Unique Salt Effect on Highly Selective Synthesis of Acid-Labile Terpene and Styrene Oxides with a Tungsten/H₂O₂ Catalytic System under Acidic Aqueous Conditions

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Abstract: Acid-labile epoxides such as terpene and styrene oxides are effectively synthesized in high yields with good selectivities using tungsten-catalyzed hydrogen peroxide epoxidation in the presence of Na₂SO₄. The salt effect is thought to originate with the addition of a saturated amount of Na₂SO₄ to aqueous H₂O₂; this addition strongly inhibited the undesired hydrolysis of the acid-labile epoxy products, despite the biphasic conditions of substrate as oil phase and H₂O₂ as acidic aqueous phase.

Key words: oxidation, catalysis, epoxides, terpenoids, green chemistry

The epoxidation of olefins is a fundamental process for the laboratory and for industrial manufacturing because epoxy compounds include a wide variety of useful chemicals.¹ While various oxidants are now being used for epoxidation,² they often give equimolar amounts of the deoxygenated compounds as waste that no longer meets current environmental constraints.

Hydrogen peroxide (H_2O_2) is an ideal oxidant because water is the only side product,³ its atom efficiency⁴ is excellent, and it is cheap, readily available, and easy to handle. Although a number of metal-catalyzed H₂O₂ epoxidation reactions have been reported thus far,^{5,6} the chemical processes using organic solvent and halide compounds should be converted to organic solvent- and halide-free processes from both an industrial perspective, taking costs into account, and an environmental perspective. In this context, we have developed various epoxidation reactions of olefins, including terminal aliphatic olefins with aqueous H₂O₂ under halide- and organic-solvent-free conditions.7 This oxidation process gives the corresponding epoxides in good yields catalyzed by highly active tungsten peroxide species that are effectively formed at 90 °C under acidic conditions.7b

However, acid-labile terpene and styrene oxides were not obtained under these reaction conditions because the generated epoxides easily underwent ring opening, rearrangement, and hydrolysis by acid catalysis or by the application of heating.⁸ Terpene and styrene oxides are key raw materials; they are some of the most useful inter-

SYNTHESIS 2012, 44, 1672–1678 Advanced online publication: 26.04.2012 DOI: 10.1055/s-0031-1290948; Art ID: SS-2012-F0145-OP © Georg Thieme Verlag Stuttgart · New York mediates and/or precursors for chemical production, including resins, paints, glues, flavors, and pharmaceuticals.⁸ Although various types of aqueous H₂O₂ epoxidation of terpenes and styrenes have been reported,^{9–13} their reaction is still a challenging task due to their sensitivity toward H₂O₂ acidic media.⁸ For example, the isomerization of α -pinene in the presence of acid catalysts with acidic media has been widely studied, and it produces a complex mixture of mono- and bicyclic terpenes such as β -pinene, limonene, camphene, 3-carene, terpineol, and so on.⁸ And through the H₂O₂ epoxidation of α -pinene, isomerization and/or hydrolysis of the product also lead to a complex mixture of terpenoids (campholenic aldehyde, pinanediol, sobrerol, etc.) as shown in Scheme 1.^{8,14}



Scheme 1 Isomerization and/or hydrolysis of α-pinene oxide

A few successful examples utilizing an immobilized catalyst of polyoxometalates on mesoporous silica gel and methyltrioxorhenium catalysts have been shown to effectively catalyze α -pinene epoxidation.^{15,16} However, these methods are not fully satisfactory for practical syntheses because of the requirement of hazardous organic solvents, more than equimolar amounts of H₂O₂, and/or the complicated multistep preparation of catalysts using organic solvents. Therefore, a catalytic system applicable to the avoidance of the decomposition of acid-labile terpene and styrene oxides was employed under organic solvent-free conditions. Recently, the epoxidation of terpene and styrene under weak acidic conditions in which the pH was adjusted by adding NaOH was also employed.¹⁷ It was also revealed that the combination of Na₂WO₄, [Me(n- C_8H_{17} , N]HSO₄, PhP(O)(OH)₂, and NaOH was effective for the epoxidation of terpene and styrene at 25-35 °C.

