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Paper

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Pivalic anhydride mediated esterification of phenols with carboxylic acids through sodium thiosulfate catalysis

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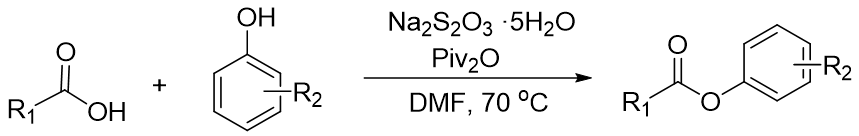
Received 10-20-2024 **Accepted Manuscript** 01-08-2025 **Published on line** 02-03-2025

Abstract

An improved method for the generation of acyl-Bunte salts has been developed by the reaction of carboxylic acids with sodium thiosulfate pentahydrate in the presence of inexpensive and easy to handle pivalic anhydride, which offers a simple and efficient pathway to generate phenolic esters from carboxylic acids and electron-rich phenols.



R_1 = (hetero)aryl, alkenyl
R_2 = methyl, methoxyl, halogen, Acyl

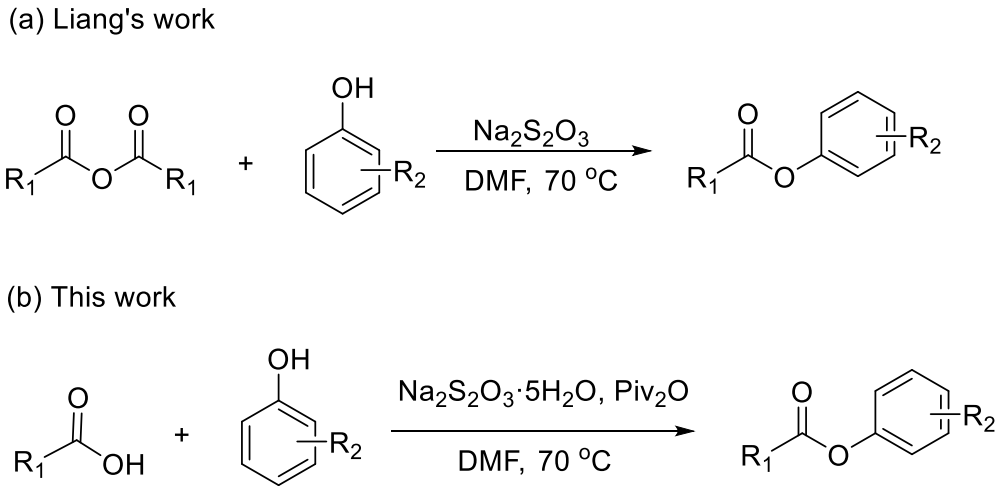
20 examples
50-94% yields

Keywords: Pivalic anhydride, sodium thiosulfate pentahydrate, esterification, phenolic esters

Introduction

Phenolic esters are a versatile class of carboxylic acid derivatives that have found broad applications in medicinal chemistry[1-2] and material science.[3-4] Although various transition-metal catalyzed process have been developed,[5-7] the most convenient and straightforward method for the preparation of phenolic esters is esterification of phenols. As phenol is generally less nucleophilic than alcohols, the esterification of phenols often requires more reactive anhydride[8-11], acyl halide[12-15] and diacyl disulfide[16-17] instead of carboxylic acids. To simplify the process, a variety of in situ activation method using carboxylic acids have also been developed over the years. However, the activation reagents, such as trifluoroacetic anhydride (TFAA),[18-19] 2-chloro-1-methylpyridinium iodide,[20] BOP,[21] DCC,[22] PPE,[23] N,N-bis(2-oxo-3-oxazolidinyl) phosphordiamidic chloride,[24] CCl_4/PPh_3,[25] diphenyl(1,2-benzisoxazol-3-yl)phosphate,[26] Me_2NSO_2Cl,[27] montmorillonite-Ti^{4+},[28] metal triflates in [bmim]PF_6,[29] $Mn(OAc)_3$,[30] $TiO(acac)_2$,[31] diarylammonium arensulfonate ,[32] were generally expensive, harmful or difficult-to-handle. Therefore, a simple process for the esterification of phenols with carboxylic acids remains highly desirable.

