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Copper-catalyzed sulfonylation of alkenes with CH_3SSO_3Na

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Abstract

A successful methodology for the copper-catalyzed dehydrogenated methylsulfonylation of alkenes utilizing CH_3SSO_3Na in conjunction with hypervalent iodine reagents was successfully established. This method offers a practical avenue to obtain allyl methyl sulfones and alkenyl methyl sulfones by forming C-S bonds. Using the C-H bond oxidation sulfonylation strategy with alkenes and Bunte salts, we successfully synthesized a total of twenty two compounds, including four examples of deuterium-substituted molecules, and demonstrated one example of a scale-up reaction.

Keywords Allyl sulfone, Alkenyl sulfone, Sulfonation reaction, C-H functionalization, Trideuteromethylsulfonylation

Introduction

Methyl sulfone is a fundamental structural unit found in various bioactive molecules and natural products. For instance, methylgerambullin has the potential for anti-hepatocellular carcinoma activity [1, 2]. Furthermore, it serves as a versatile intermediate for the synthesis of sophisticated functional materials, as depicted in Scheme 1A [3]. It is remarkable that $AMSO_2$ has the potential to mitigate nephrotoxicity induced by cisplatin through the suppression of the ROS/MAPK/NF-κB signaling pathway [4]. Therefore, there is a driving force for the development of novel synthetic methods that could produce these structurally diverse sulfone compounds [5–9]. Currently, the reliable synthesis of alkenyl sulfones can be accomplished by sulfonylating various alkenylating agents with sulfonyl chlorides, sulfinic acids, sulfinates and sulfonyl hydrazides etc. (Scheme 1B) [10–14]. In addition, radical hydrosulfonylation of alkynes with sulfonylation reagents has been developed as a complementary protocol [15–17]. C-H sulfonylation reactions of alkenes are considered an ideal synthetic strategy because they effectively avoid the pre-functionalization of alkene substrates [18–20]. In 2019, Pan group developed a copper-catalyzed oxidative coupling between styrene and thiophenols to synthesize aryl alkenyl sulfones [21–23]. However, there are still significant challenges in efficiently preparing alkenyl methyl sulfones while circumventing the utilization of malodorous starting materials.

As for the preparation of allyl sulfone compounds [24–26], traditional methods typically employ oxidative reactions of allyl sulfides. However, strong oxidants are unable to differentiate between unsaturated bonds and sulfur atoms. Afterwards, transition-metal catalyzed sulfonylation reactions with allyl precursors have been gradually developed (Scheme 1B) [27–29]. However, issues such as the preassembly of leaving groups, harsh reaction conditions, and the necessity for expensive organic ligands remain evident and often unavoidable. Despite significant advancements in allyl C-H functionalization [30], direct sulfonylation remains a major challenge due

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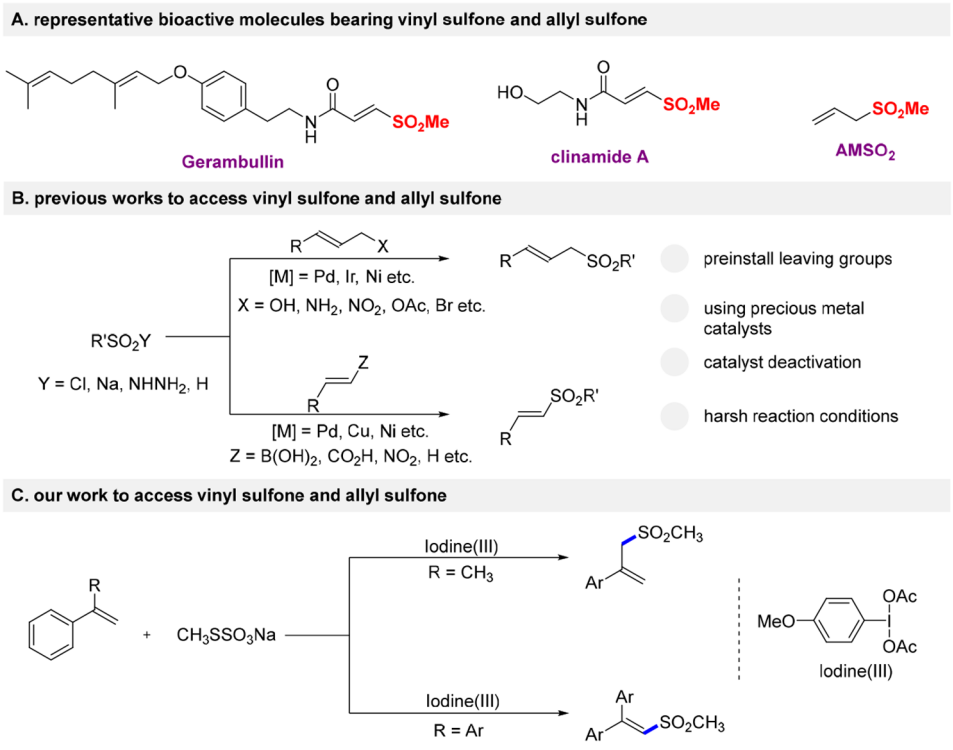


Scheme 1 Synthetic protocols to access allyl methyl sulfone and alkenyl methyl sulfone

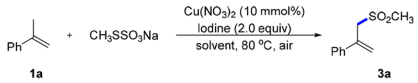
to the strong coordination effect between sulfur atoms and transition metal salts. The free radical addition/dehydrogenation between sulfonyl radicals and α-methyl styrenes offers a new pathway for the preparationof allyl sulfone [31]. However, this strategy is only effective for aryl sulfonyl groups. There is no corresponding report on preparing allyl alkyl sulfones using this reaction pathway. Hence, an efficient and green approach towards the sulfonylation of alkenes that can complementary to the prior arts is in high demand.

