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NaI-Mediated Acetamidosulfenylation of Alkenes with Bunte Salts as Thiolating Reagent Leading to β-Acetamido Sulfides

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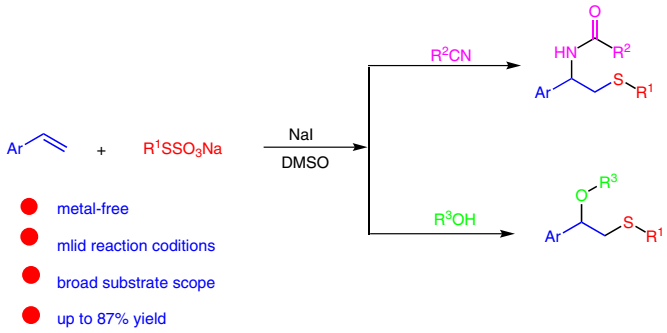

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Abstract A direct and efficient method for the acetamidosulfenylation reaction of alkenes was developed, in which NaI was used as a catalyst, DMSO as the oxidant, nitriles as both the solvent and nucleophiles and stable, readily available Bunte salts as thiolating reagents. The reactions were carried out under mild conditions generating β-acetamido sulfides in good yields. Moreover, the reaction can be performed when alcohols are used as nucleophiles providing the corresponding β-alkoxysulfides in moderate yields, respectively.

Key words alkenes, Bunte salts, β-acetamido sulfides, nitriles, nucleophiles

Organosulfur compounds, over the past decades, not only receive wide application in material science,[1] but also play an important role in medicinal chemistry,[2] natural products,[3] and food chemistry.[4] It is an effective strategy to obtain organosulfur products through the difunctionalization of alkenes in synthetic organic chemistry.[5] Among them, sulfenylation of alkene employing various sulfur reagents has gained great attention and progress in recent years.[6] Different sulfur sources, such as thiols,[6a] disulfides,[6b] arylsulfonyl chlorides,[6c] and arylsulfonyl cyanides,[6d] etc.,[6e] have been well developed for these transformations. However, in order to meet the requirements for multifunctionalized organosulfur compounds, simpler, more effective, and green methods for difunctionalization of alkenes are still highly desirable.

β-Acetamido sulfides, as an important member in sulfur-containing compounds, exist widely as moieties in natural products and biologically active molecules,[7] such as lactacystin,[7a] which is a proteasome inhibitor, frenolicin C[7b] with anticoccidial activity, and lucensimycin D[7c] with antibacterial activities (Figure 1).

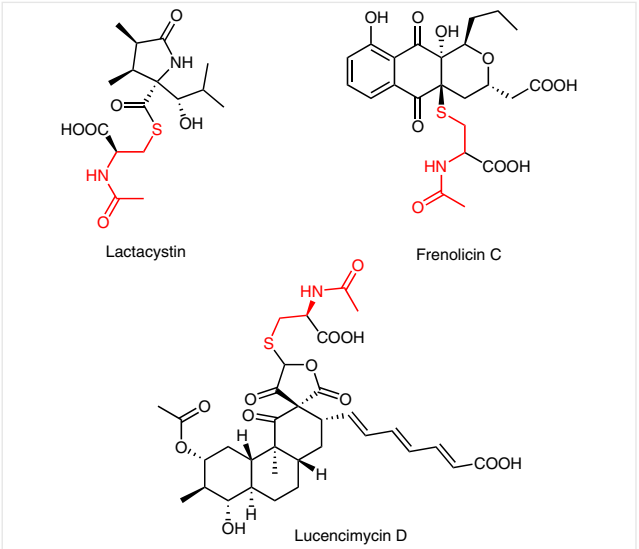
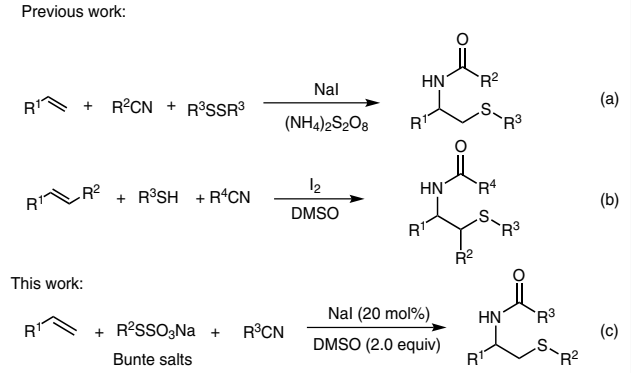


