Strategies for the direct oxidative esterification of thiols with alcohols

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This review paper provides an overview of the main strategies for the oxidative esterification of thiols with alcohols. The review is divided into two major parts according to final products. The first includes the methods for the synthesis of sulfenic esters, while the second contains the procedures for the fabrication of sulfonic ester derivatives.

1. Introduction

Organosulfur compounds are some of the most versatile building blocks in organic chemistry and occupy a very special place in medicinal, pharmaceutical, and agricultural science.1,2 In this family of compounds, sulfenic and sulfonic esters are of interest due to their biological and therapeutic activities3–4 as well as their application as chemical probes in living cell imaging (Scheme 1).5,6 Furthermore, the title compounds are highly useful synthetic precursors and intermediates in organic synthesis. For example, sulfenic esters were recently applied as efficient sulfenylation agents7 and sulfonic esters as sulfonylating agents.8 The classical methods for the synthesis of these classes of organosulfur compounds involve the reaction of sulf(o,i)nly chlorides,9,10 sulf(o,i)nlic acids,11,12 or sodium sulfonates13 with alcohols. However, corrosion, instability, and/or difficult preparability of some of the sulf(o,i)nlyating agents limited the utility of these methods.

In the light of the above limitations and due to the versatile synthetic and biological activity of the titled compounds, their synthesis from easily accessible basic starting materials under mild conditions is a field of growing research interest. In this context, recently, the direct oxy-esterification of thiols with alcohols has emerged as an ideal atom- and step-economic strategy for the construction of these compounds which makes the synthetic route more quick and clean than conventional pathways that rely on the use of pre-functionalized starting materials. As a continuation of our previous works on modern synthetic methods in organic chemistry14 and novel strategies in the preparation of organosulfur compounds,15 in this review, we will highlight the most important developments on the synthesis of sulfenic and sulfonic esters through the direct oxidative esterification of thiols with alcohols (Fig. 1) with emphasis on the mechanistic features of the reactions, by hoping that it further stimulating research and development of this interesting field. It is noteworthy that, despite wide biological and synthetic importance of sulfenic ester derivative,16–17 to date no reporting guideline exists for their direct construction from the corresponding thiols and alcohols. Therefore, in this review no comment was made regarding the cross-dehydrogenative coupling between thiols and alcohols.

2. Synthesis of sulfenic esters

In this section we would like to focus on the oxidative esterification of thiols with alcohols into sulfenic esters. To aid the reading, the section is divided into three sub-sections according to catalytic systems. The first includes the electrochemical reactions, the second contains the metal-catalyzed reactions, and the third covers metal-free reactions.

2.1. Electrochemical reactions

Electrochemistry provides some of the greenest, cleanest, and more cost-efficient synthetic strategies, as the use of often hazardous or waste-generating chemical reductants or oxidants can be substituted by electrical power.18 In this context, electrochemical oxidative cross-coupling reactions have recently attracted tremendous attention as cleaner and more sustainable synthetic alternative to traditional coupling procedures which rely on the use of external oxidants, catalysts or ligands.19

The first report on the electrochemical oxidative esterification of thiols with alcohols was published by Nokami and co-workers in 1979,20 who showed that the treatment of thiophenol 1 with aliphatic alcohols 2 in an undivided cell with platinum electrodes, employing NaOAc as the supporting electrolyte in acetic acid, resulted in the formation of alky phenylsulfinate 3 in good to excellent yields (Scheme 2a). The
diphenyl disulfide was also examined under the identical conditions and the desired products were obtained in satisfactory yields. However, the excess use of alcohols would be a significant drawback for this protocol and may limit its range of applications. Moreover, in this preliminary work, only one thiol was employed, without any substrate scope exploration. Four decades later, Gong and Lu along with their co-workers developed a robust electrochemical oxidative cross-coupling between thiophenols and aliphatic alcohols for the synthesis of alkyl benzenesulfonates. In an undivided cell assembled with a graphite rod anode and platinum plate cathode, the best reaction conditions were achieved with tetrabutylammonium tetrafluoroborate ($^{+}$Bu$_4$NBF$_4$) as the electrolyte and acetonitrile as the solvent, with a constant current of 12 mA with platinum plates as electrodes supporting electrolyte. The transformation was performed in an undivided cell under a constant current of 6 mA with platinum plates as electrodes employing $^{+}$Bu$_4$NBF$_4$ as the electrolyte and DCM as the solvent under an inert atmosphere, which afforded the sulfonic ester products 9 in 58–90% yields. Noteworthy, the constant current affected the reaction dramatically; either increasing or decreasing the constant current led to decreased efficiency. As shown in Scheme 4 this electrochemical reaction is applicable for not only aromatic and heteroaromatic thiols but also aliphatic thiols. However, like previous works, the scope of alcohols was restricted to the use of aliphatic and benzyl alcohol. Based on the experimental results, the authors suggested that alcohols may act not only as reactants but also as oxidants to oxidize the S(II) to S(IV) species. The isotopic labeling experimental using H$_2$18O indicated that oxygen in sulfur could also come from water.