Bunte salts are commonly utilized as reagents for sulfuration, mainly for the preparation of thioether compounds by forming new sulfur-carbon bonds [32]. Their use as a sulfonation reagent hasn't been documented, though. Based on our intriguing research on Bunte salts [33, 34], we envisioned that, given the proper oxidant, CH_3SSO_3Na may potentially function as a sulfonyl source (Scheme 1C). In this study, we present a novel method that uses CH_3SSO_3Na as the sulfonating reagent and hypervalent iodine as the oxidant to directly access allyl methyl sulfones and alkenyl methyl sulfones. Significantly, the trideuteromethylsulfonylation of α-methyl styrenes with CD_3SSO_3Na further illustrated the effectiveness of this tactic, creating a large space for the synthesis of deuterated molecules.

Results and discussion

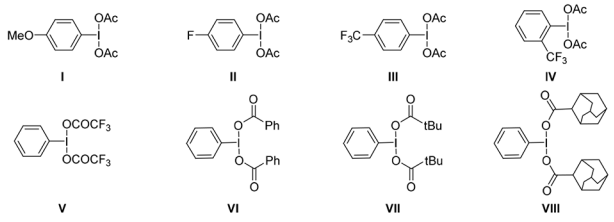
Initially, we chose α-methyl styrene and CH_3SSO_3Na as model substrates to optimize reaction conditions and screened various copper salts and oxidants (Table 1). Surprisingly, the combination of $Cu(NO_3)_2$ with PIDA led to the formation of allyl sulfone instead of allyl sulfides (entry 5). However, other commonly used copper salts, such as CuI and $CuBr_2$ performed relatively poorly (entries 6, 7). When other oxidants, such as DDQ and NFSI were used, no sulfonylation reactions were observed (entries 1–4). Next, we prepared and screened PIDA analogs to adjust their oxidizability [35–36]. It was discovered that electron-donating functional groups promoted reaction efficiency, while electron-withdrawing functional groups inhibited it (entries 8–11). The results showed that PIFA directly inhibited the initiation of the transformation, and benzoyloxy and bulky adamantoyloxy groups were also unfavorable for substrate conversion (entries 12–15). During the screening of various solvents (entries 16–18), we found that toluene, acetonitrile, and THF significantly hindered the coupling reaction, resulting in a substantial amount of unreacted starting material. Furthermore, the reaction atmosphere had a slight influence on the transformation, with a noticeable decrease in yield observed under nitrogen conditions (entry 19). Furthermore, the sulfonylation reactions were significantly impacted by changes in

Table 1 Screening study of C-H sulfonation with CH_3SSO_3Na[a]



1a 3a

Entry	Catalyst	Oxidant	Solvent	Yield of 4a[b]
1	$Cu(NO_3)_2$	NFSI	DMA	0
2	$Cu(NO_3)_2$	I_2	DMA	0
3	$Cu(NO_3)_2$	DDQ	DMA	0
4	$Cu(NO_3)_2$	TBHP	DMA	0
5	$Cu(NO_3)_2$	PIDA	DMA	49
6	CuI	PIDA	DMA	30
7	$CuBr_2$	PIDA	DMA	14
8	$Cu(NO_3)_2$	**I**	DMA	76
9	$Cu(NO_3)_2$	**II**	DMA	36
10	$Cu(NO_3)_2$	**III**	DMA	29
11	$Cu(NO_3)_2$	**IV**	DMA	22
12	$Cu(NO_3)_2$	**V**	DMA	0
13	$Cu(NO_3)_2$	**VI**	DMA	30
14	$Cu(NO_3)_2$	**VII**	DMA	55
15	$Cu(NO_3)_2$	**VIII**	DMA	59
16	$Cu(NO_3)_2$	**I**	CH_3CN	0
17	$Cu(NO_3)_2$	**I**	THF	0
18	$Cu(NO_3)_2$	**I**	Toluene	0
19[c]	$Cu(NO_3)_2$	**I**	DMA	59
20[d]	$Cu(NO_3)_2$	**I**	DMA	65
21[e]	$Cu(NO_3)_2$	**I**	DMA	48