Recently, the Liang group reported that acyl-Bunte salts, generated via the reaction of symmetric anhydrides with sodium thiosulfate, could be nucleophilic attacked by phenols to form phenolic esters (Scheme 1a).[33] With the insight gained from this strategy, we questioned whether it would be possible to generate acyl-Bunte salts using carboxylic acids instead of symmetric anhydrides. We recognized that inexpensive and easy to handle pivalic anhydride might be a suitable activating agent as we have reported that the in situ generated pivaloyl mixed anhydride could undergo regioselective amidation by N-alkyl anilines.[34] Herein, we detail the successful execution of this idea and present a simple and practical sodium thiosulfate pentahydrate catalyzed esterification of phenols with carboxylic acids in the presence of pivalic anhydride (Scheme 1b). Compared with Liang group's work,[33] the formation of anhydride prior to effecting the esterification is unnecessary. The byproduct is nontoxic pivalic acid which could be removed by simple basic workup.

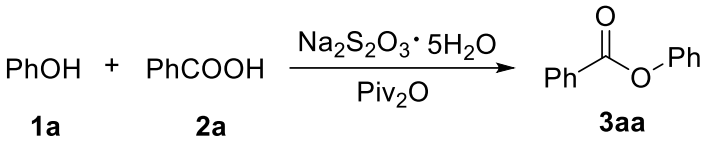


Scheme 1. Approaches for Phenolic ester formation.

Results and Discussion

To test the feasibility of our envisaged plan, we selected phenol (**1a**) and benzoic acid (**2a**) as model substrate to react with Piv_2O and sodium thiosulfate pentahydrate (Table 1). After optimization of solvents, stoichiometric ratio and temperature, the reaction was found to be the most effective when 1.3 equivalents of benzoic acid (**2a**), **2** equivalent of Piv_2O, and 30 mol % of sodium thiosulfate pentahydrate were used in DMF at 70 ℃ (Table 1, entry 7). In these conditions, the phenolic ester **3aa** was obtained in 77% yield.

Table 1. Optimization of reaction conditions [a,b]