In 2020, Wei and co-workers reported a closely related electrochemical oxidative cross-coupling reaction of thiols 10 with alcohols 11 employing an undivided cell with platinum electrodes and tetrabutylammonium chloride ($^{+}$Bu$_4$NCl) as the supporting electrolyte. The reaction was conducted in MeCN under ambient conditions and yields of up to 81% were obtained (Scheme 5a). The reaction, however, appears to be limited to aromatic thiols and aliphatic alcohols. The synthetic applicability of the reaction was nicely demonstrated by converting some of the prepared sulfonic esters to thioether, diaryl sulfoxide, trifluoromethyl sulfoxide, and thiosulfonate derivatives. Notably, when the reaction was performed under O$_2$...
atmosphere, sulfonates were obtained instead of the desired sulfinates, however, this transformation proceeded more slowly. In the same year, Yang and Wang along with their co-workers demonstrated the similar esterification under electrochemical and catalyst-free conditions. The transformation was carried out in an undivided cell with platinum plate electrodes at room temperature by using LiClO₄ as the supporting electrolyte, under 10 mA in MeCN. Under these conditions several thiophenol derivatives carrying various substituents (e.g., OMe, F, Cl, Br) on different positions of phenyl rings were converted to the corresponding alkyl phenylsulfonates in moderate to excellent yields by treatment with aliphatic alcohols (Scheme 5b). However, benzyl thiols were inert under the standard conditions and applicability of aliphatic thiols as starting materials was not investigated in this study. Regarding the reactivity of alcohols, primary alcohols were found to be more reactive than the secondary alternatives. The results also proved that the lengths of carbon chain in alcohols had no impact on the outcome of the reaction. Of note, the authors demonstrated the scalability of the reaction since methyl

Scheme 2  (a) Electroxyesterification of thiophenol 1 with aliphatic alcohols 2 to alkyl phenylsulfonates 3; (b) electrochemical synthesis of alkyl benzenesulfonates 6 from thiophenols 4 and alcohols 5.

Scheme 3  Proposed mechanism for electrosynthesis of sulfinic esters 6.
benzenesulfinate could be obtained in 1.43 g scale in high yield of 84%. Based on some control experiments, the O₂ in air proved to be the sole oxygen source.

Concurrently, Kaboudin and co-workers developed an interesting electrochemically enabled nickel-catalyzed methodology for oxidative dehydrogenative coupling between thiols 16 and alcohols 17 under ambient conditions. The efficient combination of Ni(ClO₄)₂, 2,2'-bipyridine and LiClO₄ with a modified graphite anode and nickel foam cathode in an undivided cell, under constant current of 10 mA, provided the sulfinic esters 18 in modest to high yields, ranging from 35% to 92% (Scheme 6). It is noteworthy that the presence of both catalyst and electricity were crucial for the success of this reaction. No transformation was observed without any of them. Concerning the substrate scope, the protocol limited to the use of only (4-methyl)benzenethiols and simple aliphatic alcohols. Based on a series of control experiments and literature, a plausible mechanism was suggested for the formation of sulfinic esters 18, as illustrated in Scheme 7. The reaction starts with the formation of a thiol radical A via anodic oxidation of the starting thiol 16 and Ni(0) by cathodic reduction of the nickel complex. Next, the interaction of the thiol radical A with Ni(0) in the

Scheme 4  Ling–Zhong’s synthesis of sulfinic esters 9.