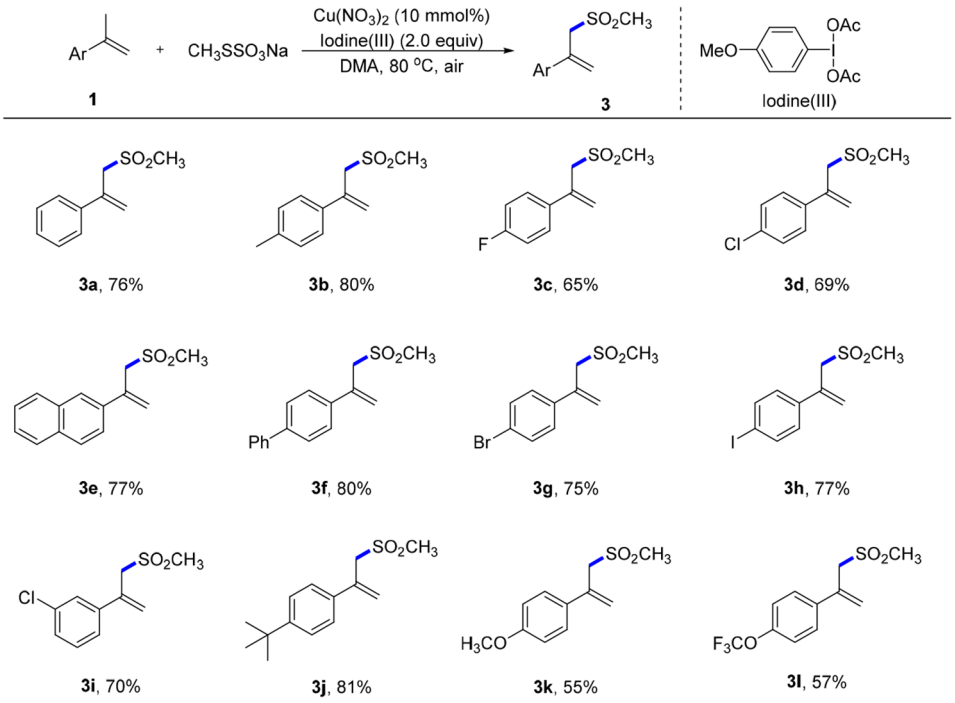


[a] The experimental conditions were as follows: **1a** (0.2 mmol), CH_3SSO_3Na (0.4 mmol), $Cu(NO_3)_2$ (0.02 mmol), an oxidizing agent (0.4 mmol), and solvent (2.0 mL) were subjected to heating at 80 °C for 24 hours. [b] Separated yield. [c] Under N_2. [d] At 90 °C. [e] At 70 °C.

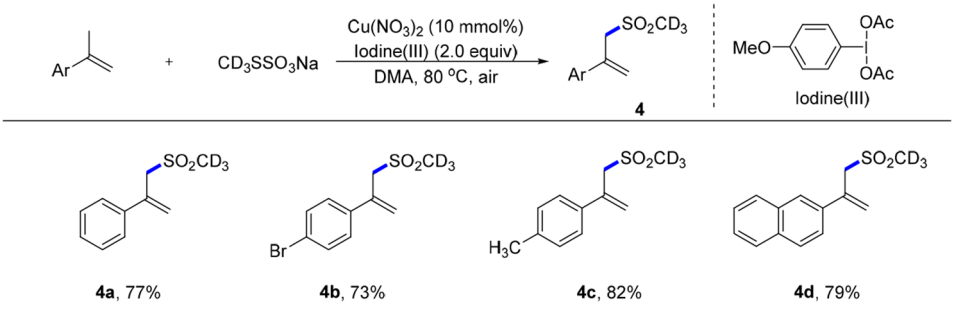
the reaction temperature, which hindered the process (entries 20, 21).

Following the determination of the optimal reaction conditions, we conducted a study examining the alkene substrates. As depicted in Scheme 2, various styrenes underwent C-H bond sulfonylation reactions, all given the target products in generally good yields and exhibiting excellent site selectivity. For styrene derivatives, it was found that a wide range of function-group such as methoxy, fluoride, chloride, bromide, iodide, are compatible under our reaction conditions. However, when the styrene contains electron-withdrawing functional groups, it becomes incompatible under standard reaction conditions. We speculate that the primary factor underlying this phenomenon is the destabilization of the benzyl radical, which occurs due to the addition of thiyl radicals to styrenes that contain electron-withdrawing groups. Furthermore, naphthylene was identified as an appropriate coupling substrate, producing the expected product (**3e**) with an efficiency of 88%.