But this process required as much as 0.08 equivalent of catalysts and 1.3 equivalents of intractable 60% H₂O₂ for the reaction to proceed. Based on these results, we have developed another synthetic approach that effectively protects the generated acid-labile terpene and styrene oxides from hydrolysis under organic solvent-free acidic conditions, maintaining the intrinsic catalyst reactivity at the same time.¹⁴ We report here the effective and convenient tungsten-catalyzed H₂O₂ epoxidation of terpenes and styrenes by the simple addition of inorganic neutral salts to give the acid-labile epoxides in good to excellent yields. This process required as much as 0.02 equivalent of tungsten, 0.02 equivalent of phase-transfer catalyst, 0.01 equivalent of phenyl phosphonic acid or phosphoric acid, and 1.0 equivalent of commercially available 30% H_2O_2 aqueous solution for the reaction to proceed under organic solvent-free biphasic conditions of substrate as the oil phase and aqueous H_2O_2 as the acidic water phase. The H_2O_2 epoxidation of α -pinene (1) was examined as the screening substrate, because 1 is not only a major component of gum turpentine but also a challenging terpene that is difficult to inhibit the hydrolysis during the reaction. The reaction was conducted with 30% H₂O₂ (1.0 equiv to 1), Na_2WO_4 (tungsten catalyst, 0.02 equiv), $[Me(n-C_8H_{17})_3N]HSO_4$ (phase-transfer catalyst, 0.02)

equiv) at 25 °C for 16 hours with vigorous stirring. As

shown in Table 1, entry 1, the epoxidation reaction in the

absence of any additional salts proceeded moderately, but

the produced epoxide 2 decomposed under acidic conditions (55% conversion of 1 and 1% yield of 2). The addition of 0.6 equivalent of NaHCO₃ to the aqueous phase created an alkaline solution (pH 9.0), and as a result the H_2O_2 epoxidation did not proceed (Table 1, entry 2). The addition of 0.6 equivalent of NaCl to the epoxidation reaction afforded only 20% conversion of 1 and 15% yield of 2 (Table 1, entry 3). The addition of 0.6 equivalent of $NaNO_3$ did not give 2 at all (Table 1, entry 4). One of the reasons for the low conversion of 1 in Table 1, entries 1-4, is that sobrerol (3) formed by the hydrolysis of 2 might be chelated with tungstate metal at the diol moiety of 3^{18} which would prohibit any possibility of the epoxidation proceeding. It is noteworthy that the Na_2WO_4 , [Me(*n*- C_8H_{17} N]HSO₄, and PhP(O)(OH)₂ catalyzed H₂O₂ epoxidation of 1 with 0.3 equivalent of Na_2SO_4 as divalent neutral salts, exhibits excellent efficiency despite the acidic conditions (pH 2.0) and produced 2 in 89% yield and 100% selectivity (Table 1, entry 5). The catalytic H₂O₂ epoxidation of 1 with sulfates of other cation species such as Li⁺, NH₄⁺, and Mg²⁺ proceeded moderately to give 40%, 44%, and 30% yields of 2 with selectivity of 55%, 60%, and 43%, respectively (each 0.3 equivalent, Table 1, entries 6, 8, and 9). In contrast, the reaction in the presence of 0.3 equivalent of K_2SO_4 afforded 2 in only 6% yield (Table 1, entry 7). The addition of 0.3 equivalents of $Na_2SO_4 \cdot 10H_2O$ to the epoxidation reaction afforded 69% conversion of 1 and 23% yield of 2 (Table 1, entry 10).

Table 1 Effects of Salts on Tungsten-Catalyzed H₂O₂ Epoxidation of 1 under Acidic Conditions^a

	30% H ₂ O ₂ (1.0 equiv) Na ₂ WO ₄ (0.02 equiv) [Me(<i>n</i> -C ₈ H ₁₇) ₃ N]HSO ₄ (0.02 equiv) PhP(O)(OH) ₂ (0.01 equiv) salt 25 °C, 16 h			
Entry	Salt (equiv)	Conversion (%) ^b	Yield (%) ^b	Selectivity (%) ^c
1	none (0)	55	1	2
2	NaHCO ₃ (0.6)	3	0	0
3	NaCl (0.6)	20	15	75
4	NaNO ₃ (0.6)	31	0	0
5	$Na_2SO_4(0.3)$	89	89	100
6	Li ₂ SO ₄ (0.3)	73	40	55
7	$K_2 SO_4 (0.3)$	57	6	11
8	$(NH_4)_2SO_4(0.3)$	74	44	60
9	MgSO ₄ (0.3)	69	30	43
10	Na ₂ SO ₄ ·10H ₂ O (0.3)	69	23	33

^a Reaction conditions: **1** (1.0 equiv), 30% H_2O_2 (1.0 equiv), Na_2WO_4 (0.02 equiv), $[Me(n-C_8H_{17})_3N]HSO_4$ (0.02 equiv), $PhP(O)(OH)_2$ (0.01 equiv), salt, 25 °C, 1000 rpm, 16 h.