Figure 1 Examples of β-acetamido sulfides

In the last years, the acetamidosulfenylation of alkene has emerged as a direct and efficient protocol for the synthesis of β-acetamido sulfides. Cui[8a] and Zheng,[8b] respectively, described a three-component oxidative acetamidosulfenylation of alkenes in which disulfides and thiols with unpleasant odor served as thiolating reagents (Scheme 1, a and b).

Bunte salts, which can be prepared by the reaction of sodium thiosulfate with various halides, are stable, readily available, and odorless solid compounds.[9] They have been widely applied in the synthesis of organosulfur compounds.[10] In 2014, Reeves reported the synthesis of sulfides via the reaction of Grignard reagent and Bunte salts.[10a] In 2015, Yi's group described thia-Michael addition using



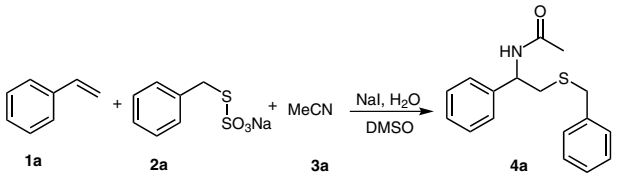
Scheme 1 Methods for acetamidosulfenylation of alkenes

Bunte salts.[10b] Very recently, Luo[10c] and Ji,[10d] respectively, explored the application of Bunte salts as thiolating regents in the synthesis of 3-thioindoles. To the best of our knowledge, Bunte salts have not yet been applied in the sulfenylation reaction of alkenes.

In consideration of the fact that the odorless and stable Bunte salts can be easily converted into disulfides in solvents, we envisioned that they should be better candidates as thiolating sources for the acetamidosulfenylation of alkenes. As a continuation of our project directed toward the C–S bond formation, herein we present a direct and efficient method for the acetamidosulfenylation reaction of alkenes in which NaI was used as a catalyst, DMSO as the oxidant, nitriles as both the solvent and nucleophiles, and Bunte salts as thiolating reagents (Scheme 1, c).

Initially, we conducted the reaction of styrene (**1a**, 0.30 mmol) with sodium *s*-benzyl thiosulfate (**2a**, 0.45 mmol) in the presence of $(NH4)_2S_2O_8$ and iodine in acetonitrile at 80 °C for nine hours (Table 1, entry 1), but no desired product **4a** was observed. It is worth noting that **4a** was detected, respectively, in 56% and 58% yields when iodide salts such as NH_4I and NaI were used instead of iodine in acetonitrile as solvent (Table 1, entries 3 and 4). In order to improve productivity, various oxidants for example $K_2S_2O_8$, TBHP, DTBP, DDQ, and DMSO were then screened, and results indicated that DMSO was the best choice and no reaction took place when TBHP, DTBP, and DDQ were used as oxidants (Scheme 2, entries 5–9). Next, the effect of reaction temperature was explored (Table 1, entries 9–12). It was found that the yield of **4a** was improved to 84% when the reaction temperature was increased to 100 °C (Table1, entry 11). Decreasing the amount of DMSO led to a negative effect and no reaction occurred without DMSO (Table 1, entries 13 and 14). Similarly, the yield of **4a** decreased when reducing the loading of NaI, and the reaction did not take place at all without NaI (Table 1, entries 15 and 16). Thus, the optimized reaction conditions are as follows: alkenes (1.0 equiv), Bunte salts (1.5 equiv), H_2O (2.0 equiv), NaI (20 mol%) as catalyst, DMSO (2.0 equiv) as oxidant, and nitriles as both the solvent and nucleophiles at 100 °C in a sealed tube.