It is worth mentioning that among all reported literature, there is no procedure to prepare allyl trideuteromethyl sulfones. Deuteration of drugs is primarily done to optimize the pharmacokinetic characteristics while preserving their original pharmaceutical activity [37]. In 2024, Wang group successfully designed and synthesized



Scheme 2 Synthesis of various allyl methyl sulfones. [a] The experimental conditions were as follows: α-methyl styrenes (0.2 mmol), CH_3SSO_3Na (0.4 mmol), $Cu(NO_3)_2$ (0.02 mmol), hypervalent iodine (0.4 mmol), and solvent (2.0 mL) were subjected to heating at 80 °C for 24 h. [b] Separated yield



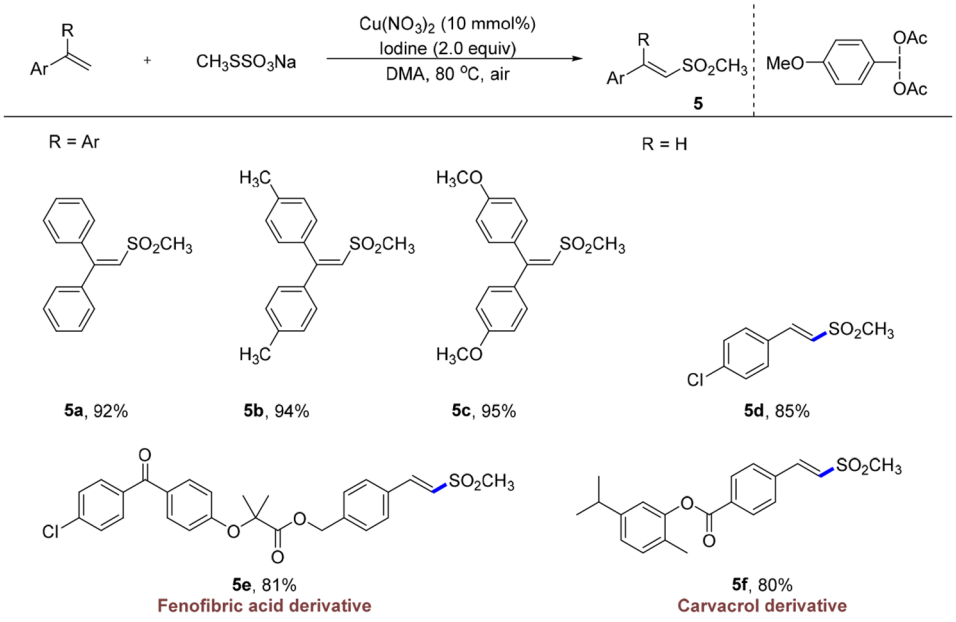
Scheme 3 Synthesis of various allyl trideuteromethyl sulfones. [a] The experimental conditions were as follows: α-methyl styrenes (0.2 mmol), CD_3SSO_3Na (0.4 mmol), $Cu(NO_3)_2$ (0.02 mmol), hypervalent iodine (0.4 mmol), and solvent (2.0 mL) were subjected to heating at 80 °C for 24 h. [b] Separated yield

((methyl-d_3)sulfonyl)ethyne, which was applied in radical addition with thiols to generate alkenyl trideuteromethyl sulfones [38]. We reasoned that the construction of diverse deuterated molecules and the development of direct trideuteromethylsulfonylation of alkenes would be beneficial for the late-stage diversification of alkene-containing pharmaceuticals. When CH_3SSO_3Na is replaced with CD_3SSO_3Na, the oxidative trideuteromethylsulfonylation of α-methylstyrene can be successfully achieved, resulting in the corresponding allyl trideuteromethyl sulfone compounds with a high deuteration rate (Scheme 3). This method highlights the significant potential applications for the efficient construction of deuterated compounds.

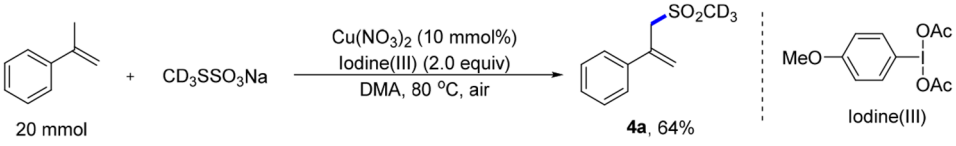
Next, we examined a diverse range of 1,1-diarylalkenes to evaluate the synthetic versatility of our approach (Scheme 4). Notably, important functional groups like methyl and methoxy were well-tolerated on the benzene rings. Additionally, our strategy proved effective for styrene derivatives, affording the E-stereoselective target product (**5d**) in excellent yield. Furthermore, the late-stage alteration of natural products successfully exemplified this methodology, as styrene derivatives of carvacrol and fenofibric acid smoothly underwent sulfonylation with CH_3SSO_3Na to yield the corresponding α,β-unsaturated sulfones (**5e**, **5f**).

Gram-scale oxidative sulfonylation of α-methylstyrene with CD_3SSO_3Na illustrates the feasibility of this strategy and its potential for other commercial applications (Scheme 5).