^b Determined by GC analysis with *n*-decane as an internal standard.

^c Yield/conversion (%).

To clarify the effect of the addition of salt on H₂O₂ epoxidation, a simple hydrolysis reaction of 2 was carried out with aqueous 30% H₂O₂ (1.0 equiv to 2) in the presence of Na_2SO_4 (0.3 equiv) without any other catalysts at 25 °C for 16 hours (Table 2). As a result, the hydrolysis of 2 was only 5% with 0.3 equivalent of Na₂SO₄ when the biphasic mixture of 2 was stirred with 30% H₂O₂ (Table 2, entry 4). On the other hand, the hydrolysis of 2 occurred completely in the absence of Na_2SO_4 , and the hydrolysis of 2 to give 3 was observed in 62% yield as main product (Table 2, entry 1). The amount of the added salts is also crucial to effectively protect the generated epoxides from hydrolysis. Table 2 shows the results of the investigation regarding the relationship between the conversion of 2 and the amount of Na₂SO₄ in the biphasic reaction. The amount of Na_2SO_4 increased from 0 to 0.4 equivalent, and the decomposition rate of 2 decreased from 100% to 4% (Table 2, entries 1 and 5). These results suggest that the addition of Na₂SO₄ clearly enhanced the inhibition of the hydrolysis of 2. But in comparing entries 4 and 5, the addition of more than 0.3 equivalent of Na₂SO₄ seems less effective because the aqueous H_2O_2 solution was saturated by the addition of 0.3 equivalent of Na₂SO₄. The results clearly showed that the addition of a saturated amount of Na₂SO₄ effectively inhibited the hydrolysis of 2 under the H_2O_2 epoxidation reaction conditions at room temperature without deactivation of the tungsten peroxide species.

Table 2 Effects of Na_2SO_4 on the Inhibition of Hydrolysis of 2 in the Presence of 30% $H_2O_2^{\bar{a}}$



^a Reaction conditions: 2 (1.0 equiv), 30% H_2O_2 (1.0 equiv), Na_2SO_4 , 25 °C, 1000 rpm, 16 h.

^b Determined by GC analysis with *n*-decane as an internal standard.

This epoxidation reaction using Na₂SO₄ as an additive under the biphasic conditions can be adopted for various terpenes to generate the corresponding terpene oxides. And the concentration of H_2O_2 in the solution was 30% regardless of the presence or absence of Na₂SO₄. These results are summarized in Table 3. As previously shown in Table 1, entries 1 and 5, tungsten-catalyzed H_2O_2 epoxidation reaction of **1** proceeded in good yield in the presence of

Na₂SO₄, and the reaction in the absence of Na₂SO₄ showed low yield (Table 3, entries 1 and 2). The reaction with α -terpineol and terpinen-4-ol having a hydroxy group that causes intramolecular addition reactions in its product under acidic conditions¹⁹ also gave the corresponding epoxides in good to high yield (67% and 82%, respectively, Table 3, entries 3 and 4). A reaction with isopulegol gave the corresponding epoxides in excellent yield (97%, Table 3, entry 5). The hydroxy group in allylic alcohols has been known to facilitate the epoxidation.^{7b,c} The hydroxy group at homoallylic position in isopulegol might also facilitate the epoxidation of limonene, which has two alkene moieties in the molecule, also successfully produced the corresponding monoepoxides in high yield (89%, Table 3, entry 6).

