal, antibiotic, antitumor, antiviral, and \textit{anti}-inflammatory activity, which suggests that they have potential as leads for pharmaceutical discovery [58–61]. Moreover, \(\gamma\)-lactones have been frequently used as synthetic intermediates for the assembly of complex molecules [62].
Kerrigan’s group investigated γ-lactone synthesis by studying the reaction of lithium enediolates 156 with α,β-unsaturated sulfoxonium salts 154 [63]. This approach complemented their previously reported one-pot methodology for the preparation of γ-lactones from sulfoxonium ylides and disubstituted ketenes, in that it mainly provided access to γ-lactones 155 bearing α- and β-tertiary stereogenic centers [63,64]. The sulfoxonium salt 154 was prepared by procedures previously described by Johnson and co-workers [19–21].

The reaction proved to be tolerant of a range of aryl substituents α to the carboxyl group of the carboxylic acid, including both electron-donating and electron-withdrawing substituents (Scheme 50). Impressively, even substitution at the 2-position on aryl substituents was tolerated without any significant effect on yield in reactions with styrenyl sulfoxonium salt 154a (R^2 = Ph). Good results were also achieved with the i-Pr-substituted vinyl sulfoxonium salt 154b (R^2 = i-Pr). Invariably, high diastereoselectivity (dr ≥ 88:12), favoring formation of the trans-diastereomer as the major isomer, was observed. Significantly, the reactions of lithium enediolates derived from α,α-disubstituted acetic acids were found to proceed smoothly to provide access to the desired α-quaternary center substituted γ-lactones, albeit with lower diastereoselectivity (dr 80:20) [63,64].

Two possible mechanisms were proposed for the formation of γ-lactone 155. In the first mechanism, Pathway 1 (Scheme 51), the lithium enediolate 156 adds to the sulfur of the vinylsulfoxonium salt 154 to give enolate intermediate 159 in stereoselective fashion as the E-isomer. Subsequent [3,3]-sigmatropic rearrangement, ylide protonation (by acid/lactone/intramolecular proton transfer), and 5-exo-tet cyclization would lead to the formation of lactone 155 as the trans-diastereomer [64,65]. This mechanism is consistent with the one that Kerrigan and co-workers have proposed for the formation of γ-lactones from sulfoxonium ylide, aldehydes, and ketenes in that both involve enolate 159 as a key intermediate [64,66]. In the second pathway, ylide intermediate 157 would be formed through conjugate addition of lithium enediolate 156 to the β-position of vinyl sulfoxonium 154 (Pathway 2, Scheme 51) [67]. Protonation of ylide 157 (by acid/lactone/intramolecular proton transfer) followed by cyclization would provide access to γ-lactone 155. It was speculated that such a mechanism could account for the high trans-diastereoselectivity observed if a closed transition state (through Li chelation) was involved in the conjugate addition step (Scheme 51) [68,69]. Alternatively, the high trans-diastereoselectivity may be obtained through equilibration (reversible deprotonation-protonation) of the lactone product under the reaction conditions (presence of excess enediolate) to favor the more thermodynamically stable trans-isomer. Curiously, vinylsulfonium salts failed to undergo the desired cyclization reaction, while the reaction of vinylphosphonium salts stopped at an intermediate phosphonium ylide analogous to ylide 157 (Scheme 51).
Scheme 50. Synthesis of γ-lactones through reaction of enediolates with α,β-unsaturated sulfoxonium salts.

Scheme 51. Possible reaction mechanisms for the formation of γ-lactone from vinylsulfoxonium salt.

6.6. Asymmetric Synthesis of γ-Lactones through Koga Amine-Controlled Addition of Enediolates to α,β-Unsaturated Sulfoxonium Salts

Subsequently, Kerrigan et al. were motivated to utilize chiral amine ligands to control the enantioselectivity of the reaction of lithium enediolates 156 with α,β-unsaturated sulfoxonium salts 154 [70]. cis-γ-Lactones 155 were obtained through a formal [3 + 2] cycloaddition process. The desired γ-lactones were formed in moderate to good yields (50–71%), with moderate to very good diastereoselectivity (dr up to 10:1), favoring the cis-isomer, and good to excellent enantioselectivity.
(Scheme 52). When enantioenriched aminosulfoxonium salts 154 were employed in combination with the appropriate enantiomer of Koga amine, a significant enhancement in asymmetric induction was observed. This increase in enantioselectivity was due to a match between the chirality of the sulfoxonium salt and that of the Koga amine [70,71].