Table 1 Optimization of Reaction Conditions[a]

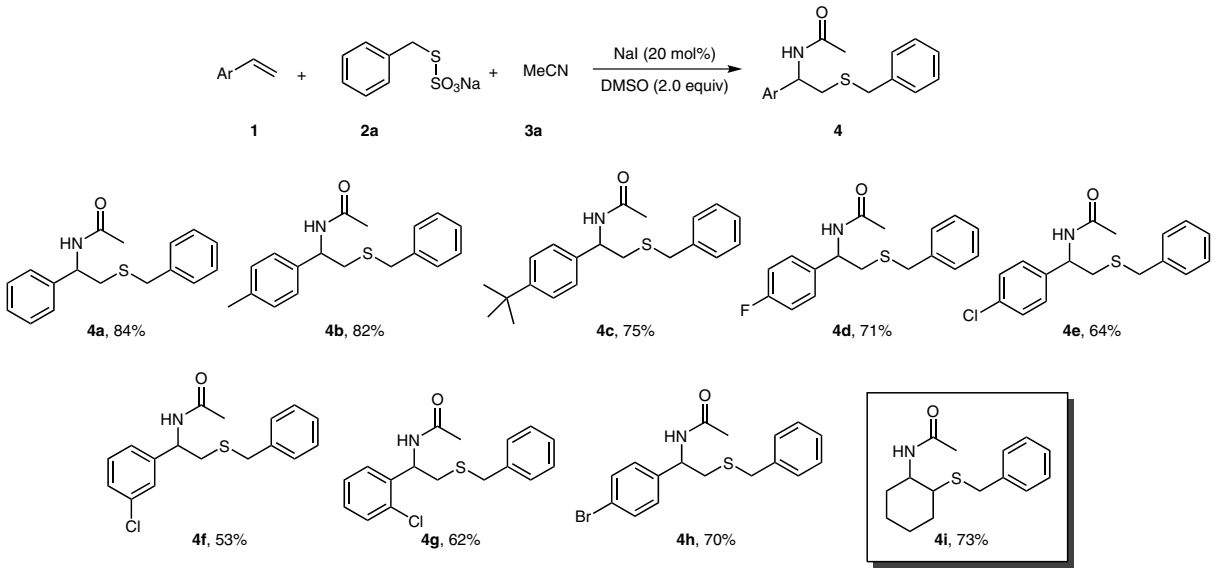


Entry	Iodide (mol%)	Oxidant (equiv)	Temp (°C)	Yield (%)[b]
1	I_2 (20)	$(NH_4)_2S_2O_8$ (2.0)	80	n.r.
2	TBAI (20)	$(NH_4)_2S_2O_8$ (2.0)	80	trace
3	NaI (20)	$(NH_4)_2S_2O_8$ (2.0)	80	58
4	NH_4I (20)	$(NH_4)_2S_2O_8$ (2.0)	80	56
5	NaI (20)	$K_2S_2O_8$ (2.0)	80	41
6	NaI (20)	TBHP(2.0)	80	n.r.
7	NaI (20)	DTBP (2.0)	80	n.r.
8	NaI (20)	DDQ (2.0)	80	n.r.
9	NaI (20)	DMSO (2.0)	80	75
10	I_2 (10)	DMSO (2.0)	80	47
11	NaI (20)	DMSO (2.0)	60	52
12	NaI (20)	DMSO (2.0)	100	84
13	NaI (20)	DMSO (1.0)	100	65
14	NaI (20)	–	100	n.r.
15	NaI (10)	DMSO (2.0)	100	74
16	–	DMSO (2.0)	100	n.r.

