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Aerobic Oxidative Esterification and Thioesterification of Aldehyde using Dibromoisocyanuric Acid under Mild Condition: No Metal Catalysts Required

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Abstract

A practical direct method for the direct preparation of esters and thioesters from aldehydes is described. Esters and thioesters were synthesized by oxidative esterification and thioesterification via *in situ* generated acyl bromide intermediates, which were used to react with various alcohols and thiols. The esterification and thioesterification were readily performed in the presence of dibromoisocyanuric acid in dichloromethane, without any metal catalysts and under mild conditions. By using this reaction protocol, various esters and thioesters were prepared in high yields. This effective method offers a promising approach for the facile esterification and thioesterification of aldehydes.

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Introduction

Esters are one of the most fundamental structural units in organic chemistry. These compounds are frequently found in numerous natural products and bioactive materials, such as enzyme inhibitors,[1] antitumor agents,[2] anti-mycobacteria agents,[3] and antagonists of natural receptors.[4] Thioesters are also biologically important compounds, which are commonly utilized as intermediates for the preparation of various bioactive compounds.[5]

Due to the significance of esters and thioesters, development of an efficient method for their synthesis is highly valuable. One of the traditional approaches for synthesizing of esters and thioesters involves the nucleophilic substitution of carboxylic acid derivatives with alcohols and thiols.[6] Additionally, aldehydes have been utilized to generate esters and thiols by oxidative esterification and thioesterifcation.[7–16] The classical oxidative esterification and thioesterification of aldehydes requires two reaction steps: a hemiacetal unit generation, followed by the oxidation. Various reagents, such as iodine and its derivatives,[7] oxone,[8] hydrogen peroxide,[9] and *tert*-butyl hydroperoxide-tris(pentafluorophenyl)borane[10] have been developed and utilized in numerous oxidative esterifications and thioesterifications using hemiacetal intermediates. Although these methods are widely used, the drawbacks of using such reagents include instability of the hemiacetal intermediate and steric hindrance from the key structure, such as the aldehyde or alcohol. Thus, only more reactive aldehydes can be used to prepare esters or thioesters, or non-bulky esters can be produced in good yield via reactions using these reagents. Metal-catalyzed methods have also been developed for oxidative esterification and thioesterification of aldehydes. A variety of transition metals, such as cobalt,[11] copper,[12] iron,[13] gold,[14] and palladium[15] have been utilized to generate esters and thioesters. Even though these methods were efficient, they need harsh and air-protected reaction conditions. Thus, metal-catalyzed esterification and thioesterification are only

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suitable for a limited range of substrates. Besides, such expensive reagents are disadvantageous for reactions on an industrial scale. Alternatively, treatment of alcohols and thiols with *N*-heterocyclic carbene (NHC) catalysts has been developed for oxidative esterification and thioesterification of aldehydes, without generation of the hemiacetal intermediates.[16] However, in large-scale NHC-catalyzed esterification and thioesterification, only primary alcohols and thiols can be coupled with aldehydes to give esters and thioesters.

Thus, the development of a practical synthetic method for esters and thioesters remains a challenge. In this context, acyl halides are a potential intermediate to synthesize esters and thioesters because they lend themselves as useful tools in various organic syntheses.[17] Especially, the utilization of a bromo source can offer an effective approach because the successful formation of the acyl bromides from aldehydes could result in the facile preparation of the target esters and thioesters. Dibromoisocyanuric acid (DBI) is attractive for the preparation of esters and thioesters, as it is a well-established and effective brominating agent and oxidant.[18] Furthermore, DBI is interesting because it can brominate organic compounds under mild condition in high yield, and it can be treated safely without the need for an inert atmosphere. Moreover, a synthetic method using DBI for the direct esterification and thioesterification of aldehydes has not yet been described in the literature. Herein, we report a DBI-mediated direct synthetic protocol to produce a variety of esters and thioesters from aldehydes (Scheme 1).