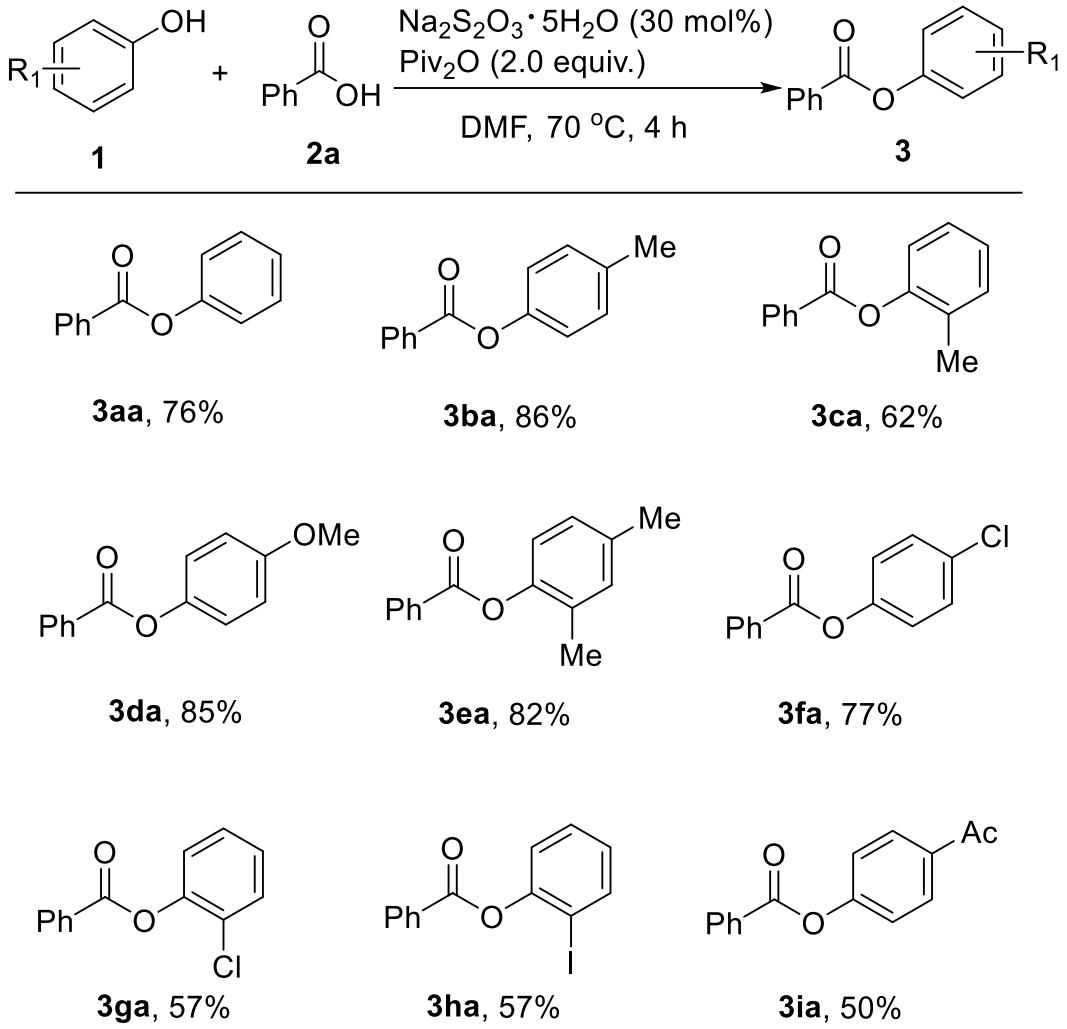


1a **2a** **3aa**

Entry	Solvent	Temp/°C	Yield/%[b]
1	Toluene	70	42
2	MeCN	70	37
3	DCM	70	47
4	EtOAc	70	32
5	THF	70	36
6	DMF	70	72
7[c]	DMF	70	77
8[c]	DMF	60	69
9[c]	DMF	80	58

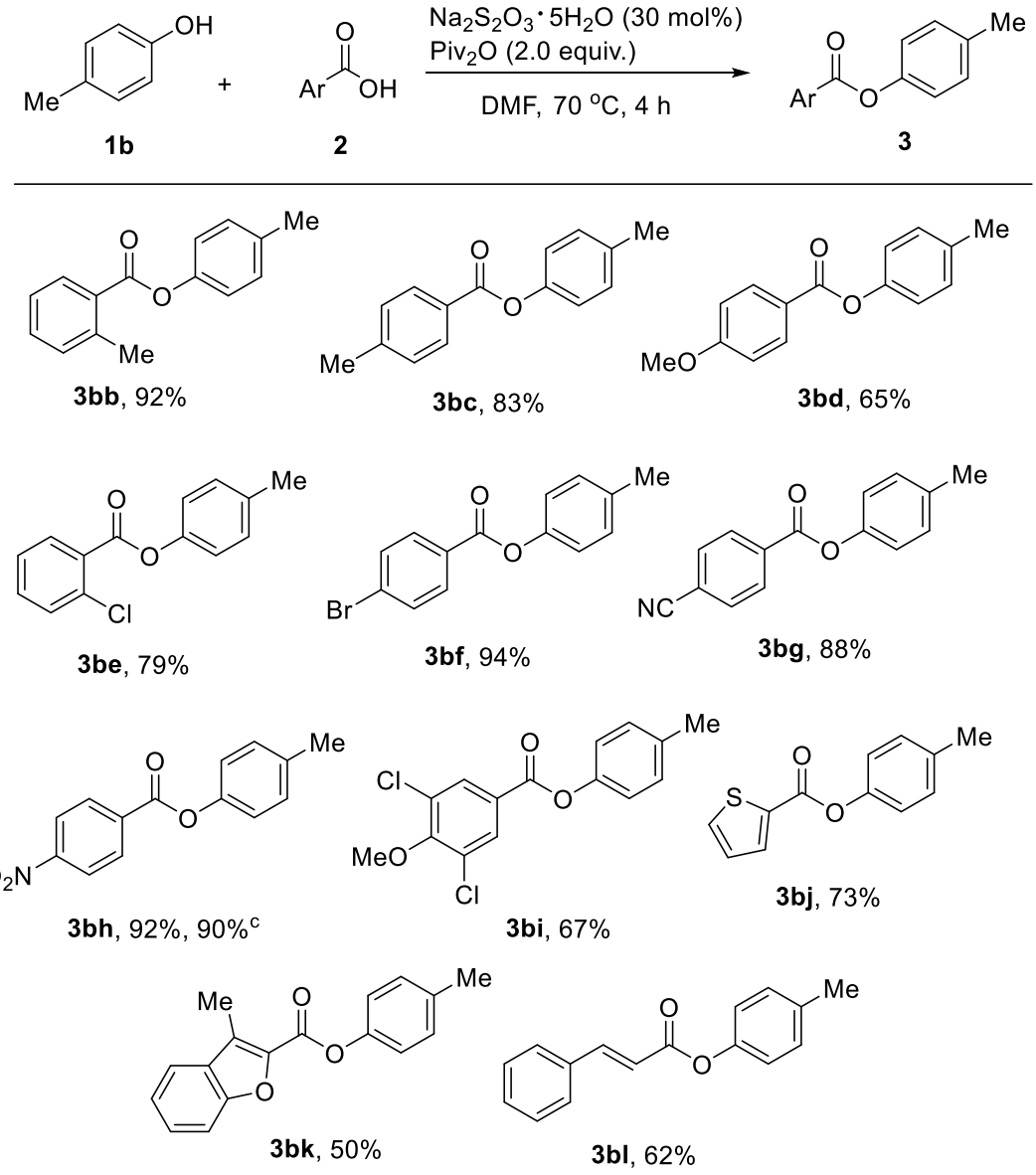
[a] Reaction conditions: 1a (1.0 mmol, 1.0 equiv.), 2a (1.1 mmol, 1.1 equiv.), Piv_2O (1.3 mmol, 1.3 equiv.) and $Na_2S_2O_3$ (0.3 mmol, 0.3 equiv.) in 2.0 mL solvent at 70 ℃ for 4 h. [b] Isolated yield. [c] 1a: 2a: Piv_2O=1:1.3:2.