Scheme 52. Asymmetric synthesis of γ-lactones through Koga amine-controlled reaction.

The synthetic versatility of the technology was demonstrated by the simple conversion of enantioenriched 155a and 155b into the corresponding trans-isomers (155aa and 155bb) through utilization of a base-mediated isomerization procedure (Scheme 53). As a result, all four stereoisomers of a given γ-lactone (155a) could be efficiently accessed with good to excellent diastereoselectivity (dr 6:1 to 24:1) and with good to excellent enantioselectivity (75−91% ee).

Scheme 53. Asymmetric synthesis of all stereoisomers of 155a.

The reaction most likely proceeds through a conjugate addition-ylide protonation–cyclization mechanism (Scheme 54). Ylide intermediate 157a would be formed through conjugate addition of lithium enediolate 156 to the β-position of the vinyl sulfoxonium 154a [67]. Subsequent protonation of ylide 157a by added acetic acid would lead to the formation of intermediate 158a, followed by
cyclization, to provide γ-lactone 155. The complete change in the sense of diastereoselectivity to favor the cis-isomer, in contrast to the stereochemical outcome of Kerrigan group’s earlier studies conducted in the absence of Koga amine, may be explained by the conjugate addition step proceeding through an open antiperiplanar transition state [63,68,69]. This differs from the previously proposed transition state for the reaction conducted in the absence of Koga amine where a closed transition state, involving lithium chelation of the sulfoxonium oxygen and enediolate, would lead to the trans-isomer dominating (Scheme 54) [63].

![Scheme 54. Proposed reaction mechanism.](image)

### 7. Conclusions

Vinylsulfonium and vinylsulfoxonium salts are classes of important, and valuable Michael acceptor reagents providing opportunities for the synthesis of an array of useful cyclic products. They are widely used in organic synthesis due to their unique capability. They generally play a double role in the reactions serving as an activating group, for nucleophilic addition β to the sulfur moiety, and then acting as a leaving group, enabling cyclization. These special salts possessing dual function are vital in enabling the streamlined synthesis of three to seven membered heterocycles, fused heterocycles, and other essential synthetic intermediates. Diastereoselective and enantioselective reactions of these salts have been recently developed through use of chiral reactant partners or chiral onium salts (substrate/chiral auxiliary control) or the use of chiral ligands (reagent control). These recent advances in asymmetric synthesis methodologies should lead to an increase in practical applications such as the synthesis of pharmaceutical, agrochemical, and biologically active compounds. While the groups of Aggarwal and others have exploited the chemistry of vinylsulfonium salts to a great extent in recent times, much work remains to be carried out in the exploration of the chemistry of the analogous vinylsulfoxonium salts. To enable such studies, improvements in methods for the synthesis of vinylsulfoxonium salts will first need to be achieved. In addition, the development of catalytic reactions involving vinylsulfonium and vinylsulfoxonium salts remains uncharted territory.

**Acknowledgments:** Support has been provided by the National Science Foundation and the National Institutes of Health: Grant Nos. CHE-1463728 to N.J.K. and R15GM107800 to N.J.K.

**Conflicts of Interest:** The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.
References

1. Johnson, A.W.; LaCount, R.B. The Chemistry of Ylids. VI. Dimethylsulfonyl Fluorenyle—the Formation of Epoxides. J. Am. Chem. Soc. 1961, 83, 417–423. [CrossRef]

2. Corey, E.J.; Chaykovsky, M. Dimethyloxosulfonium Methyldide ((CH$_3$)$_2$SOCH$_3$) and Dimethylsulfonium Methyldide ((CH$_3$)$_2$SCH$_2$). Formation and Application to Organic Synthesis. J. Am. Chem. Soc. 1965, 87, 1353–1364. [CrossRef]

3. Li, A.-H.; Dai, L.-X.; Aggarwal, V.K. Asymmetric Ylide Reactions: Epoxidation, Cyclopropanation, Aziridination, Olefination, and Rearrangement. Chem. Rev. 1999, 97, 2341–2372. [CrossRef] [PubMed]

4. Block, E. Reactions of Organosulfur Compounds; Academic Press: New York, NY, USA, 1975; ISBN 0121070506.

5. Trost, B.M.; Melvin, L.S., Jr. Sulfur Ylides: Emerging Synthetic Intermediates; Academic Press: New York, NY, USA, 1975; ISBN 0127010602.