[a] Reaction conditions: **1a** (0.30 mmol), **2a** (0.45 mmol), **3a** (1.5 mL), H_2O (0.60 mmol), 9 h in a sealed tube.
[b] Yield of isolated product.

Under the optimized reaction conditions, we investigated the scope and limitation of the reaction of sodium *s*-benzylthiosulfate (**2a**) with various alkene substrates, and the results are listed in Scheme 2. Styrenes having electron-rich groups on the benzene ring such as 4-methyl and 4-*tert*-butyl gave the corresponding target products in good yields(**4b** and **4c**; Scheme 2). The reaction of styrenes possessing electron-withdrawing groups offered the corresponding products in slightly poor 53–71% yields (**4d–h**; Scheme 2). Notably, the reaction of cyclohexene as aliphatic alkene with sodium *s*-benzyl thiosulfate (**2a**) also proceeds well generating **4i** in good yield (**4i**; Scheme 2).

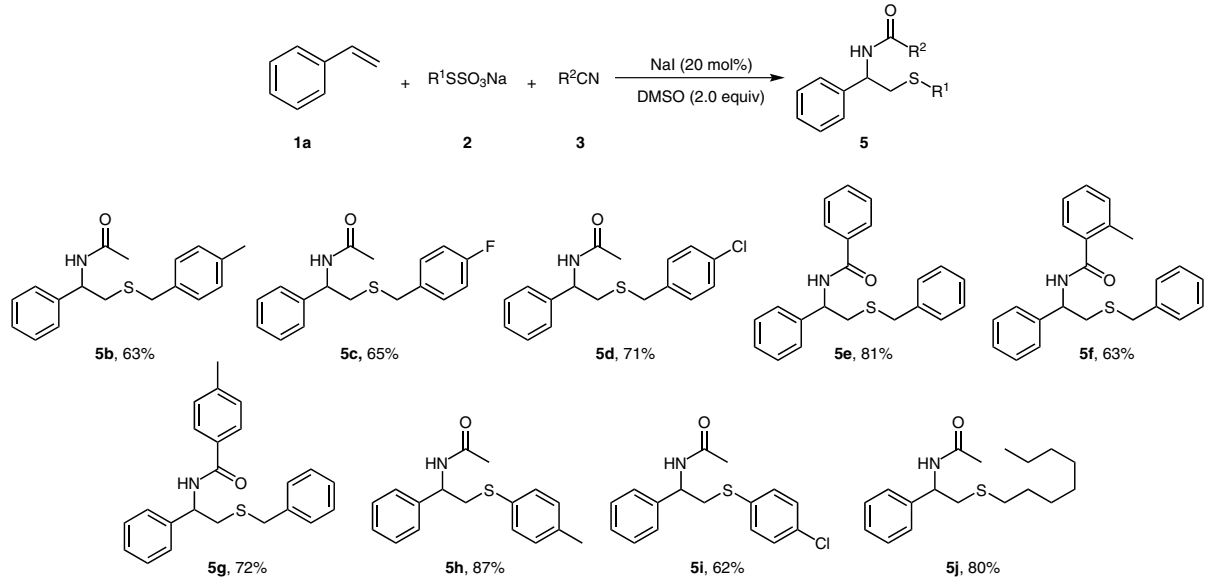
Next, the participation of various Bunte salts and aryl nitriles in this protocol were studied, and the results are shown in Scheme 3. The use of sodium *s*-(4-methyl)benzylthiosulfate and sodium *s*-benzylthiosulfates possessing electron-poor groups on benzene ring resulted in the formation of the corresponding β-acetamido sulfides in moderate yields (**5b–d**; Scheme 3). The yield of products slightly