With the optimized reaction conditions in hand, we then explored the scope and the limitations of the reaction (Scheme 2). For phenols, both electron-donating groups such as methyl **3ba**，**3ca**，**3ea**, and methoxyl and electron-withdrawing halogen group were well compatible, providing the esters in 57–86% yields **3ba–3oa**. When the position of the substituents was shifted from para to ortho, we observed a decrease in the yield of the products **3ca, 3ga**, indicating that the coupling is sensitive to steric hindrance. Additionally, the reaction was less effective for phenols with strong electron-withdrawing groups, such as acyl group (**3ia**), due to its weaker nucleophilicity. It is noteworthy that, in addition to the expected product, the above reaction also produced a small amount of pivalate ester formed directly by the reaction of phenol with pivalic anhydride. For weak nucleophilic 4-acetylphenol, 4-acetylphenyl pivalate was isolated as the byproduct in 45% yield.



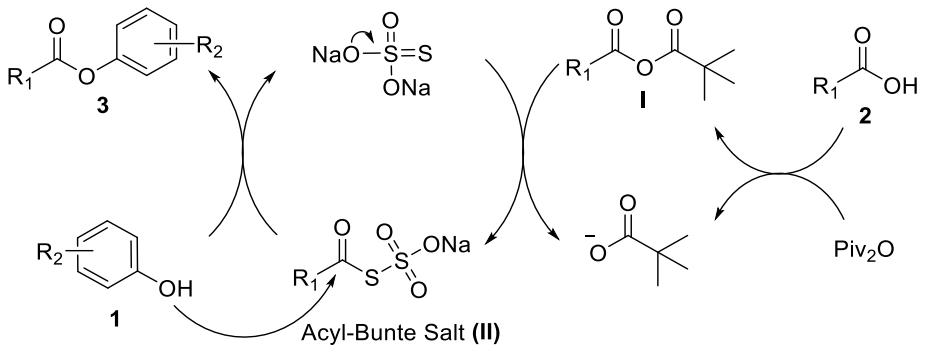
Scheme 2. Scope of the phenols. [a] Reaction conditions: 1(1 mmol, 1 equiv.), 2a (1.3 mmol, 1.3 equiv.), $Na_2S_2O_3·5H_2O$ (0.3 mmol, 30 mol %) and Piv_2O (2.0mmol, 2.0 equiv.) in 2 mL DMF at 70 °C for 4 h. [b] Isolated yield.