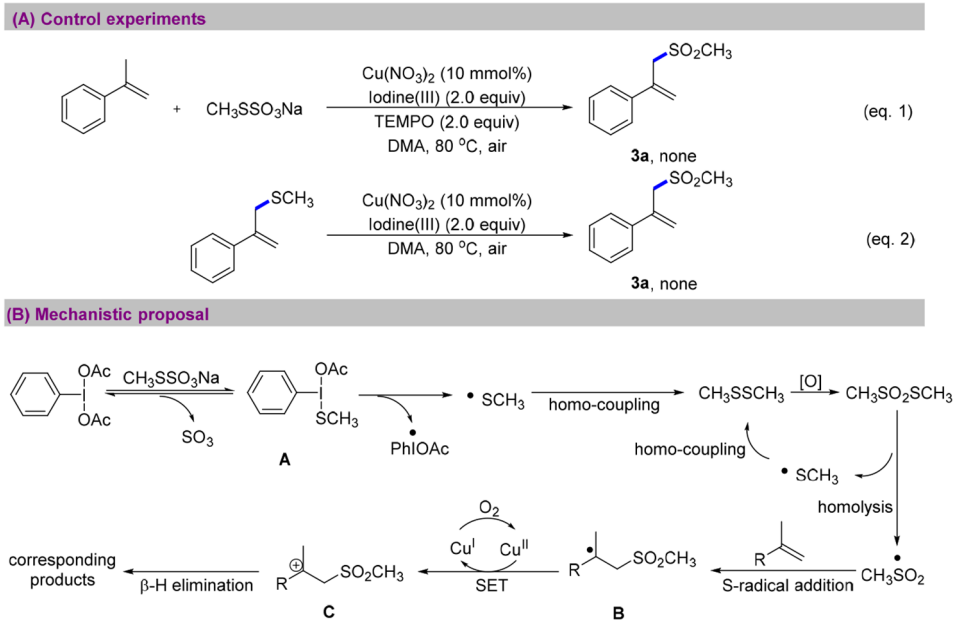
We conducted several control studies to elucidate the potential reaction mechanism (Scheme 6A). Initially, the



Scheme 4 Synthesis of various alkenyl methyl sulfones. [a] The experimental conditions were as follows: 1,1-diarylalkenes (0.2 mmol), CH_3SSO_3Na (0.4 mmol), $Cu(NO_3)_2$ (0.02 mmol), hypervalent iodine (0.4 mmol), and solvent (2.0 mL) were subjected to heating at 80 °C for 24 h. [b] Separated yield



Scheme 5 Gram-scale reactions



Scheme 6 Reaction mechanistic investigation and proposed mechanism

observation that the modular reaction did not generate the anticipated product **3a** upon the addition of TEMPO suggests the participation of a radical species during the reaction progress (entry 1). Additionally, the allyl methyl sulfide failed to form an oxidized product under standard reaction conditions (entry 2). This result indicates that the sulfonylation product is formed through the generation of mesyl radicals, rather than a thiolation followed by an oxidation process. Based on the integration of prior literature and experimental findings, we have proposed a tenable reaction mechanism, which is depicted in Scheme 6B. Initially, the hypervalent iodine interacts with the Bunte salts, releasing sulfur trioxide and forming an iodine-sulfur intermediate **A** [39]. This intermediate homolytically dissociates into an aryl iodide radical and sulfur radical [40]. Subsequently, the sulfur radical undergoes homo-coupling to form CH_3SSCH_3, which easily undergoes oxidation to produce $CH_3SO_2SCH_3$ in the presence of oxidants [41]. The sulfonothioate undergoes homolytic cleavage to form sulfur and a mesyl radical. Due to the stronger electrophilicity of the hypervalent mesyl radical, it preferentially undergoes a radical addition reaction with the olefin, forming an alkyl radical intermediate **B**. Next, Cu^{II} further oxidizes this alkyl radical into a carbocation intermediate **C** via single-electron oxidation. Finally, a β-H elimination reaction occurs to obtain the target product.

Conclusions

In conclusion, we have devised a straightforward method for the direct transformation of readily available α-methyl styrenes into allyl methyl sulfones and α-aryl styrenes into alkenyl methyl sulfone compounds. This process employs copper-catalyzed methylsulfonylation of alkenes with CH_3SSO_3Na as the key step. Late-stage alteration of complicated substrates is made possible by the wide functional group compatibility, robustness, and simplicity of the reaction conditions. Furthermore, gram-scale reactions have successfully validated the practical applicability of this protocol, providing a reliable means to incorporate trideuteromethyl sulfonyl groups into organic molecules, which is certainly beneficial to the research and development of deuterium-substituted drug molecules. Owing to its straightforward nature, compatibility with a wide range of substrates and excellent functional group tolerance, our laboratory is actively investigating trideuteromethyl sulfone-containing small molecules for the development and discovery of lead compounds.

Experiment

General procedure of Trideuteromethylsulfonylation of α-methyl styrenes

General procedure of trideuteromethylsulfonylation of α-methyl styrenes.

A stir bar-fitted 25 mL Schlenk tube, was assembled containing α-methyl styrenes (0.2 mmol), $Cu(NO_3)_2$ (0.02 mmol), hypervalent iodine (III) (0.4 mmol), and CD_3SSO_3Na (0.4 mmol). Subsequently, 2.0 mL of dimethylacetamide was introduced into the mixture, a rubber septum was used to seal the tube. The reaction tube was subjected to 80 °C for 24 h. Upon cooling to room temperature, 10 mL of diethyl ether and water were added to dilute it. After extraction process, the organic layer was subjected to drying using sodium sulfate and subsequently concentrated under vacuo. The resultant mixture underwent further purification via flash chromatography to obtain different products.