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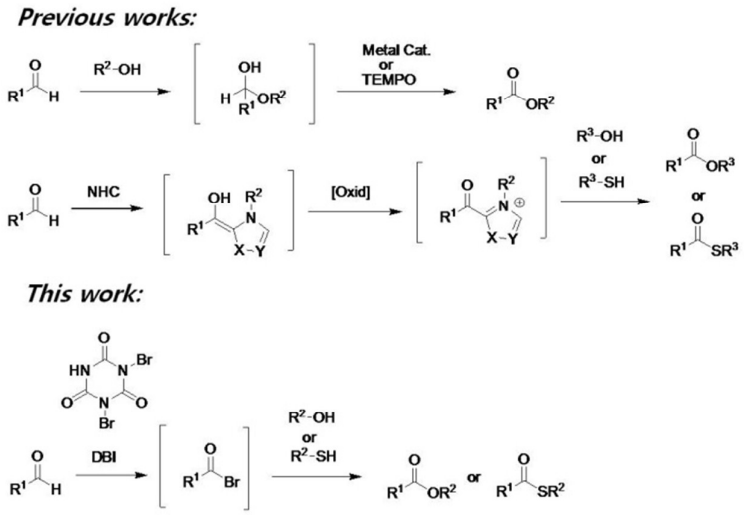

Scheme 1 Oxidative esterification and thioesterification of aldehydes**.**

Results and discussion

The main difficulty in the synthesis of esters and thioesters from aldehydes is the low reactivity of the aldehyde group to give the corresponding acyl halide. Only a few methods have been developed for conversion of aldehydes to acyl bromide, to date.[19] We envisioned that under more efficient reaction conditions, a direct synthesis of esters and thioesters utilizing acyl bromide intermediates starting from aldehydes would be realizable. We hypothesized that a reaction of DBI as a bromo donor with aldehyde could be employed for the *in situ* generation of acyl bromides, which are active intermediates to give esters and thioesters. To test our hypothesis, benzaldehyde was selected as the model substrate, and the possibility of DBI as an agent for the conversion of aldehydes into esters was examined.

The initial reaction involved the treatment of aldehyde along with DBI in dichloromethane at room temperature. The reactions of benzaldehyde (**1a**) with a series of equivalents of DBI (0.2, 0.5, 1.0, 1.5, and 2.0 equiv.) were performed to produce the desired benzoyl bromide (**2a)**, and the reaction was evaluated by TLC. During the reaction, the reaction mixture

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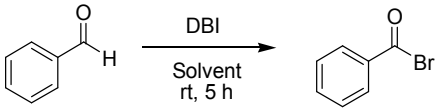
changed from white to orange, indicating production of benzoyl bromide. Also, the benzoyl bromide was readily prepared in quantitative yield from the reaction with 0.5 equiv. or more DBI after the reaction proceeded for 5 h. Several solvents were also tested to identify the optimal reaction condition. Reactions in toluene, tetrahydrofuran (THF), and 1,4-dioxane resulted in low yields of benzoyl bromide, while dichloromethane and acetonitrile showed the more effective synthesis of the desired product (100% and 92%, respectively; Table 1). Thus, the reaction conditions, including 0.5 equiv. DBI and dichloromethane were chosen for the subsequent studies.

Table 1 Screening of reaction conditions for the *in situ* preparation of benzoyl bromide[a]



1a **2a**

Entry	DBI (equiv.)	Solvent	Temp.	Yield[b] (%)
1	0.2	CH_2Cl_2	rt	44
2	0.5	CH_2Cl_2	rt	100
3	1.0	CH_2Cl_2	rt	100
4	1.5	CH_2Cl_2	rt	100
5	2.0	CH_2Cl_2	rt	100
6	0.5	toluene	rt	4
7	0.5	THF	rt	8
8	0.5	1,4-dioxane	rt	35
9	0.5	CH_3CN	rt	92

[a] Reaction conditions: benzaldehyde (**1a**) (2.0 mmol) and 4.0 mL of solvent. [b] Isolated yield after purification (fraction distillation).