6. Doering, W.V.E.; Schreiber, K.C. d-Orbital Resonance. III. Deuterium Exchange in Methyl “Onium” Salts and in Bicyclo[2.2.1]heptane-1-sulfonium Iodide. J. Am. Chem. Soc. 1955, 77, 521–526. [CrossRef]

7. Doering, W.V.E.; Schreiber, K.C. d-Orbital Resonance. II. Comparative Reactivity of Vinyldimethylsulfonium and Vinyltrimethylammonium Ions. J. Am. Chem. Soc. 1955, 77, 514–520. [CrossRef]

8. Mitchell, K.A.R. The Use of Outer d Orbitals in Bonding. Chem. Rev. 1969, 69, 157–178. [CrossRef]

9. Lehnh, J.-M.; Wipff, G. Stereoelectronic Properties, Stereospecificity, and Stabilization of α-Oxa and α-Thia Carbanion. J. Am. Chem. Soc. 1976, 98, 7498–7505. [CrossRef]

10. Bernardi, F.; Csizmadia, I.G.; Mangini, A.; Schlegel, H.B.; Whangbo, M.H.; Wolfe, S. The Irrelevance of α-Oxa and α-Thia Carbanion. A Comparative Quantum Chemical Study of the Static and Dynamic Properties and Proton Affinities of Carbanions Adjacent to Oxygen and to Sulfur. J. Am. Chem. Soc. 1979, 97, 2209–2218. [CrossRef]

11. Streitwieser, A., Jr.; Williams, J.E., Jr. Ab initio SCF-MO calculations of thiomethyl anion. Polarization in stabilization of carbanions. J. Am. Chem. Soc. 1975, 97, 191–192. [CrossRef]

12. Hoffmann, R.; Howell, J.M.; Muettterties, E.L. Molecular Orbital Theory of Pentacoordinate Phosphorus. J. Am. Chem. Soc. 1972, 94, 3047–3058. [CrossRef]

13. Zbang, X.-M.; Bordwell, F.G. Equilibrium Acidities and Homolytic Bond Dissociation Energies of the Acidic C-H Bonds in P-Substituted Triphenylphosphonium Cations. J. Am. Chem. Soc. 1994, 116, 968–972. [CrossRef]

14. Dobado, J.A.; Martinez-Garcia, H.; Molina, J.M.; Sundberg, M.R. Chemical Bonding in Hypervalent Molecules Revised. 3. Application of the Atoms in Molecules Theory to Y$_3$X-CH$_2$ (X = N, P, or As; Y = H or F) and H$_2$X-CH$_2$ (X = O, S, or Se) Ylides. J. Am. Chem. Soc. 2000, 122, 1144–1149. [CrossRef]

15. Gosselck, J.; Béress, L.; Schenk, H. Reactions of Substituted Vinylsulfonium Salts with CH-Acidic Compounds—A New Route to Polysubstituted Cyclopropanes. Angew. Chem. Int. Ed. Engl. 1966, 5, 996–997. [CrossRef]

16. Gosselck, J.; Albrecht, H.; Dost, F.; Schenk, H.; Schmidt, G. Eine Stereosezifische Synthese fur H$_2$H$_2$-trans-cyclopropane. Tetrahedron Lett. 1969, 9, 995–998. [CrossRef]

17. Gosselck, J.; Schmidt, G. Zur Stereochemie der cyclopropansynthese über 1,4-sulfoniumbetaine. Tetrahedron Lett. 1969, 10, 2615–2618. [CrossRef]

18. Schmidt, G.; Gosselck, J. Cycloprenyl-sulfoniumsalze durch umsetzung von sulfonium-yliden mit dimethyl-vinyl-sulfonium bromid. Tetrahedron Lett. 1969, 10, 3445–3448. [CrossRef]

19. Johnson, C.R.; Lockard, J.P. (Dimethylamino)-Phenyl-[2-phenylvinyl]-oxosulfonium fluoroborate. A Model reagent for ethylene transfer to dibasic nucleophiles. Tetrahedron Lett. 1971, 12, 4589–4592. [CrossRef]