Characterization of products in details

(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3a)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (29.8 mg, 76% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.52–7.50 (m, 2 H), 7.45–7.38 (m, 3 H), 5.81 (s, 1 H), 5.61 (s, 1 H), 4.24 (s, 2 H), 2.76 (s, 3 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 138.71, 136.72, 128.95, 128.69, 126.38, 122.27, 60.86, 40.35. **HRMS** (ESI): calcd for $C_{10}H_{13}O_2S$ $[M+H]^+$ 197.0630, found 197.0634.

1-methyl-4-(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3b)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (33.6 mg, 80% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.40 (d, *J* = 8.2 Hz, 2 H), 7.23 (d, *J* = 8.0 Hz, 2 H), 5.77 (s, 1 H), 5.55 (s, 1 H), 4.22 (s, 2 H), 2.75 (s, 3 H), 2.40 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 138.68, 136.59, 135.76, 129.63, 126.24, 121.36, 60.91, 40.31, 21.21. **HRMS** (ESI): calcd for $C_{11}H_{15}O_2S$ $[M+H]^+$ 211.0787, found 211.0789.

1-fluoro-4-(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3c)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (27.8 mg, 65% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.49 (dd, *J* = 8.6, 5.3 Hz, 2 H), 7.11 (t, *J* = 8.6 Hz, 2 H), 5.76 (s, 1 H), 5.57 (s, 1 H), 4.20 (s, 2 H), 2.82 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 162.90 (d, *J* = 248.7 Hz), 135.82, 134.84 (d, *J* = 3.4 Hz), 128.25 (d, *J* = 8.1 Hz), 122.11, 115.83 (d, *J* = 21.7 Hz), 60.91, 40.30. **^{19}F NMR** (375 MHz, $CDCl_3$) δ -113.03; **HRMS** (ESI): calcd for $C_{10}H_{12}O_2FS$ $[M+H]^+$ 215.0536, found 215.0538.

1-chloro-4-(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3d)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (31.7 mg, 69% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.46 (d, *J* = 8.6 Hz, 2 H), 7.39 (d, *J* = 8.7 Hz, 2 H), 5.81 (s, 1 H), 5.61 (s, 1 H), 4.20 (s, 2 H), 2.83 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 137.15, 135.74, 134.61, 129.04, 127.77, 122.63, 60.62, 40.31. **HRMS** (ESI): calcd for $C_{10}H_{12}O_2ClS$ $[M + H]^+$ 231.0241, found 231.0244.

2-(3-(methylsulfonyl)prop-1-en-2-yl)naphthalene (3e)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (37.9 mg, 77% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.96 (d, *J* = 1.9 Hz, 1 H), 7.91–7.86 (m, 3 H), 7.64 (dd, *J* = 8.7, 1.9 Hz, 1 H), 7.56–7.53 (m, 2 H), 5.95 (s, 1 H), 5.71 (s, 1 H), 4.35 (s, 2 H), 2.78 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 136.62, 135.90, 133.29, 133.21, 128.78, 128.43, 127.70, 126.78, 126.75, 125.61, 124.08, 122.66, 60.85, 40.39. **HRMS** (ESI): calcd for $C_{14}H_{15}O_2S$ $[M + H]^+$ 247.0787, found 247.0790.

4-(3-(methylsulfonyl)prop-1-en-2-yl)-1,1′-biphenyl (3f)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow solid (43.5 mg, 80% yield), Mp = 116–117℃. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.67–7.58 (m, 6 H), 7.51–7.47 (m, 2 H), 7.43–7.38 (m, 1 H), 5.88 (s, 1 H), 5.63 (s, 1 H), 4.27 (s, 2 H), 2.82 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 141.49, 140.23, 137.48, 136.33, 128.95, 127.73, 127.56, 127.08, 126.79, 122.04, 60.77, 40.35. **HRMS** (ESI): calcd for $C_{16}H_{16}O_2NaS$ $[M + Na]^+$ 295.0769, found 295.0771.

1-bromo-4-(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3 g)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (41.1 mg, 75% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.54 (d, *J* = 8.5 Hz, 2 H), 7.39 (d, *J* = 8.6 Hz, 2 H), 5.81 (s, 1 H), 5.61 (s, 1 H), 4.19 (s, 2 H), 2.82 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 137.62, 135.80, 132.03, 128.05, 122.85, 122.72, 60.61, 40.35. **HRMS** (ESI): calcd for $C_{10}H_{11}O_2NaSBr$ $[M + Na]^+$ 296.9561, found 296.9569.

1-iodo-4-(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3 h)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow solid (49.6 mg, 77% yield), Mp = 100–101℃. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.75 (d, *J* = 8.6 Hz, 2 H), 7.25 (d, *J* = 8.5 Hz, 2 H), 5.82 (s, 1 H), 5.60 (s, 1 H), 4.19 (s, 2 H), 2.82 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 138.20, 138.01, 135.91, 128.19, 122.74, 94.54, 60.54, 40.33. **HRMS** (ESI): calcd for $C_{10}H_{11}O_2NaSI$ $[M + Na]^+$ 344.9422, found 344.9428.