 $\label{eq:Table 3} \begin{array}{l} \mbox{Table 3} & \mbox{Tungsten-Catalyzed H_2O_2 Epoxidation of Terpenes under Acidic Conditions Using $Na_2SO_4^a$} \end{array}$

Entry	Alkene	Product	Conversion (%) ^b	n Yield (%) ^b
1 2°			89 55	89 1
3	ОН	ОН	77	67 ^d
4	ОН	ОН	100	82
5	ОН	ОН	97	97
6			91	89
7	0		51	50 (41:9)

^a Reaction conditions: terpenes (1.0 equiv), 30% H_2O_2 (1.0 equiv), Na_2WO_4 (0.02 equiv), $[Me(n-C_8H_{17})_3N]HSO_4$ (0.02 equiv), $PhP(O)(OH)_2$ (0.01 equiv), Na_2SO_4 (0.3 equiv), 25 °C, 1000 rpm, 16

^b Determined by GC analysis with *n*-decane or biphenyl as an internal standard.

^c The reaction was run in the absence of Na₂SO₄.

^d Ratio *cis/trans* = 1:1.

Meanwhile, it should be noted that the addition of a catalytic amount of Na_2SO_4 for H_2O_2 epoxidation of limonene has already been reported,²⁰ while the reaction required an organic solvent. In this reaction, three alkyl substituted cyclic alkene moiety was epoxidized preferentially.^{7b} The epoxidation of carvone, which has a carbonyl group and two alkenes, also gave two types of mono epoxides in a total 50% yield with a specific rate. Carvone 7,8-oxide was obtained in 41% yield, and carvone 1,6-oxide was formed in 9% yield (Table 3, entry 7). The cyclic alkene in carvone is in conjugation with the carbonyl group. In the case of tungsten-catalyzed epoxidation, the stabilization by the conjugation might be one reason for the low reactivity of carvone.^{7b,c}

This catalytic system using Na₂SO₄ as an additive under the acidic aqueous biphasic conditions was also applied to the syntheses of various styrene oxides that are easily hydrolyzed under acidic conditions. Generally, a reaction with styrene gives the corresponding styrene oxides,²¹ which easily undergo rearrangement, overoxidation, and hydrolysis to give 1-phenylethane-1,2-diol, benzaldehyde, benzoic acid, etc., with aqueous H₂O₂.¹³ As shown in Table 4, entry 1, epoxidation of styrene effectively gave styrene oxide in 85% yield and 98% selectivity, while the reaction without Na₂SO₄ did not give styrene oxide at all (Table 4, entry 3). Epoxidation of electron-deficient styrenes such as p-fluoro-, p-chloro-, and p-bromostyrene gave the corresponding oxides in moderate to good yields (75%, 79%, and 83%, Table 4, entries 4, 5, and 6, respectively). Epoxidation of α -methylstyrene gave its oxide in high yield (96%, Table 4, entry 7). A reaction with trans- β -methylstyrene and *cis*- β -methylstyrene gave the corresponding oxides in moderate to high yields (55% and 89%, Table 4, entry 8 and 9, respectively). The high reactivity of *cis*-β-methylstyrene relative to the *trans*-β-methvlstyrene could be explained by the steric hindrance of the substituent of olefin with a peroxotungsten complex in the spiro-structured model in the transition state.^{7c} The present method can be carried out on gram-scale synthesis of acid-labile epoxides. That is, with 1.06 grams of styrene as the starting material, 1.01 grams of the corresponding epoxides was obtained after column chromatography on silica gel using ethyl acetate as an eluent (83% yield, Table 4, entry 2). However, the epoxidation of various substrates is often quite exothermic. Although the reaction proceeded in the presence of Na₂SO₄, careful reaction temperature control was found to be crucial to a largescale preparation.

Recently, specific salt effects on the structure of water have been the subject of increasing attention.²² Under the biphasic conditions of benzene (oil phase) and aqueous solution (water phase), the solubility of benzene to the water phase was effectively reduced by Na₂SO₄.²³ The greater abilities of sulfate anion (SO₄²⁻) and sodium cation (Na⁺) compared with other anions and cations, respectively, to decrease protein solubility in aqueous solution is known as the Hofmeister effect.²⁴ Among the neutral salts containing monovalent cations such as Na⁺, Li⁺, K⁺, and H₂O₂ Epoxidation of Terpenes and Styrenes

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^a Reaction conditions: styrenes (1.0 equiv), 30% H_2O_2 (1.0 equiv), Na_2WO_4 (0.02 equiv), $[Me(n-C_8H_{17})_3N]HSO_4$ (0.02 equiv), H_3PO_4 (0.01 equiv), Na_2SO_4 (0.3 equiv), 25 °C, 1000 rpm, 16 h. ^b Determined by GC analysis with *n*-decane or biphenyl as an internal

standard.