Next, we investigated the second reaction condition of esterification. Once the aldehyde disappeared, the *in situ* prepared benzoyl bromide was treated with benzyl alcohol at room temperature. The desired ester was readily prepared after 20 min of reaction. In order to

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derive the optimal reaction conditions for ester formation, reactions with benzyl alcohol (**3a**) were screened in the presence of a series of commercially available bases. Our initial screening results indicated that the formation of esters from benzoyl bromide varied significantly, according to the bases, as shown in Table 2. The activities of K_2CO_3, $NaHCO_3$, 4-dimethylaminopyridine (DMAP), 1,4-diazabicyclo[2.2.2]octane (DABCO), and 1,8-diazabicyclo(5.4.0)undec-7-ene (DBU) were considered moderate and low, respectively, while triethylamine, diisopropylethylamine (DIPEA), and pyridine displayed better activity. However, the yield for the synthesis of ester was still insufficient to provide the corresponding product in high yield (Table 2, entries 3, 4, and 8). It was reported that DMAP catalyzed several reactions including esterification and acetylation of alcohols and amines, and the effect of auxiliary base on catalytic activity of DAMP was also studied.[20] Thus, the combination effect of base and DAMP was investigated. In the present study, although DMAP alone had poor activity, it revealed a profound influence on the yield of the desired product, when combined with either DIPEA or pyridine. Specifically, the addition of 0.1 equiv. DMAP as the catalyst significantly enhanced the conversion yield for the ester (85% for pyridine with DMAP and 93% for DIPEA with DMAP). In addition, reaction was performed under N_2 atmosphere to compare the yield with that of the reaction under air. The result indicated that there was no difference between reaction with N_2 and without N_2 (Table 2, entry 11). Thus, the second reaction conditions (conversion of acyl bromide into ester), including 1.5 equiv. DIPEA and 0.1 equiv. DMAP, and dichloromethane were selected for the next studies.

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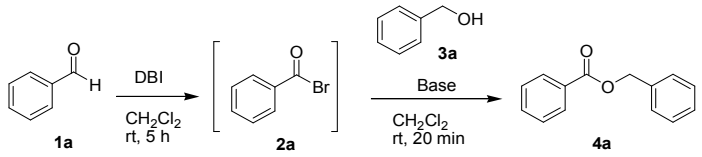
Table 2 Screening of reaction conditions for the preparation of esters[a]



Entry	Alcohol (equiv.)	Base	Temp.	Yield[b] (%)
1	1.5	K_2CO_3	rt	41
2	1.5	$NaHCO_3$	rt	35
3	1.5	Et_3N	rt	60
4	1.5	DIPEA	rt	71
5	1.5	DMAP	rt	27
6	1.5	DABCO	rt	14
7	1.5	DBU	rt	8
8	1.5	Pyridine	rt	63
9	1.5	Pyridine/DMAP[c]	rt	85
10	1.5	DIPEA/DMAP[c]	rt	93
11	1.5	DIPEA/DMAP[c]	rt	93[d]

[a] Reaction conditions: benzaldehyde (**1a**) (2.0 mmol), DBI (1.0 mmol), base (3.0 mmol), and CH_2Cl_2 (4.0 mL). [b] Isolated yield after purification by flash column chromatography. [c] 0.1 equiv. DMAP. [d] Reaction was conducted under N_2 atmosphere.

With the optimized reaction conditions established, the scope of this direct procedure for esters was explored (Table 3). The reactions were carried out with various alcohols, and the desired esters were obtained in high yields (76–93%). Alkyl alcohols, including *n*-butyl alcohol were used to assess the breadth of our method. Besides the reaction protocol proving useful for the synthesis of the corresponding esters, the introduction of cyclohexanol (a general secondary alcohol) and diphenylmethanol (a relatively bulkier secondary alcohol) to the reaction generated the corresponding esters in high yields (**4c** and **4d**). In addition, phenol, an aromatic compound, was treated with the benzoyl bromide and proved effective to produce the corresponding ester in satisfactory yield, without production of side products.