Next, the substrate scope of the reaction with respect to carboxylic acid substrates was explored. As shown in Scheme 3, the benzoic acids containing methyl **3bb-3bc**, methoxy **3bd**, halogen **3be-3bf** and strong electron-withdrawing cyanide **3bg**, nitro **3bh** groups have good tolerance to the system and corresponding phenolic ester products have been synthesized with moderate to excellent yields. Gram-scale preparation of 3bh proceeded in 90% yield, testifying to the robustness and synthetic potential of this method. Generally, carboxylic acids bearing strong electron-withdrawing groups were more effective, due to the stronger nucleophilicity of the carbonyl groups of the resulted pivaloyl mixed anhydride intermediates. In addition, heterocyclic carboxylic acids, such as thiophene **3cj** and benzofuran **3ck**, were proved to be feasible coupling partners, providing the corresponding esters in 50-73% yields **3pa-3ra**. Besides aromatic acids, cinnamic acid was also found to be viable substrate, providing the corresponding phenolic ester **3cl** in 62% yield.



Scheme 3. Scope of the carboxylic acids [a] Reaction conditions: 1b (1 mmol, 1 equiv.), 2 (1.3 mmol, 1.3 equiv.), $Na_2S_2O_3·5H_2O$ (0.3 mmol, 30 mol %) and Piv_2O (2.0mmol, 2.0 equiv.) in 2 mL DMF at 70 ℃ for 4 h. [b] Isolated yield. [c] Gram scale.

From the above experimental results and previous reports,**21-22** a plausible mechanism is proposed (Scheme 4). Frist, carboxylic acid **2** was in situ activated by Piv_2O to produce the pivaloyl mixed anhydride (I),[34] which then reacted with sodium thiosulfate pentahydrate to produce Acyl-Bunte salt (II).[33] Finally, the nucleophilic attack of phenols **1** to acyl-Bunte salt (II) to form phenolic esters **3** and regenerate sodium thiosulfate.



Scheme 4. Proposed mechanism.

Conclusions

In conclusion, we have developed a simple and efficient method for the synthesis of phenolic esters via esterification of phenols with carboxylic acids. The reactions are conducted using inexpensive and easy to handle pivalic anhydride and sodium thiosulfate pentahydrate and found to be compatible with a range of carboxylic acids and electron-rich phenols.

Experimental Section

General. Unless stated otherwise, all reactions were carried out under an air atmosphere. All commercial reagents were used without additional purification. Flash chromatography was carried out with silica gel (200−300 mesh). 1H NMR and 13C NMR spectra were recorded with 400 MHz and 101 MHz spectrometers in $CDCl_3$ by using tetramethylsilane (TMS) as the internal standard, respectively. High-resolution mass spectra (HRMS) were recorded using a positive-ion electrospray ionization (ESI+) source.

Experimental procedures and characterization of products. An 8 mL reaction flask was charged with phenols (1.0 mmol), carboxylic acid (1.3 mmol), sodium thiosulfate pentahydrate (0.3 mmol, 74.4 mg) in 2.0 mL of DMF at r.t. under an air atmosphere. Then, pivalic anhydride (2.0 mmol, 372.5 mg) was added and reacted in an air atmosphere at 70 ℃ for 4 h. At the end of the reaction, 30 mL of water was added and extracted with ethyl acetate (20 mL) for three times, and the organic phase was combined. The combined organic layers were washed with 2 M sodium hydroxide solution and brine, dried over Na_2SO_4, filtered, and concentrated in vacuum. The residue was purified by column chromatography on silica gel to give the products **3**.