^c Synthesis scale: 1 gram.

^d Isolated yield, epoxide (mol)/styrene (mol) × 100 (%).

^e The reaction was run in the absence of Na₂SO₄.

 NH_4^+ with sulfate anion SO_4^{2-} , Na^+ is the most effective salt for the salting-out process under biphasic conditions using various solvents as the oil phase and aqueous solution as the water phase.²⁵ On the other hand, nitrate anion NO_3^- is known to have the smallest salting-out effect; this is one reason why the epoxidation reaction of **1** using NaNO₃ did not give **2** at all (Table 1, entry 4). However, the findings regarding hydrolysis inhibition in the biphasic epoxidation reaction cannot simply explain the reactivity due to the interaction between substrate **2** and cations, or to the interaction between the catalyst species and anions.

In summary, we have demonstrated the effective and selective salt effects on the high yield syntheses of acid-labile epoxides using H_2O_2 with Na_2WO_4 , [Me(*n*- $C_8H_{17})_3N$]HSO₄, and PhP(O)(OH)₂ or H_3PO_4 catalysts under not only organic solvent-free but also acidic aqueous biphasic conditions. The simple addition of a saturated amount of Na_2SO_4 strongly promotes the production of terpene and styrene oxides due to the suppression of hydrolysis without deactivation of the catalytic H_2O_2 epoxidation system. We consider that the present synthetic improvement by the addition of salt will be quite promising for the practical preparation of a variety of acid-labile epoxides using H_2O_2 .

¹H (400 MHz) and ¹³C NMR (100 MHz) spectra were recorded on a Jeol ECX-400P spectrometer using CDCl₃, CD₃OD, and DMSO d_6 as solvents. Chemical shifts (δ) are reported in parts per million relative to internal TMS at 0.00 ppm for ¹H and ¹³C. GC analyses were performed on a Shimadzu GC-17A instrument using a TC-1 column (0.25 mm × 30 m, GL Sciences Inc.). H₂O was obtained on a Millipore Direct-Q UV.

α-Pinene, 3-carene, α-terpineol, terpinen-4-ol, isopulegol, limonene, carvone, sobreol, styrene derivatives, PhP(O)(OH)₂, and [Me(n-C₈H₁₇)₃N]HSO₄ were obtained from Tokyo Chemical Industry Co., Ltd. Na₂WO₄·2H₂O, 30% aq H₂O₂, and NaNO₃ were obtained from Kanto Chemical Co., Inc. NaHCO₃, NaCl, Na₂SO₄, (NH₄)₂SO₄, K₂SO₄, MgSO₄, and H₃PO₄ were obtained from Wako Pure Chemical Industries., Ltd. Li₂SO₄ was obtained from Aldrich Chemical Co.

Epoxidation of α-Pinene; Typical Procedure for GC Analysis

A test tube equipped with a magnetic stirring bar was charged with α -pinene (475 µL, 3.0 mmol), 30% H₂O₂ (308 µL, 3.0 mmol), Na₂WO₄·2H₂O (19.8 mg, 0.06 mmol), [Me(*n*-C₈H₁₇)₃N]HSO₄ (29.1 mg, 0.06 mmol), PhP(O)(OH)₂ (4.7 mg, 0.03 mmol), and Na₂SO₄ (129.2 mg, 0.9 mmol). The mixture was vigorously stirred at 25 °C for 16 h and extracted with toluene (3 × 6 mL). The conversion and yield were determined by GC analysis of the toluene solution with ca. 0.2 mmol of *n*-decane as an internal standard.

Epoxidation of α-Pinene; Typical Procedure for Isolation

A test tube equipped with a magnetic stirring bar was charged with α -pinene (475 µL, 3.0 mmol), 30% H₂O₂ (308 µL, 3.0 mmol), Na₂WO₄·2H₂O (19.8 mg, 0.06 mmol), [Me(n-C₈H₁₇)₃N]HSO₄ (29.1 mg, 0.06 mmol), PhP(O)(OH)₂ (4.7 mg, 0.03 mmol), and Na₂SO₄ (129.2 mg, 0.9 mmol). The mixture was vigorously stirred at 25 °C for 16 h. After 16 h, the two phases were separated, and the organic phase was washed with 10% aq Na₂S₂O₃ (5 mL). The organic phase was purified by column chromatography on silica gel using EtOAc as an eluent to give α -pinene oxide as a colorless oil; yield: 408 mg (89%).