1-chloro-3-(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3i)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (32.2 mg, 70% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.49–7.49 (m, 1 H), 7.39–7.34 (m, 3 H), 5.82 (s, 1 H), 5.64 (s, 1 H), 4.19 (s, 2 H), 2.82 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 140.65, 135.66, 134.91, 130.14, 128.71, 126.63, 124.61, 123.29, 60.57, 40.38. **HRMS** (ESI): calcd for $C_{10}H_{11}O_2NaSCl$ $[M + Na]^+$ 253.0066, found 253.0064.

1-(tert-butyl)-4-(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3j)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (40.8 mg, 81% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.44 (m, 4 H), 5.80 (s, 1 H), 5.57 (s, 1 H), 4.23 (s, 2 H), 2.78 (s, 3 H), 1.36 (s, 9 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 151.87, 136.44, 135.64, 126.00, 125.84, 121.31, 60.81, 40.26, 34.67, 31.28. **HRMS** (ESI): calcd for $C_{14}H_{20}O_2NaS$ $[M + Na]^+$ 275.1082, found 275.1086.

1-methoxy-4-(3-(methylsulfonyl)prop-1-en-2-yl)benzene (3k)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (24.9 mg, 55% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.47 (d, *J* = 8.6 Hz, 2 H), 6.96 (d, *J* = 8.6 Hz, 2 H), 5.74 (s, 1 H), 5.51 (s, 1 H), 4.22 (s, 2 H), 3.88 (s, 3 H), 2.78 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 159.94, 136.13, 130.95, 127.59, 120.37, 114.22, 61.02, 55.35, 40.22. **HRMS** (ESI): calcd for $C_{11}H_{14}O_3NaS$ $[M + Na]^+$ 249.0561, found 249.0568.

1-(3-(methylsulfonyl)prop-1-en-2-yl)-4-(trifluoromethoxy) benzene (3 L)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow solid (31.9 mg, 57% yield), Mp = 59–60℃. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.54 (d, *J* = 8.8 Hz, 2 H), 7.25 (d, *J* = 8.3 Hz, 2 H), 5.81 (s, 1 H), 5.61 (s, 1 H), 4.21 (s, 2 H), 2.84 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 149.29, 137.34, 135.50, 127.94, 122.93, 121.44 (q, *J* = 205.8 Hz), 121.12, 60.57, 40.23. **^{19}F NMR** (375 MHz, $CDCl_3$) δ -57.81; **HRMS** (ESI): calcd for $C_{11}H_{11}O_3F_3NaS$ $[M + Na]^+$ 303.0279, found 303.0288.

(3-((methyl-d3)sulfonyl)prop-1-en-2-yl)benzene (4a)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (30.6 mg, 77% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.52–7.48 (m, 2 H), 7.45–7.38 (m, 3 H), 5.80 (s, 1 H), 5.60 (s, 1 H), 4.23 (s, 2 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 138.73, 136.73, 128.95, 128.69, 126.38, 122.24, 60.86. **HRMS** (ESI): calcd for $C_{10}H_9D_3O_2NaS$ $[M + Na]^+$ 222.0644, found 222.0653.

1-bromo-4-(3-((methyl-d3)sulfonyl)prop-1-en-2-yl)benzene (4b)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (40.4 mg, 73% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.54 (d, *J* = 8.6 Hz, 2 H), 7.38 (d, *J* = 8.6 Hz, 2 H), 5.81 (s, 1 H), 5.60 (s, 1 H), 4.18 (s, 2 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 137.64, 135.82, 132.04, 128.04, 122.87, 122.66, 60.60. **HRMS** (ESI): calcd for $C_{10}H_8D_3O_2NaSBr$ $[M + Na]^+$ 299.9749, found 299.9753.

1-methyl-4-(3-((methyl-d3)sulfonyl)prop-1-en-2-yl)benzene (4c)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (34.9 mg, 82% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.39 (d, *J* = 8.2 Hz, 2 H), 7.23 (d, *J* = 7.9 Hz, 2 H), 5.77 (s, 1 H), 5.55 (s, 1 H), 4.21 (s, 2 H), 2.39 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 138.68, 136.60, 135.77, 129.62, 126.23, 121.31, 60.91, 21.17. **HRMS** (ESI): calcd for $C_{11}H_{11}D_3O_2NaS$ $[M + Na]^+$ 236.0801, found 236.0804.

2-(3-((methyl-d3)sulfonyl)prop-1-en-2-yl)naphthalene (4d)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow solid (39.3 mg, 79% yield), Mp = 87–88℃. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.96 (d, *J* = 2.0 Hz, 1 H), 7.90–7.86 (m, 3 H), 7.63 (dd, *J* = 8.6, 2.0 Hz, 1 H), 7.55–7.53 (m, 2 H), 5.95 (s, 1 H), 5.70 (s, 1 H), 4.34 (s, 2 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 136.63, 135.92, 133.30, 133.21, 128.76, 128.42, 127.69, 126.76, 126.73, 125.61, 124.07, 122.60, 60.82. **HRMS** (ESI): calcd for $C_{14}H_{11}D_3O_2NaS$ $[M + Na]^+$ 272.0801, found 272.0804.