Benzoic acid phenyl ester (3aa). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1a** (94.1 mg, 1.0 mmol) gives **3aa** as a white solid (150.6 mg, 76%); melting point: 65-68 ℃(lit.mp 71-72 ℃)[35]; R_f = 0.43 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.21 (d, *J* 6.9 Hz, 2H), 7.62 (t, *J* 7.4 Hz, 1H), 7.50 (t, *J* 7.7 Hz, 2H), 7.45-7.39 (m, 2H), 7.29-7.24 (m, 1H), 7.23-7.19 (m, 2H). ^{1}H NMR is consistent with the literature precedent.[33]

Benzoic acid 4-methylphenyl ester (3ba). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1c** (108.1 mg, 1.0 mmol) gives **3ba** as a white solid (139.9 mg, 66%); melting point: 68-70 ℃(lit.mp 72 ℃)[36]; R_f = 0.66 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.20 (dd, *J* 1.4, 8.4 Hz, 2H), 7.67-7.58 (m, 1H),

7.50 (t, *J* 7.6 Hz, 2H), 7.22 (d, *J* 8.0 Hz, 2H), 7.13-7.04 (m, 2H), 2.37 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[37]

Benzoic acid 2-methylphenyl ester(3ca). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3ca** as a light yellow liquid (132.2 mg, 62%); melting point:60-61 ℃(lit.mp 62-64 ℃)[38]; R_f = 0.63 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.23 (dd, *J* 1.4, 8.3 Hz, 2H), 7.63 (t, *J* 7.4 Hz, 1H), 7.51 (t, *J* 7.7 Hz, 2H), 7.30-7.22 (m, 2H), 7.19 (dd, *J* 1.4, 7.4 Hz, 1H), 7.14 (d, J 7.8 Hz, 1H), 2.23 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[33]

4-methoxyphenyl benzoate(3da). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1d** (124.1 mg, 1.0 mmol) gives **3da** as a white solid (193.9 mg, 85%); melting point: 82-84 ℃(lit.mp 87-88 ℃)[31]; R_f = 0.47 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.24-8.16 (m, 2H), 7.62 (t, *J* 7.4 Hz, 1H), 7.50 (t, *J* 7.7 Hz, 2H), 7.16-7.10 (m, 2H), 6.96-6.92 (m, 2H), 3.81 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[39]

Phenol-2,4-dimethyl-1-benzoate(3ea). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1e** (122.2 mg, 1.0 mmol) gives **3ea** as a colorless transparent liquid (185.1 mg, 82%); R_f = 0.59 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.22 (d, *J* 6.9 Hz, 2H), 7.62 (t, *J* 7.4 Hz, 1H), 7.50 (t, *J* 7.8 Hz, 2H), 7.07 (s, 1H), 7.04-6.98 (m, 2H), 2.33 (s, 3H), 2.19 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[35]

Benzoic acid 4-chlorophenyl ester(3fa). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1f** (128.6 mg, 1.0 mmol) gives **3fa** as a white solid (178.1 mg, 77%); melting point: 82-85 °C(lit.mp 85-87 ℃)[40]; R_f = 0.53 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.18 (dd, *J* 1.4, 8.4 Hz, 2H), 7.64 (t, *J* 7.5 Hz, 1H), 7.50 (t, *J* 7.8 Hz, 2H), 7.38 (d, *J* 8.8 Hz, 2H), 7.16 (d, *J* 8.8 Hz, 2H). ^{1}H NMR is consistent with the literature precedent.[41]

Benzoic acid 2-chlorophenyl ester(3ga). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1g** (128.6 mg, 1.0 mmol) gives **3ga** as a colorless transparent liquid (133.0 mg, 57%);melting point: 64-67 °C(lit.mp 66-67.5 ℃)[41]; R_f = 0.50 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.28-8.21 (m, 2H), 7.69-7.63 (m, 1H), 7.57-7.47 (m, 3H), 7.33 (dd, *J* 1.5, 7.1 Hz, 1H), 7.28 (dd, *J* 1.8, 8.1 Hz, 1H), 7.25-7.21 (m, 1H). ^{1}H NMR is consistent with the literature precedent.[41]

Benzoic acid 2-iodophenyl ester(3ha). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1h** (220.0 mg, 1.0 mmol) gives **3ha** as a light yellow liquid (183.2 mg, 57%); melting point: 58-59 °C(lit.mp 60-61 ℃)[42]; R_f = 0.50 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.30-8.24 (m, 2H), 7.86 (dd, J 1.5, 7.9 Hz, 1H), 7.64 (t, *J* 7.4 Hz, 1H), 7.52 (t, *J* 7.7 Hz, 2H), 7.43-7.37 (m, 1H), 7.24 (dd, *J* 1.6, 8.3 Hz, 1H), 7.00 (td, J 1.5, 7.6 Hz, 1H). ^{1}H NMR is consistent with the literature precedent.[43]