20. Johnson, C.R.; Rogers, P.E. Chemistry of sulfoxides and related compounds. XL. Preparation and reactions of stabilized (dialkylamino)methylsulfoxonium methylides. Synthesis of 1,3-oxathiol 3-oxides. J. Org. Chem. 1973, 38, 1798–1803. [CrossRef]

21. Johnson, C.R.; Lockard, J.P.; Kennedy, E.R. S-Ethenylsulfoximine derivatives. Reagents for ethenolation of protic nucleophiles. J. Org. Chem. 1980, 45, 264–271. [CrossRef]

22. Koep, S.; Gais, H.-J.; Raabe, G. Asymmetric synthesis of unsaturated, fused bicyclic proline analogues through amino alklylation of cyclic bis(allylsulfoximine)titaniun complexes and migratory cyclization of δ-amino alkylaminosulfoxonium salts. J. Am. Chem. Soc. 2003, 125, 13243–13251. [CrossRef] [PubMed]
23. Gais, H.-J.; Reddy, L.R.; Babu, G.S.; Raabe, G. Asymmetric synthesis of 2,3-dihydrofurans and of unsaturated bicyclic tetrahydrofurans through α-elimination and migratory cyclization of silyloxy alkenyl aminosulfoxonium salts. Generation and intramolecular O,Si-bond insertion of chiral disubstituted β-silyloxy alkylidene carbenes. J. Am. Chem. Soc. 2004, 126, 4859–4864. [CrossRef] [PubMed]

24. Tiwari, S.K.; Gais, H.-J.; Lindenmaier, A.; Babu, G.S.; Raabe, G.; Reddy, L.R.; Köhler, F.; Günter, M.; Koep, S.; Iska, V.B.R. Functionalized Chiral Vinyl Aminosulfoxonium Salts: Asymmetric Synthesis and Application to the Synthesis of Enantiopure Unsatuated Prolines, β,γ-Dehydro Amino Acids, and Cyclopentanoid Keto Aminosulfoxonium Ylides. J. Am. Chem. Soc. 2006, 128, 7360–7373. [CrossRef] [PubMed]

25. Yar, M.; McGarrigle, E.M.; Aggarwal, V.K. Sulfonium, Ethenyldiphenyl-1,1,1-Trifluoromethanesulfonate. In e-EROS Encyclopedia of Reagents for Organic Synthesis; John Wiley & Sons, Ltd.: Hoboken, NY, USA, 2012; pp. 1–6. [CrossRef]

26. Matlock, J.V.; Aggarwal, V.K.; McGarrigle, E.M. (2-Bromoethyl)diphenylsulfonium Trifluoromethanesulfonate. In e-EROS Encyclopedia of Reagents for Organic Synthesis; John Wiley & Sons, Ltd.: Hoboken, NY, USA, 2016; pp. 1–5. [CrossRef]

27. Johnson, C.R.; Haake, M.; Schroeck, C.W. Chemistry of sulfoxides and related compounds. XXVI. Preparation and synthetic applications of (dimethylamino)phenyloxosulfonium methylide. J. Am. Chem. Soc. 1970, 92, 6594–6598. [CrossRef]

28. Gais, H.-J.; Hainz, R.; Müller, H.; Bruns, P.; Giesen, N.; Raabe, G.; Runsink, J.; Nienstedt, S.; Decker, J.; Schleusner, M.; et al. N-Methylsulfonimidoyl-Substituted (2-Alkenyl)titanium Complexes: Application to the Synthesis of β- and δ-Sulfonimidoyl-Substituted Chiral Homoallylic Alcohols, X-ray Crystal Structure Analysis, and Fluxional Behavior. Eur. J. Org. Chem. 2000, 3973–4009. [CrossRef]

29. Yar, M.; Unthank, M.G.; McGarrigle, E.M.; Aggarwal, V.K. Remote Chiral Induction in Vinyl Sulfonium Salt-Mediated Ring Expansion of Hemiaminals into Epoxide-Fused Azepines. Chem. Asian J. 2011, 6, 372–375. [CrossRef] [PubMed]

30. Kokotos, C.G.; McGarrigle, E.M.; Aggarwal, V.K. Sulfur Ylide Mediated Three-Component Aziridination and Epoxidation Reactions Using Vinyl Sulfonium Salts. Synlett 2008, 2191–2195. [CrossRef]