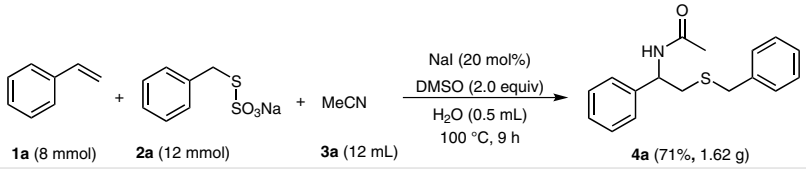
Scheme 2 *Reagents and conditions*: **1** (0.30 mmol), **2a** (0.45 mmol), **3a** (1.5 mL), H_2O (0.60 mmol), NaI (20 mol%), 9 h in a sealed tube. Yields are for the isolated products.

decreased when aryl nitriles as nucleophiles were employed, which probably resulted from steric hindrance especially in the case of **5f** (**5e–g**, Scheme 3). On the other hand, sodium *s*-arylthiosulfate possessing 4-methyl on the benzene ring was used in reaction with good yield (**5h**; Scheme 3), similarly, sodium *s*-(4-chloro)phenylthiosulfate underwent the same acetamidosulfenylation reaction with the formation of **5i** in 62% yield (**5i**; Scheme 3) which may be influenced by electron-poor effect. Moreover, aliphatic Bunte salt can partcipate in the reaction with good yield (**5j**; Scheme 3).

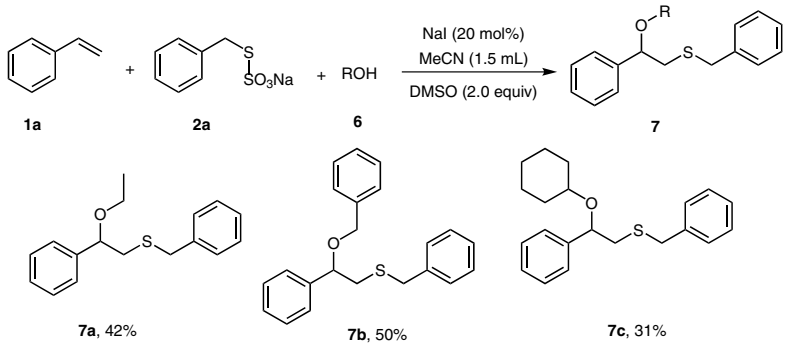
Furthermore, the potential industrial application of this reaction was demonstrated on a gram scale. As shown in Scheme 4, the reaction could afford 1.62 grams of **4a** in 71% yield, demonstrating the potential applications of the reaction for a large-scale synthesis of β-acetamido sulfides.



Scheme 3 *Reagents and conditions*: **1a** (0.30 mmol), **2** (0.45 mmol), **3** (1.5 mL), H_2O (0.60 mmol), NaI (20 mol%), 9 h in a sealed tube. Yields are for the isolated products.



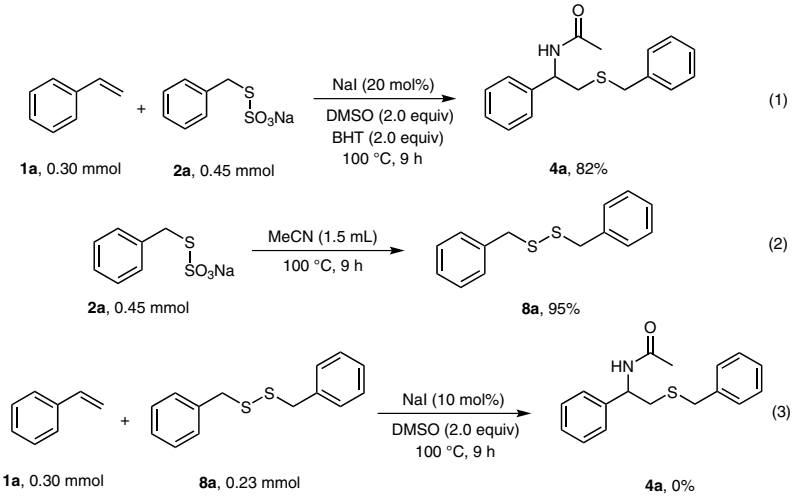
Scheme 4 Gram-scale reaction



Scheme 5 *Reagents and conditions*: **1a** (0.30 mmol), **2** (0.45 mmol), **6** (100 μL), H_2O (0.60 mmol), NaI (20 mol%), 9 h in air. Yields are for the isolated products.