Benzoic acid 2-iodophenyl ester(3ia). The reaction of **2a** (158.8 mg, 1.3 mmol) and **1h** (220.0 mg, 1.0 mmol) gives **3ia** as a white solid (156.2 mg, 50%); melting point: 130-132 ℃(lit.mp 132-134 ℃)[44]; R_f = 0.50 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.21 (d, *J* 7.8 Hz, 2H), 8.05 (d, *J* 8.7 Hz, 2H), 7.66 (t, *J* 7.4 Hz, 1H), 7.53 (t, *J* 7.7 Hz, 2H), 7.34 (d, *J*.8.7 Hz, 2H), 2.63 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[33]

Benzoic acid 2-methyl-4-methylphenyl ester(3bb). The reaction of **2b** (177.0 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3bb** as a colorless transparent liquid (207.8 mg, 92%); R_f = 0.74 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.14 (d, *J* 7.2 Hz, 1H), 7.44 (t, *J* 6.8 Hz, 1H), 7.30 (d, *J* 8.2 Hz, 2H), 7.20 (d, *J* 8.2 Hz, 2H), 7.08 (d, *J* 8.1 Hz, 2H), 2.66 (s, 3H), 2.35 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[33]

Benzoic acid 4-methyl-4-methylphenyl ester(3bc). The reaction of **2c** (177.0 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3bc** as a white crystals (187.7 mg, 83%); melting point: 86-88 ℃(lit.mp 89-89.5 ℃)[45]; R_f = 0.67 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.08 (d, *J* 8.2 Hz, 2H), 7.29 (d, *J* 8.0

Hz, 2H), 7.21 (d, *J* 8.2 Hz, 2H), 7.08 (d, *J* 8.5 Hz, 2H), 2.43 (s, 3H), 2.36 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[33]

Benzoic acid 4-methoxy-4-methylphenyl ester(3bd). The reaction of **2d** (197.8 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3bd** as a white crystals (156.8 mg, 65%); melting point: 62-65 ℃(lit.mp 66-68 ℃)[46]; R_f = 0.56 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.15 (d, *J* 8.7 Hz, 2H), 7.21 (d, *J* 8.1 Hz, 2H), 7.08 (d, *J* 8.3 Hz, 2H), 6.97 (d, *J* 8.8 Hz, 2H), 3.88 (s, 3H), 2.36 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[33]

Benzoic acid 2-chloro-4-methylphenyl ester(3be) The reaction of **2e** (203.5 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3be** as a light yellow viscous liquid (194.4 mg, 79%);melting point: 61-64 ℃(lit.mp 67-69 ℃)[47]; R_f = 0.63 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.01 (d, *J* 7.8 Hz, 1H), 7.52-7.42 (m, 2H), 7.39-7.33 (m, 1H), 7.21 (d, *J* 8.2 Hz, 2H), 7.14 (d, *J* 8.4 Hz, 2H), 2.36 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[33]

Benzoic acid 4-bromo-4-methylphenyl ester(3bf). The reaction of **2f** (261.3 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3bf** as a white crystals (274.6 mg, 94%); melting point: 112-115 ℃(lit.mp 118-119 ℃)[48]; R_f = 0.67 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.05 (d, *J* 8.6 Hz, 2H), 7.64 (d, *J* 8.5 Hz, 2H), 7.22 (d, *J* 8.2 Hz, 2H), 7.08 (d, *J* 8.4 Hz, 2H), 2.37 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[48]

Benzoic acid 4-cyano-4-methylphenyl ester(3bg). The reaction of **2g** (191.3 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3bg** as a white crystals (208.4 mg, 88%); melting point: 86-90 ℃; R_f = 0.52 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.30 (d, *J* 8.2 Hz, 2H), 7.81 (d, *J* 8.2 Hz, 2H), 7.24 (d, *J* 8.2 Hz, 2H), 7.09 (d, *J* 8.4 Hz, 2H), 2.38 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[49]