(2-(methylsulfonyl)ethene-1,1-diyl)dibenzene (5a)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a white liquid (47.5 mg, 92% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.51–7.38 (m, 8 H), 7.33–7.30 (m, 2 H), 6.90 (s, 1 H), 2.72 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): 154.9, 139.8, 135.7, 130.5, 129.9, 129.6, 128.8, 128.4, 128.1, 43.3. **HRMS** (ESI): calcd for $C_{15}H_{15}O_2S$ $[M + H]^+$ 259.0787, found 259.0791.

4,4′-(2-(methylsulfonyl)ethene-1,1-diyl)bis(methylbenzene) (5b)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a white liquid (53.8 mg, 94% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.30 (brs, 4 H), 7.20 (brs, 4 H), 6.83 (s, 1 H), 2.71 (s, 3 H), 2.45 (s, 3 H), 2.41 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 140.87, 139.71, 136.56, 132.96, 129.96, 129.42, 129.05, 128.41, 127.03, 43.33, 21.46, 21.31. **HRMS** (ESI): calcd for $C_{17}H_{18}O_2NaS$ $[M + Na]^+$ 309.0925, found 309.0928.

4,4′-(2-(methylsulfonyl)ethene-1,1-diyl)bis(methoxybenzene) (5c)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow solid (60.4 mg, 95% yield), Mp = 156–157℃. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.36 (d, *J* = 8.8 Hz, 2 H), 7.25 (d, *J* = 8.9 Hz, 2 H), 6.99 (d, *J* = 8.8 Hz, 2 H), 6.90 (d, *J* = 8.9 Hz, 2 H), 6.75 (s, 1 H), 3.89 (s, 3 H), 3.86 (s, 3 H), 2.71 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 161.52, 160.64, 154.43, 131.79, 131.67, 130.09, 127.95, 125.48, 114.02, 113.68, 55.40, 55.29, 43.19. **HRMS** (ESI): calcd for $C_{17}H_{18}O_4NaS$ $[M + Na]^+$ 341.0823, found 341.0823.

(E)-1-chloro-4-(2-(methylsulfonyl)vinyl)benzene (5d)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (36.7 mg, 85% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.62 (d, *J* = 15.5 Hz, 1 H), 7.50–7.43 (m, 4 H), 6.93 (d, *J* = 15.5 Hz, 1 H), 3.07 (s, 3 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 142.71, 137.58, 130.62, 129.83, 129.58, 126.78, 43.32. **HRMS** (ESI): calcd for $C_9H_{10}O_2ClS$ $[M + H]^+$ 217.0084, found 217.0087.

(E)-4-(2-(methylsulfonyl)vinyl)benzyl 2-(4-(4-chlorobenzoyl) phenoxy)-2-methylpropanoate (5e)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid (82.9 mg, 81% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.72 (d, *J* = 8.4 Hz, 2 H), 7.67–7.63 (m, 2 H), 7.59 (s, 1 H), 7.49–7.46 (m, 4 H), 7.31–7.29 (m, 2 H), 6.95 (d, *J* = 15.5 Hz, 1 H), 6.81 (d, *J* = 8.8 Hz, 2 H), 5.24 (s, 2 H), 3.07 (s, 3 H), 1.72 (s, 6 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 194.23, 173.48, 159.53, 143.16, 138.61, 138.44, 136.28, 132.05, 131.25, 130.45, 129.01, 128.79, 128.69, 126.91, 117.17, 79.46, 66.57, 43.30, 25.50. **HRMS** (ESI): calcd for $C_{27}H_{26}O_6ClS$ $[M + H]^+$ 513.1133, found 513.1140.

5-isopropyl-2-methylphenyl (E)-4-(2-(methylsulfonyl)vinyl) benzoate (5f)

Following the general procedure, using (petroleum ether: EtOAc = 9: 1) as the eluant afforded a yellow liquid(57.3 mg, 80% yield). **^{1}H NMR** (400 MHz, $CDCl_3$): δ 8.31 (d, *J* = 8.3 Hz, 2 H), 7.76–7.69 (m, 3 H), 7.24 (d, *J* = 7.8 Hz, 1 H), 7.12–7.07 (m, 2 H), 7.03 (m, 1 H), 3.11 (s, 3 H), 2.94 (p, *J* = 6.9 Hz, 1 H), 2.22 (s, 3 H), 1.29 (d, *J* = 6.9 Hz, 6 H). **^{13}C NMR** (100 MHz, $CDCl_3$): δ 164.08, 149.31, 148.36, 142.58, 136.80, 131.93, 131.11, 130.95, 128.88, 128.71, 127.28, 124.54, 119.78, 43.24, 33.68, 24.00, 15.92. **HRMS** (ESI): calcd for $C_{20}H_{23}O_4S$ $[M + H]^+$ 359.1311, found 359.1313.

Supplementary Information

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Supplementary Material 1

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CXL performed the experiment and data analysis. WG prepared the manuscript. All authors read and approved the fnal manuscript.

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All data generated or analyzed during this study are included in this published article.

Declarations

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