Scheme 5  (a) Electrochemical oxidative cross-coupling reaction of thiols 10 with alcohols 11 to sulfinic esters 12. (b) Yang–Wang’s synthesis of sulfinic esters 15.
presence of oxygen gives rise to a thiyloxy-Ni(i) complex B. Subsequently, the newly formed complex (or its isomer) undergoes an oxidative addition with alcohol 17 to provide a sulfinate-Ni(III) complex C. Finally, the reductive elimination of this complex C leads to the desired sulfinate ester 18 and regenerates the catalyst.

In the same year, with the aim of designing a metal-free protocol to sulfinic esters through the electrochemical oxidative esterification of thiols and alcohols, Dai and co-workers were able to reveal that a diverse set of functionalized sulfinic esters (27 examples) could be prepared in moderate to excellent yields (up to 92%) from the reaction of corresponding (hetero)aromatic thiols with aliphatic alcohols under mild conditions employing an undivided cell with graphite plates as electrodes. In 2016, Jang’s research group studied the possibility of synthesizing sulfinic esters from the corresponding thiols and alcohols under transition-metal-catalyzed conditions. By considering the coupling of thio-phenol with benzyl alcohol as the model reaction, the reaction variables such as catalysts, ligands, additives, and solvents were carefully screened. The results indicated that the merge of 5 mol% of CuI with 10 mol% of triazabicyclodecene (TBD) was the most appropriate catalytic system for this transformation and among the various common solvents (i.e., toluene, dioxane, THF, DMF, DMSO, MeCN); THF was found to be the most suitable solvent. Under optimum conditions, a library of alkyl/benzyl phenylsulfimates 21 were selectively obtained in modest yields.

2.2. Metal-catalyzed reactions

Drawing inspiration from the pioneering work by Field and co-workers on Pb(OAc)₄-catalyzed one-pot preparation of sulfinic esters from disulfides and alcohols. In 2016, Jang’s research group studied the possibility of synthesizing sulfinic esters from the corresponding thiols and alcohols under transition-metal-catalyzed conditions. By considering the coupling of thio-phenol with benzyl alcohol as the model reaction, the reaction variables such as catalysts, ligands, additives, and solvents were carefully screened. The results indicated that the merge of 5 mol% of CuI with 10 mol% of triazabicyclodecene (TBD) was the most appropriate catalytic system for this transformation and among the various common solvents (i.e., toluene, dioxane, THF, DMF, DMSO, MeCN); THF was found to be the most suitable solvent. Under optimum conditions, a library of alkyl/benzyl phenylsulfimates 21 were selectively obtained in modest yields.
to excellent yields by reaction of various thiophenol derivatives 19 with alkyl/benzyl alcohols 20 under 1 atmosphere of oxygen at 65 °C (Scheme 8). The results indicated that the electron-deficient thiophenols afforded better yields compared to the electron-rich ones and benzylic alcohols gave higher yields than aliphatic alcohols. It should be mentioned that in the case of aliphatic alcohols, the amount of TBD was increased to 1 equivalent. Under the identical conditions, the reactions of aliphatic thiols with benzyl alcohols were also investigated. However, in these cases, benzyl benzoates were obtained instead of the desired sulfonic esters through the oxidation of starting thiols to form the respective thiaoaldehydes, followed by reaction with benzyl alcohols to afford benzyl benzoates via oxidative esterification followed by S–O exchange. Moreover, in this study the authors found some other limitation in their procedure, when they used heteroaromatic thiols (e.g., 2-mercaptobenzimidazole, 2-mercaptopyrimidine, and 4-mercaptopypyridine) as substrates. Unfortunately, in all cases no desired product was observed. Based on the experimental results, a plausible mechanism was proposed by the authors for this esterification protocol which involves the following key steps (Scheme 9): (i) oxidation of thiophenol 19 in the presence of the copper catalyst to generate thyl radical; (ii) formation of thyl-oxo-Cu(II) complex A (or its isomer) via interaction of in situ generated thyl radical with the Cu(i) catalyst; (iii) addition of alcohol 20 to complex A (or A') to give the observed product 21 and Cu(0) species; and (iv) oxidation of Cu(0) with O2 to recover the Cu(i) catalyst and completes the catalytic cycle.