Benzoic acid 4-nitro-4-methylphenyl ester(3bh). The reaction of **2h** (217.3 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3bh** as a white solid (237.1 mg, 92%); melting point: 93-96 ℃(lit.mp 98-99 ℃)[45]; R_f = 0.57 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.41-8.33 (m, 4H), 7.24 (d, *J* 8.2 Hz, 2H), 7.11 (d, *J* 8.5 Hz, 2H), 2.39 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[50]

***p*-Tolyl 3,5-dichloro-4-methoxybenzoate(3bi).** The reaction of **2i** (287.4 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives 3bl as a white solid (209.1 mg, 67%); melting point: 62-66 ℃; R_f = 0.52 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 8.13 (s, 2H), 7.22 (d, *J* 8.2 Hz, 2H), 7.06 (d, *J* 8.5 Hz, 2H), 3.98 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-d) δ 163.0, 156.6, 148.4, 136.0, 130.8, 130.1, 129.8, 126.8, 121.2, 61.0, 20.9. HRMS (ESI) *m/z* calcd for $C_{15}H_{13}Cl_2O_3^+$ $(M+H)^+$ 311.0263, found 311.0260.

3-Thiophenecarboxylic acid 4-methylphenyl ester(3bj). The reaction of **2j** (166.6 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3bj** as a white crystals (159.5 mg, 73%); melting point: 78-83 ℃; R_f = 0.41 (petroleum ether/ethyl acetate 20: 1); 1H NMR (400 MHz, Chloroform-d) δ 8.29 (dd, *J* 1.2, 3.1 Hz, 1H), 7.65 (dd, *J* 1.2, 5.1 Hz, 1H), 7.36 (m, 1H), 7.20 (d, *J* 7.9 Hz, 2H), 7.07 (d, *J* 8.5 Hz, 2H), 2.36 (s, 3H). 13C NMR (101 MHz, Chloroform-d) δ 161.3, 148.5, 135.6, 134.0, 130.0, 128.3, 126.4, 121.4, 27.2, 21.0. HRMS (ESI) *m/z* calcd for $C_{12}H_{11}O_2S^+$ $(M+H)^+$ 219.0474, found 219.0475.

2-Benzofurancarboxylic acid 3-methyl-4-methylphenyl ester(3bk). The reaction of **2k** (229.0 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3bk** as a white solid (132.4 mg, 50%); melting point: 78-82 ℃; R_f = 0.37 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 7.66 (d, *J* 7.8 Hz, 1H), 7.58 (d, *J* 8.4 Hz, 1H), 7.51-7.45 (m, 1H), 7.32 (t, *J* 7.5 Hz, 1H), 7.23 (d, *J* 8.3 Hz, 2H), 7.14 (d, *J* 8.6 Hz, 2H), 2.65 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-d) δ 159.10, 154.72, 147.97, 140.22, 135.87, 130.09, 129.05, 128.30, 127.61, 123.36, 121.44, 112.36, 27.18, 20.96, 9.63. HRMS (ESI) *m/z* calcd for $C_{17}H_{15}O_3^+$ $(M+H)^+$ 267.1016, found 267.1014.

2-Propenoic acid 3-phenyl-4-methylphenyl ester(3bl). The reaction of **2i** (192.6 mg, 1.3 mmol) and **1b** (108.1 mg, 1.0 mmol) gives **3ci** as a white solid (147.0 mg, 62%); melting point: 93-95 ℃(lit.mp 96-97 ℃)[51]; R_f = 0.33 (petroleum ether/ethyl acetate 20: 1); ^{1}H NMR (400 MHz, Chloroform-d) δ 7.86 (d, *J* 16.0 Hz, 1H), 7.58 (m, 2H), 7.44-7.38 (m, 3H), 7.20 (d, *J* 8.5 Hz, 2H), 7.05 (d, *J* 8.4 Hz, 2H), 6.62 (d, *J* 16.0 Hz, 1H), 2.35 (s, 3H). ^{1}H NMR is consistent with the literature precedent.[52]

Acknowledgements

We thank the National Natural Science Foundation of Zhejiang Province (LY21B020008) for financial support.

Supplementary Material

Supplemental material for this article is available online.

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