Hydrolysis of a-Pinene Oxide; General Procedure

A test tube equipped with a magnetic stirring bar was charged with α -pinene oxide (471 µL, 3.0 mmol), 30% H₂O₂ (308 µL, 3.0 mmol) or H₂O (178 µL, 3.0 mmol), and adding the corresponding neutral salt as given in Table 1 (0.9 or 1.8 mmol). The mixture was vigorously stirred at 25 °C for 16 h and extracted with toluene (3 × 6 mL). The conversion and yield were determined by GC analysis of the toluene solution with ca. 0.2 mmol of *n*-decane as an internal standard.

Epoxidation of Styrene; Typical Procedure for GC Analysis

A test tube equipped with a magnetic stirring bar was charged with styrene (344 μ L, 3.0 mmol), 30% H₂O₂ (308 μ L, 3.0 mmol), Na₂WO₄·2H₂O (19.8 mg, 0.06 mmol), [Me(*n*-C₈H₁₇)₃N]HSO₄ (29.1 mg, 0.06 mmol), 5 M aq P(O)(OH)₂ (6 μ L, 0.03 mmol), and Na₂SO₄ (129.2 mg, 0.9 mmol). The mixture was vigorously stirred at 25 °C for 16 hours and extracted with toluene (3 × 6 mL). The conversion and yield were determined by GC analysis of the toluene solution with ca. 0.2 mmol of biphenyl as an internal standard.

Gram-Scale Epoxidation of Styrene; Typical Procedure for Isolation

A test tube equipped with a magnetic stirring bar was charged with styrene (1.06 g, 10 mmol), 30% H_2O_2 (1.14 g, 10 mmol), Na_2WO_4 ·2H₂O (97.2 mg, 0.2 mmol), $[Me(n-C_8H_{17})_3N]HSO_4$ (66.1 mg, 0.2 mmol), 5 M aq P(O)(OH)₂ (20 µL, 0.1 mmol), and Na_2SO_4 (0.43 g, 3 mmol). The mixture was vigorously stirred at 25 °C for 16 h. After stirring, the two phases were separated, and the organic phase was washed with 10% aq $Na_2S_2O_3$ (17 mL). The organic phase was purified by column chromatography on silica gel using EtOAc as an eluent to give styrene oxide as a colorless oil; yield: 1.01 g (83%).

α-Pinene Oxide²⁶

Yield: 408 mg (89%); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 0.94 (s, 3 H), 1.29 (s, 3 H), 1.34 (s, 3 H), 1.62 (d, *J* = 9.6 Hz, 1 H), 1.70–1.75 (br m, 1 H), 1.87–2.03 (m, 4 H), 3.07 (dd, *J* = 4.1, 1.4 Hz, 1 H).

¹³C NMR (100 MHz, CDCl₃): δ = 20.2, 22.4, 25.9, 26.7, 27.6, 39.7, 40.5, 45.1, 56.9, 60.3.

a-Terpineol Oxide19

Obtained as a 1:1 mixture of *cis*- and *trans*-epoxides. Yield: 67% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 1.01 (qd, *J* = 12.3, 6.9 Hz, 1 H), 1.13 (s, 3 H), 1.141 (s, 3 H), 1.144 (s, 3 H), 1.16 (s, 3 H), 1.313 (s, 3 H), 1.315 (s, 3 H), 1.43–1.54 (m, 3 H), 1.58–1.69 (m, 3 H), 1.79– 1.94 (m, 2 H), 2.00–2.08 (m, 2 H), 2.19–2.24 (m, 1 H), 3.00 (d, *J* = 5.5 Hz, 1 H), 3.07 (br, s, 1 H).

¹³C NMR (100 MHz, CDCl₃): δ = 20.1, 22.8, 22.9, 24.4, 25.9, 26.2, 26.6, 27.18, 27.22, 27.4, 29.5, 30.8, 40.2, 44.1, 57.5, 57.7, 59.2, 61.2, 72.2, 72.4.