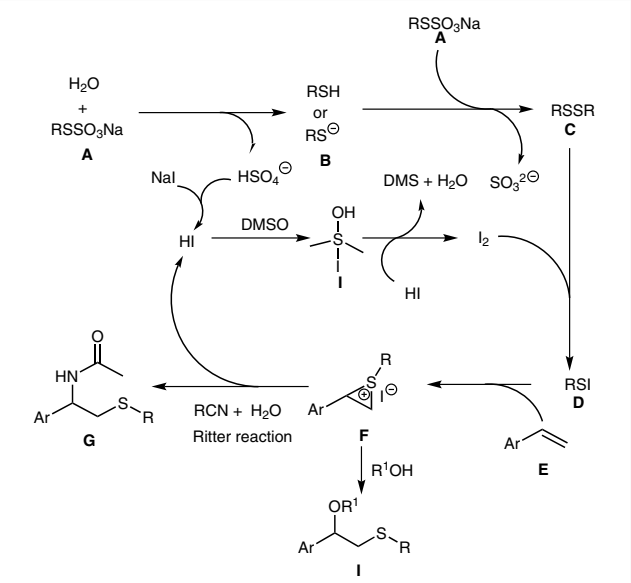
To extend the scope of sulfenylation of alkenes with Bunte salts as thiolating reagent, we tested other nucleophiles. The reactions of sodium *s*-benzyl thiosulfate (**2a**) with styrene (**1a**) and alcohols **6** were carried out, and the results are shown in Scheme 5. The results show that the alkoxysulfenylation of styrene can proceed well although β-alkoxy sulfides were only obtained in moderate yields.

In order to attain further insight into the reaction mechanism, we tried three reactions as contents of control experiments, and the results are outlined in Scheme 4. First, the reaction of **1a** with **2a** in the presence of 2,6-di-*tert*-butylphenol as free-radical inhibitor was not terminated and it still proceeds smoothly (Scheme 6, eq. 1). Sodium *s*-benzyl sulfothioate (**2a**) can be successfully transformed into dibenzyl disulfide (**8a**) in 95% yield under the standard conditions in the absence of NaI and DMSO (Scheme 6, eq. 2). No corresponding products were observed when sodium *s*-benzyl sulfothioate (**2a**) was replaced by dibenzyl disulfide (**8a**, Scheme 6, eq. 3).The above results show that the reaction mechanism of **1a** with **2a** might not be a radical pathway, and the disulfide might be an intermediate.



Scheme 6 Control experiments

On the basis of the reported literatures[8,11–14] and the above results of control experiments, a plausible mechanism is depicted in Scheme 7. Under the heating conditions, the hydrolysis of Bunte salts **A** in the presence of water leads to the formation of species bisulfate anion and thiol or thiol anion **B** in the reaction mixture.[11] The disulfide **C** are thus generated through the attack by thiol or thiol anion **B** on another Bunte salt **A**.[12] Next, the reaction of disulfide **C** with I_2 to gives RSI **D** which is an electrophilic species,[13a] and an intermediate **F** appeared via the attack of alkene **E** by RSI **D**.[8a,13b] The subsequent reaction of the intermediate **F** with nitriles followed by Ritter reaction, alcohol affords β-acetamido sulfides **G**, and β-alkoxy sulfides **I** with the release of HI.[14] Finally, two molecules of HI were oxidized by DMSO and transformed into molecular I_2 accompanied by the formation of water and dimethyl sulfide.[13a,15]



Scheme 7 Plausible reaction mechanism

In summary, a direct and facile method has been developed for the synthesis of β-acetamido sulfides through the acetamidosulfenyation of alkenes in moderate to good yields in which odorless solid Bunte salts were used as thiolating reagents, NaI as a catalyst, DMSO as the mild oxidant, and nitriles as both the solvent and nucleophiles.[16] Furthermore, the reaction can be extended for alcohols substrate leading to the synthesis of β-alkoxy sulfides, respectively.