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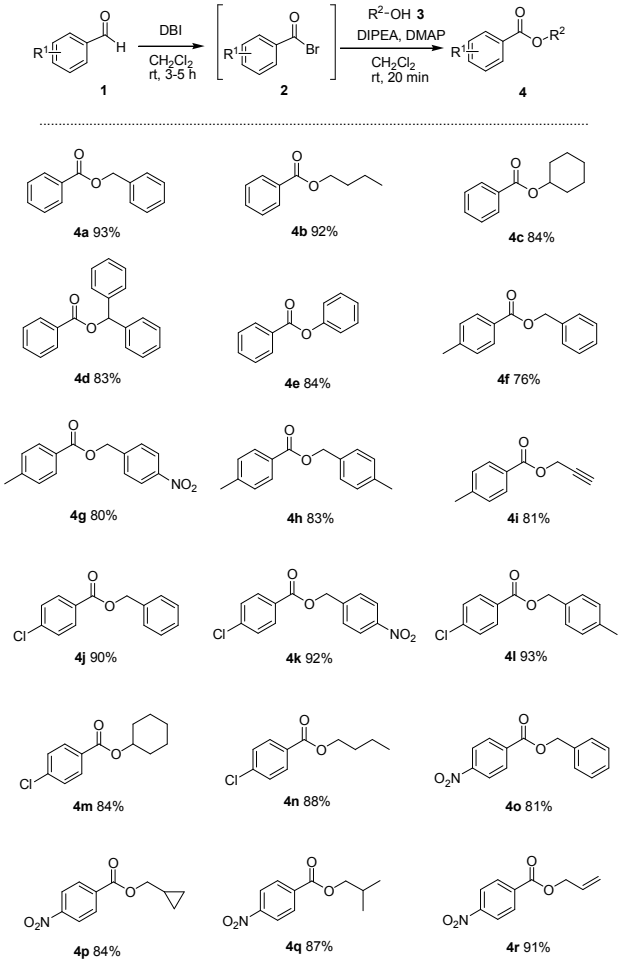
The results provided a demonstration of the importance of DBI as an agent for the conversion of aldehydes to esters.

Table 3 The scope of oxidative esterification of aromatic aldehydes[a,b]



[a] Reaction conditions: aldehyde (2.0 mmol), DBI (1.0 mmol), alcohol (3.0 mmol), DIPEA (3.0 mmol), DMAP (0.2 mmol), and CH_2Cl_2 (4.0 mL). [b] Isolated yield after purification by flash column chromatography.

In the present study, the scope of utilization of DBI was extended to different aromatic aldehydes. The syntheses of esters were not significantly affected by the electron properties of substituents on the aromatic ring. The reaction of aromatic aldehydes bearing electron-donating group (*p*-tolualdehyde) and electron-withdrawing groups (4-chlorobenzaldehyde

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and 4-nitrobenzaldehyde) with various alcohols also produced the desired ester compounds in similar and high yield. Additionally, allylic and propargylic alcohols were investigated and confirmed efficient for the direct preparation of esters from aldehydes. It was noteworthy that aromatic aldehydes bearing an electron-donating group generated acyl bromide within 3 h, suggesting that it was faster than benzaldehyde and aromatic aldehydes bearing an electron-withdrawing group.

To explore the range of reaction of aldehydes, aliphatic aldehydes were treated with DBI to generate esters. Aldehydes containing aliphatic chains were readily converted into the desired esters in high yields (77–91%) by the same protocol, using several aliphatic and aromatic alcohols (Table 4). Besides, the treatment of cyclohexanecarboxaldehyde under the optimized condition also successfully resulted in the generation of desired esters **4s**, **4t**, and **4u** in 91%, 84%, and 77% yield, respectively. In particular, when a variety of alcohols containing electron-donating and electron-withdrawing groups were employed in the reaction of aliphatic aldehydes, the reaction was successfully accomplished **4w**, **4x**, **4z**, and **4aa** in good yield. It was also observed that the conversion of aliphatic aldehydes to acyl bromides was achieved in 2 h, which was a shorter time than those of aromatic aldehydes. Moreover, no side products were found during the reactions of the aliphatic aldehydes. Besides, reaction of long aliphatic chain aldehyde and sterically hindered aldehyde were investigated. Reaction of 1-octanal with benzyl alcohol and reaction of pivalaldehyde with heptanol yielded the corresponding esters (**4ab** and **4ac**). In addition, the tolerance of heterocycles was explored. Reaction of thiophene-2-carbaldehyde with *n*-butanol and reaction of isovaleraldehyde with thiophen-2-ylmethanol successfully produced the corresponding esters (**4ad** and **4ae**).