Terpinen-4-ol Oxide^{19b,27}

Obtained as a 1:1 mixture of *cis*- and *trans*-epoxides; yield: 82% (GC yield); colorless oil.

cis-Epoxide

¹H NMR (400 MHz, CD₃OD): δ = 0.89 (d, *J* = 7.2 Hz, 3 H), 0.91 (d, *J* = 7.2 Hz, 3 H), 1.3–2.4 (m, 7 H), 1.36 (s, 3 H), 3.20 (s, 1 H), 3.53 (s, 1 H).

¹³C NMR (100 MHz, CD₃OD): δ = 6.7, 6.9, 14.0, 15.9, 19.5, 22.0, 27.1, 48.8, 52.3, 62.0.

trans-Epoxide

¹H NMR (400 MHz, DMSO- d_6): $\delta = 0.9$ (d, J = 7.2 Hz, 6 H), 1.1 (s, 1 H), 1.20–1.24 (m, 2 H), 1.35–1.40 (m, 2 H), 1.65–1.92 (m, 3 H), 2.8 (t, J = 7.0 Hz, 1 H), 4.0 (s, 1 H).

¹³C NMR (100 MHz, DMSO- d_6): δ = 16.1, 16.2, 23.0, 26.3, 29.5, 32.8, 34.5, 57.0, 59.0, 70.0.

Isopulegol Oxide²⁸

Obtained as a 1:1 mixture of *cis*- and *trans*-epoxides; yield: 97% (GC yield); white powder.

cis-Epoxide

¹H NMR (400 MHz, CDCl₃): $\delta = 0.80-1.10$ (m, 3 H), 0.93 (d, J = 6.6 Hz, 3 H), 1.15–1.27 (m, 1 H), 1.31 (s, 3 H), 1.36–1.52 (m, 1 H), 1.63–1.80 (m, 2 H), 1.98–2.08 (m, 1 H), 2.54 (d, J = 4.8 Hz, 2 H), 2.59 (d, J = 4.8 Hz, 2 H), 2.82 (s, 1 H), 3.71 (dt, J = 4.5, 10.5 Hz, 1 H).

¹³C NMR (100 MHz, CDCl₃): δ = 16.9, 22.0, 27.7, 30.9, 33.9, 43.5, 51.2, 52.8, 59.1, 71.2.

trans-Epoxide

¹H NMŘ (400 MHz, CDCl₃): δ = 0.83–1.18 (m, 3 H), 0.93 (d, *J* = 6.6 Hz, 3 H), 1.37 (s, 3 H), 1.38–1.52 (m, 2 H), 1.63–1.73 (m, 1 H), 1.83–1.97 (m, 2 H), 2.66 (d, *J* = 4.2 Hz, 2 H), 2.92 (d, *J* = 4.2 Hz, 2 H), 3.23–3.39 (m, 2 H).

¹³C NMR (100 MHz, CDCl₃): δ = 20.8, 22.0, 27.6, 31.1, 33.9, 42.9, 49.0, 52.2, 60.2, 70.5.

Limonene 2,3-Oxide²⁹

Yield: 89% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 1.13–2.27 (m, 7 H), 1.29 (s, 3 H), 1.71 (s, 3 H), 3.02 (t, *J* = 5.5 Hz, 1 H), 4.75 (s, 2 H).

¹³C NMR (100 MHz, CDCl₃): δ = 20.2, 22.1, 25.8, 28.5, 30.7, 40.7, 57.3, 59.2, 109.0, 148.8.

Carvone 1,6-Oxide³⁰

Yield: 41% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 1.42 (s, 3 H), 1.72 (s, 3 H), 1.91 (dd, *J* = 15.0, 11.1 Hz, 1 H), 2.03 (dd, *J* = 17.4, 11.1 Hz, 1 H), 2.38 (dt, *J* = 15.0, 3.0 Hz, 1 H), 2.59 (dd, *J* = 17.4, 4.5 Hz, 1 H), 2.67–2.76 (m, 1 H), 3.46 (d, *J* = 2.7 Hz, 1 H), 4.72 (s, 1 H), 4.79 (s, 1 H). ¹³C NMR (100 MHz, CDCl₃): δ = 15.2, 20.5, 28.6, 34.9, 41.7, 58.7, 61.2, 110.4, 146.2, 205.4.