Two years later, Zhang and co-workers introduced ultrafine cobalt nanoparticles supported on N–SiO2-doped activated carbon (Co/N–SiO2-AC) as an efficient catalyst for oxidative esterification of thiols with alcohols.39 Hence, a diverse range of functionalized sulfonic esters 24 were obtained in moderate to excellent yields through the reaction of corresponding thiols 22 with alkyl/benzyl alcohols 23 in the presence of 1.46 mol% Co/N–SiO2-AC as catalyst and 2 equiv. of K2CO3 as a base under O2 atmosphere at 60–80 °C. As shown in Scheme 10, apart from aromatic and heteroaromatic thiols, aliphatic thiols were also compatible with this scenario. The reaction also showed good tolerance to a number of important functional groups such as the methoxy, amino, fluoro, chloro, bromo, trifluoromethyl, and amid functionalities, and promised its potential applications in the post-functionalization of the end product. It is worthwhile to note that in this methodology alcohols not only were served as substrates but also as solvents. The recycling test established that the catalyst could be recovered and reused for six consecutive reaction runs without loss in catalytic performance. After six recycles, the inductively coupled plasma optical emission spectroscopy (ICP-OES) analysis showed negligible decrease of Co content from 1.08 wt% to 1.05 wt%. The mechanism proposed by the authors to explain the formation of sulfonic esters 24 is depicted in Scheme 11.

2.3. Metal-free reactions

In 1997, Xia and Chen published one of the earliest reports of the metal-free oxidative esterification of thiols with alcohols employing inexpensive phenyliodine(III) bis(trifluoroacetate) (PIFA) as an oxidant under neat conditions.39 The reactions were carried out under the open air in the absence of any catalyst or ligand, tolerated both aromatic and benzylic thiols 23 and a small library of aliphatic alcohols 26, and provided the
corresponding sulfinic ester products with yield ranging from 70% to 91% yield (Scheme 12a). However, in this seminal work only four examples with limited scope of the substrates were disclosed and no comment was made regarding the mechanism of the transformation. It is worthwhile to note that sulfinic esters can also be achieved in satisfactory yields when disulfides were employed instead of thiol substrates. Twenty-one years later, a similar principle was used by Qin’s research team to the synthesis of a series of methyl alkylsulfinates from the respective alkyl thiols using N-bromosuccinimide (NBS) as a mediator in the binary solvent MeOH/DCM with ratio 1:1 at room temperature (Scheme 12b). The prepared sulfinic esters were nicely applied as starting materials to the preparation of primary sulfinamides through reaction with LiNH2 or LHMDS.

In 2018, Zhang and Chen along with their co-workers unfolded the tetra-n-butylammonium iodide (TBAI)-mediated oxidative esterification of (hetero)aromatic thiols with tert-
butyl hydroperoxide (TBHP) to synthesize tert-butyl (hetero)aryl sulfinate derivatives 31 under metal-free condition (Scheme 13). The reaction exhibited broad substrate scope and functional group tolerance, irrespective of whether electron-donating (e.g., Me, Et, Pr, Bu, OMe and NH₂) or withdrawing groups (e.g., F, Cl, Br and CF₃) were at different positions of aromatic rings. Moreover, a tolerance for naphthalene-2-thiol (a bicyclic thiol) was also demonstrated. However, aliphatic thiols (e.g., benzylthiol, cyclohexylthiol) were not suitable substrates for this transformation. Unfortunately, the scope and limitation of peroxides were not investigated in this study so that the reaction appears to be limited to only TBHP. It is noteworthy that other iodine sources such as NaI and KI were also effective in this esterification reaction but gave lower yield of products. To gain mechanistic insights, several preliminary experiments were performed and it was confirmed that this reaction most likely proceeds via a radical pathway (Scheme 14). Initially, TBHP undergoes decomposition in the presence of iodides to generate tert-butyl and tert-butylperoxy radicals. Next, homolytic bond breakage of thiols 30 under the oxidative conditions leads to thyl radicals A, which after homocoupling affords disulfides B. Thereafter, tert-butyl radical reacts with disulfides B to yield tert-butyl aryl sulfides C via a radical propagation and regenerate thyl radicals A, which could recombine to disulfides B. Finally, the oxidation of the sulfide intermediates C delivers the desired (hetero)arylsulfinate 31.