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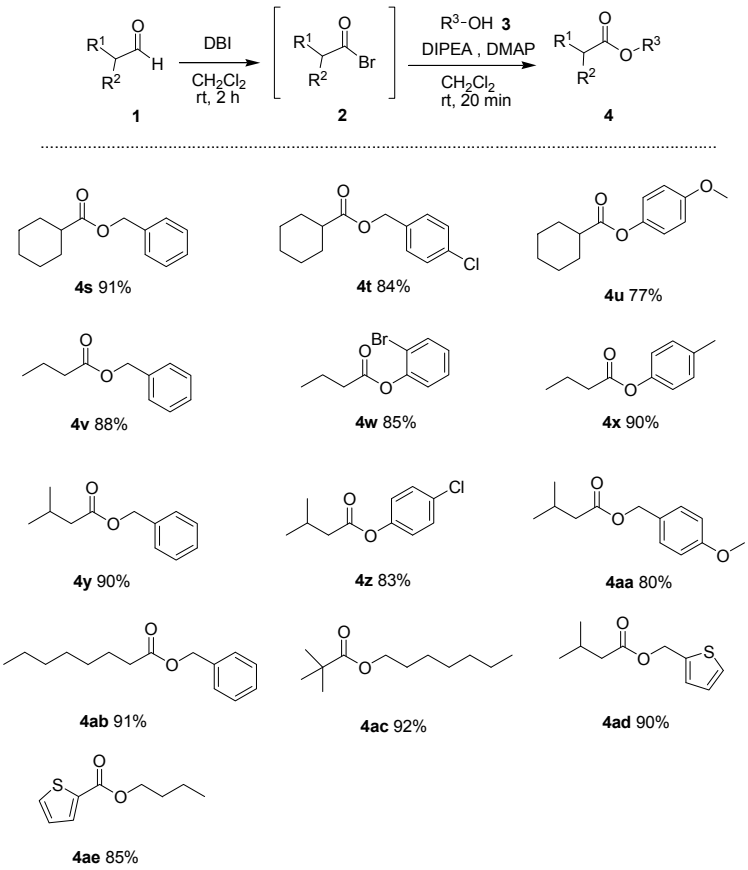
Table 4 Scope of oxidative esterification of aliphatic aldehydes[a,b]



[a] Reaction conditions: aldehyde (2.0 mmol), DBI (1.0 mmol), alcohol (3.0 mmol), DIPEA (3.0 mmol), DMAP (0.2 mmol), and CH_2Cl_2 (4.0 mL). [b] Isolated yield after purification by flash column chromatography.

Next, we explored the scope of this methodology for the synthesis of thioesters (Table 5). Various aldehydes were employed in the reaction with thiols. The aromatic and aliphatic aldehydes were treated with aromatic and aliphatic thiols under the same reaction condition. The desired thioesters were prepared in high yields (83–95%). In addition, the aldehydes were reacted with electron-rich and electron-deficient aromatic thiols to give the desired thioesters in high yield.