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Supporting Information

Supporting information for this article is available online at http://dx.doi.org/10.1055/s-0036-1588144.

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(16) **General Procedure for the Synthesis of Compound 4 or 5**

NaI (0.06 mmol), H_2O (0.60 mmol) and Bunte salt **2** (0.45 mmol) were added to a solution of nitrile **3** containing alkene **1** (0.30 mmol), followed by the addition of DMSO (0.60 mmol). The reaction mixture was stirred in a sealed tube at 100 °C for 9 h. After completion of the reaction, the reaction mixture was diluted with EtOAc, and quenched with sat. $Na_2S_2O_3$ solution and extracted with EtOAc (3 × 10 mL). The organic layer was washed with water and dried over anhydrous Na_2SO_4. The solvent was evaporated in vacuo, and the residue was subjected to column chromatography using EtOAc in PE as the eluent to afford the pure target product **4** or **5**.

Compound **4b** was obtained in 82% yield (73.7 mg) according to the general procedure for the synthesis of **4** as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.32–7.23 (m, 5 H), 7.12 (s, 4 H), 6.03 (d, *J* = 8.0 Hz, 1 H), 5.12 (q, *J* = 8.0 Hz, 1 H), 3.59 (q, *J* = 12 Hz, 2 H), 2.86–2.74 (m, 2 H), 2.32 (s, 3 H), 1.95 (s, 3 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 169.5, 138.0, 137.7, 137.4, 129.4, 129.0, 128.5, 127.1, 125.4, 51.8, 37.1, 36.4, 23.4, 21.1. ESI-HRMS: *m/z* calcd for $C_{18}H_{21}NOS$ $[M + Cl]^+$: 334.1027; found: 334.1036.

General Procedure for the Synthesis of Compound 7

NaI (0.06 mmol) and **2a** (0.45 mmol) was added to a solution of acetonitrile **3a** containing styrene **1a** (0.30 mmol) and alcohol (100 µL) or 2-allylphenol **6d** (0.3 mmol), followed by DMSO (0.60 mmol). The reaction mixture was stirred at 90 °C for 6–9 h. After completion of the reaction, the reaction mixture was diluted with EtOAc, quenched with sat. $Na_2S_2O_3$ solution and extracted twice with EtOAc (2 × 15 mL). The organic layer was washed with water and dried over anhydrous Na_2SO_4. The solvent was evaporated in vacuo, and the residue was subjected to column chromatography using EtOAc in PE as the eluent to afford the pure target product **7**.Compound **7a** was obtained in 42% yield (32.7 mg) according to the general procedure for the synthesis of **7** as a colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.37–7.21 (m, 10 H), 4.31 (q, *J* = 8.0 Hz, 1 H), 3.69 (q, *J* = 12.0 Hz, 1 H), 3.42–3.33 (m, 1 H), 2.84 (q, *J* = 8.0 Hz, 1 H), 2.60 (q, *J* = 8.0 Hz, 1 H), 1.20 (t, *J* =8.0 Hz, 3 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 141.6, 138.6, 129.0, 129.4, 128.4, 128.4, 127.8, 126.9, 126.7, 82.3, 64.5, 38.7, 37.2, 15.3. ESI-HRMS: *m/z* calcd for $C_{17}H_{20}OS$ $[M + Na]^+$: 295.1127; found: 295.1120.