Concurrently, Srivastava and co-workers disclosed a metal-free, visible-light-induced aerobic oxyesterification of various aliphatic, aromatic and heteroaromatic thiols 32 with alkyl/benzyl alcohols 33 as both substrates and solvents. No additive was used and only 2 mol% of easily available eosin Y organophotoredox catalyst was enough for preparation of a variety of sulfinic esters 34 in 51–95% yields (Scheme 15). The results indicated that aromatic and heteroaromatic thiols were high yielding compared to aliphatic ones and aliphatic alcohols gave higher yields than benzylcnic ones. Based on some control experiments, the authors suggested a plausible mechanism as shown in Scheme 16. The transformation may start with the formation of excited state of eosin (EY*) via the excitation of eosin (EY) under visible light irradiation, which reacts via a single electron transfer (SET) process with starting thiol 32 to produce thyl radical A. Subsequently, this highly active radical interactions with superoxide anion radical (generated by one-electron reduction of O₂⁻) to form sulfinyl radical B, which after coupling with another molecule of thyl radical A affords sulfinothioate intermediate C. Finally, EY* – promoted nucleophilic substitution of sulfinothioate C by the alcohol 33 affords the expected products 34.

Based on these developments, very recently, Nguyen and co-workers developed a metal-free oxidative esterification reaction of thiols 35 with alcohols 36 using NBS as the mediator and ethyl acetate as the solvent at room temperature (Scheme 17). Although both aromatic and aliphatic thiols were well tolerated under the reaction conditions, the alcohol partners were limited to the use of short-chain alcohols (i.e., MeOH, EtOH, PrOH) as evidenced that butanol totally failed to produce any product under the optimized conditions. Furthermore, under the identical conditions benzyl alcohols were oxidized into benzoic acid. Note that in some cases performing the process under irradiation of ultrasound slightly improved the efficiency of this reaction in the term of product yields within the shorter times.

### 3. Synthesis of sulfinic esters

Compared with the relatively well-developed oxy-esterification of thiols with alcohols for the synthesis of sulfinate esters, the direct fabrication of sulfinic esters from those easily available...
commodity chemicals is still uncommon. In fact, only a handful of reports of such a reaction was published in the literature till date.

One of the earliest reports on this chemistry was published by Bahrami and co-workers in 2012,\textsuperscript{36} who described that the treatment of thiols\textsuperscript{38} with phenol derivatives\textsuperscript{39} in the presence of a combination of Amberlite IRA-400/POCl\textsubscript{3}/H\textsubscript{2}O\textsubscript{2} as the catalytic system resulted in the formation of aryl sulfonic esters\textsuperscript{40} in high to almost quantitative yields within 1–20 h (Scheme 18). The reaction is noteworthy in that various aliphatic, benzylic, and aromatic thiols with either electron-donating or electron-withdrawing substituents were well tolerated. Moreover, the procedure allowed to synthesis of disulfonate esters through double dioxy-esterification reaction of corresponding dithiols. Of note, besides alcohols, amines also could be applied as nucleophiles under the identical conditions to form biologically valuable sulfonamide derivatives. Interestingly, a competition experiment using phenol and aniline revealed that phenol reacted preferentially and aniline remained untouched. Similarly, sulfonylation of 4-aminophenol produced the respective sulfonate ester with free NH\textsubscript{2} moiety. Regarding the plausible mechanistic pathway of this transformation, after NMR spectroscopy investigations, it was confirmed that the reaction most likely proceeds via a sulfonyl chloride intermediate.

In 2013, Hemmati and co-workers developed a two-step one-pot method for the preparation of sulfonic ester derivatives\textsuperscript{43} from the respective thiols\textsuperscript{41} and alcohols\textsuperscript{42} through oxidative chlorination of thiols to sulfonyl chlorides in the presence of trichloroisocyanuric acid (TCCA), tetrabutylammonium chloride (\textsuperscript{1}Bu\textsubscript{4}NCl), and water followed by reaction with alcohols under basic conditions (Scheme 19a).\textsuperscript{37} Although either aromatic and aliphatic derivatives of both starting materials exhibited good applications under standard conditions and provided the desired products in high to excellent yields, the toxicity of TCCA might limit the application profile of this synthetic strategy. Noteworthy, when disulfides were subjected...
to the reaction in place of thiols, the same set of sulfonic ester products were obtained in close yields. According to the authors proposed mechanism (Scheme 20), the oxygen atom of products originated from water. Another independent one-pot two-step method was published by Veisi and co-workers using Chloramin-T as a chlorinating agent under the same conditions (Scheme 19b). The employed substrates in this work are the same as the ones reported by Hemmati–Mojtahedi group and the product yields are almost similar.