Carvone 7,8-Oxide³¹

Yield: 9% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 1.32 (d, *J* = 6.4 Hz, 3 H), 1.78 (s, 3 H), 2.02–2.70 (m, 7 H), 6.74 (m, 1 H).

¹³C NMR (100 MHz, CDCl₃): δ = 15.7, 18.4, 19.0, 27.7, 27.9, 39.9, 40.4, 40.7, 41.4, 52.4, 52.9, 57.9, 58.0, 135.5, 135.6, 143.9, 144.2, 198.8, 198.9.

Styrene Oxide³²

Yield: 1.01 g (83%); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 2.82 (dd, *J* = 5.5, 2.5 Hz, 1 H), 3.16 (dd, *J* = 5.5, 4.0 Hz, 1 H), 3.88 (dd, *J* = 4.0, 2.5 Hz, 1 H), 7.25 (m, 5 H).

¹³C NMR (100 MHz, CDCl₃): δ = 50.8, 51.9, 125.1, 127.7, 128.1, 137.2.

4-Fluorostyrene Oxide^{13g}

Yield: 75% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 2.67 (dd, *J* = 5.6, 2.6 Hz, 1 H), 3.04 (dd, *J* = 5.6, 4.0 Hz, 1 H), 3.75 (dd, *J* = 4.0, 2.6 Hz, 1 H), 6.91–6.96 (m, 2 H), 7.12–7.17 (m, 2 H).

¹³C NMR (100 MHz, CDCl₃): δ = 51.6, 52.2, 115.9 (d, J = 20 Hz), 127.6 (d, J = 7 Hz), 133.7 (d, J = 2 Hz), 163.1 (d, J = 24 Hz).

4-Chlorostyrene Oxide³²

Yield: 79% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 2.76 (dd, *J* = 5.5, 2.5 Hz, 1 H), 3.15 (dd, *J* = 5.5, 4.0 Hz, 1 H), 3.84 (dd, *J* = 4.0, 2.5 Hz, 1 H), 7.21 (d, *J* = 8.5 Hz, 2 H), 7.32 (d, *J* = 8.5 Hz, 2 H).

¹³C NMR (100 MHz, CDCl₃): δ = 50.8, 51.3, 126.4, 128.2, 133.4, 135.7.

4-Bromostyrene Oxide³³

Yield: 83% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): $\delta = 2.74$ (dd, J = 5.5, 2.5 Hz, 1 H), 3.14 (dd, J = 5.4, 4.1 Hz, 1 H), 3.83 (dd, J = 4.1, 2.6 Hz, 1 H), 7.13– 7.17 (d, J = 8.4 Hz, 2 H), 7.45–7.48 (d, J = 8.5 Hz, 2 H).

¹³C NMR (100 MHz, CDCl₃): δ = 51.2, 51.8, 122.0, 127.1, 131.6, 136.7.

α-Methylstyrene Oxide³⁴

Yield: 96% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 1.63 (s, 3 H), 2.70 (d, *J* = 5.4 Hz, 1 H), 2.88 (d, *J* = 5.4 Hz, 1 H), 7.14–7.30 (m, 5 H).

¹³C NMR (100 MHz, CDCl₃): δ = 22.2, 57.2, 57.5, 125.7, 127.9, 129.0, 141.6.

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trans-β-Methylstyrene Oxide³⁵ Yield: 55% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 1.43 (d, *J* = 6.8 Hz, 3 H), 3.12 (dq, *J* = 6.8, 2.6 Hz, 1 H), 3.55 (d, *J* = 2.5 Hz, 1 H), 7.27 (m, 5 H). ¹³C NMR (100 MHz, CDCl₃): δ = 17.8, 58.9, 59.4, 125.4, 127.9, 128.3, 137.7.

cis-β-Methylstyrene Oxide³⁵

Yield: 89% (GC yield); colorless oil.

¹H NMR (400 MHz, CDCl₃): δ = 1.08 (d, *J* = 7.1 Hz, 3 H), 3.33 (dq, *J* = 7.1, 5.8 Hz, 1 H), 4.05 (d, *J* = 5.6 Hz, 1 H), 7.29 (m, 5 H). ¹³C NMR (100 MHz, CDCl₃): δ = 12.5, 55.0, 57.5, 126.5, 127.4, 127.9, 135.5.

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