31. Unthank, M.G.; Hussain, N.; Aggarwal, V.K. The Use of Vinyl Sulfonium Salts in the Stereocontrolled Asymmetric Synthesis of Epoxide- and Aziridine-Fused Heterocycles: Application to the Synthesis of (−)-Balanol. Angew. Chem. Int. Ed. 2006, 45, 7066–7069. [CrossRef] [PubMed]

32. Wang, Y.F.; Zhang, W.H.; Colandrea, V.J.; Jimenez, L.S. Reactivity and rearrangements of dialkyl- and diarylvinylsulfonium salts with indole-2- and pyrrole-2-carboxaldehydes. Tetrahedron 1999, 55, 10659–10672. [CrossRef]

33. Xie, C.; Han, D.; Hu, Y.; Liu, J.; Xie, T. Synthesis of pyrrolidin-2-ones via tandem reactions of vinyl sulfonium salts under mild conditions. Tetrahedron Lett. 2010, 51, 5238–5241. [CrossRef]

34. Matsuo, J.-I.; Yamanaka, H.; Kawana, A.; Mukaiyama, T. A Convenient Method for the Synthesis of 2-Arylaziridines from Styrene Derivatives via 2 Arylethenyl(diphenyl)sulfonium Salts. Chem. Lett. 2003, 32, 392–393. [CrossRef]

35. Yamanaka, H.; Matsuo, J.-I.; Kawana, A.; Mukaiyama, T. New methods for the preparations of 2-arylaziridines, α-imidostyrenes, and allylamines from olefins via diphenylsulfonium triflates. ARKIVOC 2004, 3, 42–65.

36. Zhou, M.; En, K.; Hu, Y.; Xu, Y.; Shenb, H.C.; Qian, X. Zinc triflate-mediated cyclopropanation of oxindoles with vinyl diphenyl sulfonium triflate: A mild reaction with broad functional group compatibility. RSC Adv. 2017, 7, 3741–3745. [CrossRef]

37. Yamanaka, H.; Yamane, Y.; Mukaiyama, T. A New Method for the Preparation of Nitrogen-containing Heterocycles Using Diphenylsulphonium Triﬂates. Heterocycles 2004, 63, 2813–2826. [CrossRef]

38. Fritz, S.P.; Moya, J.F.; Unthank, M.G.; McGarrigle, E.M.; Aggarwal, V.K. An Efficient Synthesis of Azetidines with (2-Bromoethyl)sulfonium Triﬂate. Synthesis 2012, 44, 1584–1590. [CrossRef]

39. Xie, C.; Han, D.; Liu, J.; Xie, T. Novel Syntheses of N-Aryloxazolidin-2-ones via Tandem Reactions of Vinyl Sulfonium Salts. Synlett 2009, 3155–3158. [CrossRef]

40. McGarrigle, E.M.; Fritz, S.P.; Favereau, L.; Yar, M.; Aggarwal, V.K. An Efficient Synthesis of Imidazolinium Salts Using Vinyl Sulfonium Salts. Org. Lett. 2011, 13, 3060–3063. [CrossRef] [PubMed]
41. Yar, M.; Fritz, S.P.; Gates, P.J.; McGarrigle, E.M.; Aggarwal, V.K. Synthesis of N-Vinylazolidinones and Morpholines from Amino Alcohols and Vinylsulfonyl Salts: Analysis of the Outcome’s Dependence on the N-Protecting Group by Nanospray Mass Spectrometry. Eur. J. Org. Chem. 2012, 160–166. [CrossRef]

42. Yar, M.; McGarrigle, E.M.; Aggarwal, V.K. An Annulation Reaction for the Synthesis of Morpholines, Thiomorpholines, and Piperazines from β-Heteroatom Amino Compounds and Vinyl Sulfonyl Salts. Angew. Chem. Int. Ed. 2008, 47, 3784–3786. [CrossRef] [PubMed]

43. Yar, M.; McGarrigle, E.M.; Aggarwal, V.K. Bromoethylsulfonyl Salt—A More Effective Annulation Agent for the Synthesis of 6- and 7-Membered 1,4-Heterocyclic Compounds. Org. Lett. 2009, 11, 257–260. [CrossRef] [PubMed]