Following these works, Lei and co-workers disclosed an interesting photoinduced oxidative cross-coupling of thio phenols with aliphatic alcohols using 9-mesityl-10-

Scheme 20  The plausible mechanism for the reactions in Scheme 19a.
methylacridinium ion (Acr\(^+\)-Mes) as a photocatalyst under metal-free conditions at room temperature.\(^{39}\) The reactions proceed under O\(_2\) atmosphere and blue light irradiation providing the alkyl benzenesulfonate compounds 46 in moderate to good yields, ranging from 45% to 70% yield (Scheme 21). Either primary or secondary alcohol substrates were successfully reacted in this system. However, tertiary alcohols failed to produce any product under the conditions employed. Moreover, the scope of thiophenols appears to be restricted to electron-rich ones. To gain mechanistic insights, several preliminary experiments were performed. No products were obtained in the lack of light, photocatalyst, or oxygen. The possibility of a radical pathway was confirmed since the reaction with TEMPO completely prevent the product formation. Furthermore, an isotope labelling experiment with \(^{18}\)O\(_2\) indicated that the oxygen atoms of S=O bonds originated from the dioxygen. Based on the above results, the authors speculated that the reaction starts with the formation of Acr\(^+\)-Mes\(^{++}\) by intramolecular photoinduced electron transfer from the mesitylene moiety to the singlet excited state of the Acr\(^+\) moiety of the catalyst. Subsequently, the Mes\(^{++}\) moiety oxidizes the thiophenol 44 to form the radical cation A, whereas the Acr\(^+\) moiety reduces O\(_2\) to O\(_2\)\(^{--}\). Next, deprotonation of the radical cation A provides the corresponding thiol radical B, which undergoes homocoupling to yield a disulfide intermediate C. Thereafter, the newly formed intermediate undergoes a further one-electron oxidation to form a disulfide radical cation D that, after oxidation affords the thiopersulfinate E. Later, nucleophilic attack of the alcohol 45 on the sulfur atom of E leads to the intermediate F, which then undergoes photooxidative

Scheme 21  Photoinduced oxidative cross-coupling between thiophenols 44 and aliphatic alcohols 45.

Scheme 22  Mechanistic proposal for the formation of alkyl benzenesulfonates 46.
fragmentation to yield alkyl benzenesulfinate G and benzene-sulfonic acid H. Finally, further oxidation of benzenesulfinate G results in the formation of the expected benzenesulfonate product 46 (Scheme 22).

Recently, in the same paper describing the electrochemical oxidative esterification of thiophenols and alcohols to sulfinic esters employing an undivided cell with platinum electrodes, the group of Xu-Wei reported the successful electrocatalyzed preparation of sulfonic esters 49 through the reaction between 4-methoxybenzenethiol 47 and aliphatic alcohols 48 under O₂ atmosphere (Scheme 23). Although only two low yields examples were disclosed, this paper represents the first example of electrocatalyzed direct dioxy-esterification of thiols. As indicated in previous section, when this reaction was performed in open air the corresponding sulfinic esters were obtained as the sole products. Therefore, of course, O₂ has the key role in the further oxidation of sulfur atom. 40–47

4. Conclusion

Sulfinic and sulfonic esters, two major kinds of organosulfur compounds containing S=O bonds, have drawn a lot of interest in diverse fields due to their crucial applications in organic synthesis, medicinal chemistry, and cell imaging. Therefore, it is always desirable to develop facile and efficient approaches to the synthesis of these special classes of organosulfur compounds from inexpensive starting materials. As summarized in this review, recently direct oxidative esterification of thiols with alcohols has emerged as an atom-efficient new strategy for the one-pot synthesis of sulfinic and sulfonic esters which beside avoids time and cost consuming prefunctionalization steps merits from low-cost easily accessible starting materials. Nevertheless, despite these advances, there are still many unsolved problems and challenges that need to be addressed. Some of these are listed below: (i) the scope of alcohols was mainly limited to aliphatic and benzylic alcohols. Therefore, of course, further research is needed to develop of efficient procedures that are compatible with phenol derivatives; (ii) the synthesis of sulfenic esters via cross-dehydrogenative coupling of thiols and alcohols has not been explored thus far. Thus, the development of efficient methods for the direct construction of sulfenic ester derivatives from thiols and alcohols would be highly desirable; and (iii) the number of reported examples on the fabrication of sulfonic esters are narrow and there is an urgent need to study the scope and limitations of this page of sulfonic ester synthesis.

Conflicts of interest

There are no conflicts to declare.

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