44. Fritz, S.P.; Mumtaz, A.; Yar, M.; McGarrigle, E.M.; Aggarwal, V.K. Sulfinamides as Highly Effective Amine Protecting Groups and Their Use in the Conversion of Amino Alcohols into Morpholines. Eur. J. Org. Chem. 2011, 3156–3164. [CrossRef]

45. Bornholdt, J.; Felding, J.; Kristensen, J.L. Synthesis of Enantiopure 3-Substituted Morpholines. J. Org. Chem. 2010, 75, 7454–7457. [CrossRef] [PubMed]

46. An, J.; Chang, N.-J.; Song, L.-D.; Jin, Y.-Q.; Ma, Y.; Chen, J.-R.; Xiao, W.-J. Efficient and general synthesis of oxazino[4,3-a]indoles by cascade addition-cyclization reactions of (1H-indol-2-yl)methanols and vinyl sulfonium salts. Chem. Commun. 2011, 47, 1869–1871. [CrossRef] [PubMed]

47. Matlock, J.V.; Svejstrup, T.D.; Songara, P.; Overington, S.; McGarrigle, E.M.; Aggarwal, V.K. Synthesis of 6- and 7-Membered N-Heterocycles Using α-Phenylvinylsulfonyl Salts. Org. Lett. 2015, 17, 5044–5047. [CrossRef] [PubMed]

48. Karahan, S.; Tanyeli, C. Organocatalytic enantioselective construction of isatin-derived N-alkoxyacyarbonyl 1,3-aminonaphthols via sterically encumbered hydrocarbon-substituted quinine-based squaramide. New J. Chem. 2017, 41, 9192–9202. [CrossRef]

49. Kim, K.; Jimenez, L.S. A camphor-derived vinylsulfonium salt as a reagent for a cycloannulation. Tetrahedron Asymmetry 2012, 6, 999–1005. [CrossRef]

50. Fritz, S.P.; Ali, Z.; Unthank, M.G.; McGarrigle, E.M.; Aggarwal, V.K. (2-Bromoethyl)sulfonium Trifluoromethanesulfonates in Stereoselective Annulation Reactions for the Formation of Fused Bicyclic Epoxides and Aziridines. Helv. Chim. Acta 2012, 95, 2384–2398. [CrossRef]

51. Unthank, M.G.; Tavassoli, B.; Aggarwal, V.K. Epoxy-Annulations by Reactions of α-Amido Ketones with Vinyl Sulfonium Salts. Reagent versus Substrate Control and Kinetic Resolution. Org. Lett. 2008, 10, 1501–1504. [CrossRef] [PubMed]

52. Fritz, S.P.; West, T.H.; McGarrigle, E.M.; Aggarwal, V.K. Diastereoselective Synthesis of CF3-Substituted, Epoxide-Fused Heterocycles with β-(Trifluoromethyl)vinylsulfonyl Salts. Org. Lett. 2012, 14, 6370–6373. [CrossRef] [PubMed]

53. Matlock, J.V.; Fritz, S.P.; Harrison, S.A.; Coe, D.M.; McGarrigle, E.M.; Aggarwal, V.K. Synthesis of α-Substituted Vinylsulfonyl Salts and Their Application as Annulation Reagents in the Formation of Epoxide- and Cyclopropane-Fused Heterocycles. J. Org. Chem. 2014, 79, 10226–10239. [CrossRef] [PubMed]

54. Frazier, C.P.; Sandoval, D.; Palmer, L.I.; de Alaniz, J.R. Electrophilic α-oxygenation reaction of β-ketoesters using N-hydroxy carbamates: Control of the ambient reactivity of nitrosoformate intermediates. Chem. Sci. 2013, 4, 3857–3862. [CrossRef]

55. Fritz, S.P.; Matlock, J.V.; McGarrigle, E.M.; Aggarwal, V.K. Efficient Synthesis of Cyclopropane-Fused Heterocycles with Bromoethylsulfonyl Slt. Chem. Eur. J. 2013, 19, 10827–10831. [CrossRef] [PubMed]

56. Siegel, S. Comprehensive Organic Synthesis; Trost, B.M., Fleming, I., Eds.; Pergamon Press: Oxford, UK, 1991; Volume 8, p. 417.

57. Reddy, L.R.; Gais, H.-J.; Woo, C.-W.; Raabe, G. Asymmetric synthesis of anti-homopropargylic alcohols from aldehydes and chiral sulfonimidoyl substituted bis(allyl)titanium complexes through generation and elimination of novel chiral alkylidenecarbene (dimethylamino)sulfoxonium ylides. J. Am. Chem. Soc. 2002, 124, 10427–10434. [CrossRef] [PubMed]

58. Seitz, M.; Reiser, O. Synthetic approaches towards structurally diverse gamma-butyrolactone natural-product-like compounds. Curr. Opin. Chem. Biol. 2005, 9, 285–292. [CrossRef] [PubMed]

59. Hoffman, H.M.R.; Rabe, J. Synthesis and Biological Activity of α-Methylene-γ-butyrolactones. Angew. Chem. Int. Ed. 1985, 24, 94–110. [CrossRef]
60. Koch, S.S.C.; Chamberlain, A.R. Studies in Natural Products Chemistry; Atta-ur-Rahman, Ed.; Elsevier Science: New York, NY, USA, 1995; Volume 16, pp. 687–725. ISBN 978-0-444-82264-2.

61. De March, P.; Figueredo, M.; Font, J.; Raya, J. Highly Efficient, Enantioselective Synthesis of (+)-Grandisol from a C2-Symmetric Bis(α,β-butenoic acid). Org. Lett. 2000, 2, 163–165. [CrossRef] [PubMed]

62. Ghosh, A.K.; Swanson, L. Enantioselective Synthesis of (+)-Cryptophycin 52 (LY355703), a Potent Antimitotic Antitumor Agent. J. Org. Chem. 2003, 68, 9823–9826. [CrossRef] [PubMed]

63. Peraino, N.J.; Wheeler, K.A.; Kerrigan, N.J. Diastereoselective Synthesis of γ-Lactones through Reaction of Enediolates with α,β-Unsaturated Sulfoxonium Salts. Org. Lett. 2015, 17, 1735–1737. [CrossRef] [PubMed]

64. Mondal, M.; Ho, H.-J.; Peraino, N.J.; Gary, M.A.; Wheeler, K.A.; Kerrigan, N.J. Diastereoselective Reaction of Sulfoxonium Ylides, Aldehydes and Ketenes: An Approach to trans-γ-Lactones. J. Org. Chem. 2013, 78, 4587–4593. [CrossRef] [PubMed]

65. Marino, J.P.; Neisser, M. Stereospecific reactions of dichloroketene with vinyl sulfoxides: A new type of polar cycloaddition. J. Am. Chem. Soc. 1981, 103, 7687–7689. [CrossRef]

66. Peraino, N.J.; Ho, H.-J.; Mondal, M.; Kerrigan, N.J. Asymmetric synthesis of γ-lactones through reaction of sulfoxonium ylides, aldehydes, and ketenes. Tetrahedron Lett. 2014, 55, 4260–4263. [CrossRef]

67. Lu, P.; Jackson, J.J.; Eickhoff, J.A.; Zakarian, A. Direct Enantioselective Conjugate Addition of Carboxylic Acids with Chiral Lithium Amides as Traceless Auxiliaries. J. Am. Chem. Soc. 2015, 137, 656–659. [CrossRef] [PubMed]

68. Oare, D.A.; Heathcock, C. Acyclic stereoselection. 47. Stereochemistry of the Michael addition of ester and ketone enolates to alpha,beta-unsaturated ketones. J. Org. Chem. 1990, 55, 157–172. [CrossRef]

69. Kwan, E.E.; Evans, D.A. Intermolecular Michael Reactions: A Computational Investigation. Org. Lett. 2010, 12, 5124–5127. [CrossRef] [PubMed]

70. Peraino, N.J.; Kaster, S.H.; Wheeler, K.A.; Kerrigan, N.J. Asymmetric Synthesis of γ-Lactones through Koga Amine-Controlled Addition of Enediolates to α,β-Unsaturated Sulfoxonium Salts. J. Org. Chem. 2017, 82, 606–615. [CrossRef] [PubMed]

71. Masamune, S.; Choy, W.; Petersen, J.S.; Sita, L.R. Double Asymmetric Synthesis and a New Strategy for Stereochemical Control in Organic Synthesis. Angew. Chem. Int. Ed. Engl. 1985, 24, 1–30. [CrossRef]