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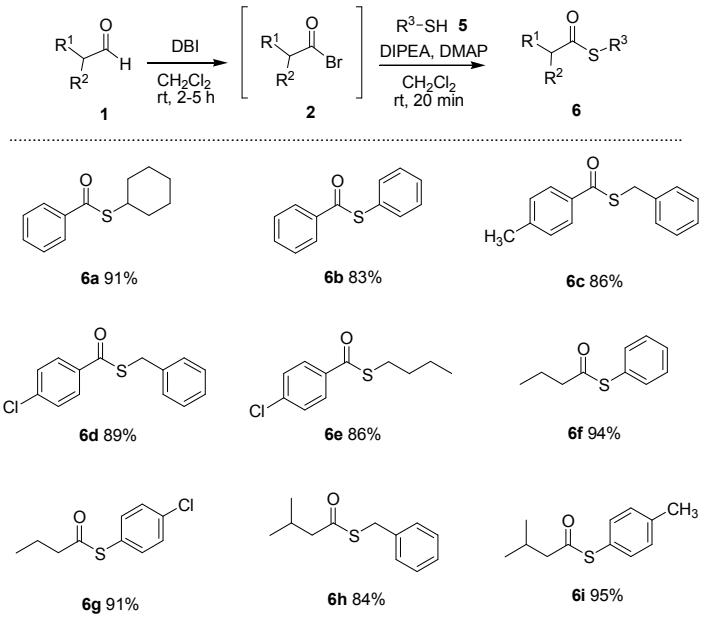
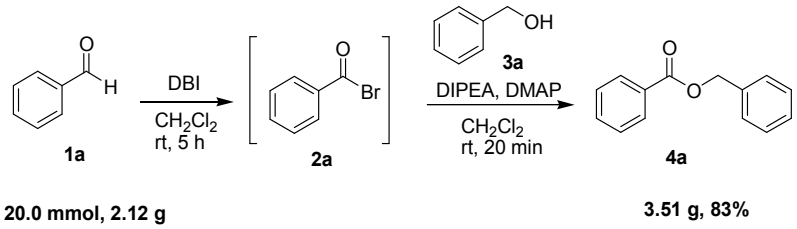
Table 5 Scope of oxidative thioesterification of aldehydes[a,b]



[a] Reaction conditions: aldehyde (2.0 mmol), DBI (1.0 mmol), thiol (3.0 mmol), DIPEA (3.0 mmol), DMAP (0.2 mmol), and CH_2Cl_2 (4.0 mL). [b] Isolated yield after purification by flash column chromatography.

Next, a scale-up oxidative esterification was carried out (Scheme 2). The reaction was proven to be scalable and practical because the gram-scale reaction was also efficiently performed. The reaction of benzaldehyde (**1a**) (20.0 mmol, 2.12 g) and benzyl alcohol (**3a**) (30.0 mmol, 1.5 equiv.) gave the corresponding product (**4a**) in 83% yield under optimized reaction conditions.



Scheme 2 The gram-scale reaction of benzaldehyde (**1a**) with benzyl alcohol (**3a**).

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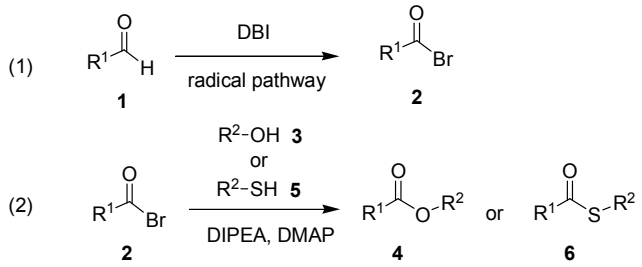
A plausible reaction pathway based on the previous report[21] and our result can be proposed, as shown in Scheme 3. The initial addition of DBI to aldehyde **1** probably produced acyl bromide **2** using a radical pathway. Then, the desired ester **4** or **6** was prepared via the treatment of acyl bromide **2** with alcohol **3** or thiol **5**.



Scheme 3 Proposed reaction pathway for thioesterification and esterification from aldehydes.

Conclusions

In summary, a novel facile direct method for the synthesis of esters and thioesters from aldehydes has been developed. In the present study, DBI was used as a bromo donor for the *in situ* preparation of acyl bromide from aromatic and aliphatic aldehydes. The use of DBI was demonstrated from the reactions of aldehydes with various alcohols and thiols, including benzylic, aliphatic, and propargylic alcohols. Moreover, the reaction protocol used mild aerobic reaction conditions. Our results suggest that a novel method to prepare esters and thioesters is practical and applicable for the synthesis of a variety of esters and thioesters from aldehydes.

Experimental

General information

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All chemicals were purchased from Sigma-Aldrich and used without further purification. Reaction progress was monitored by thin-layer chromatography (TLC) analysis. TLC analysis was performed using an aluminum plate with silica gel 60 F_{254}, and TLC spots were visualized by UV light (254nm) exposure. Flash chromatography was performed using 230–400 mesh silica gel and analytical grade solvent. Melting points were recorded using a Stuart SMP10 Melting Point Apparatus. ^{1}H and ^{13}C NMR spectra were recorded on a 600 MHz & 150 MHz respectively JEOL JNM-ECA600 spectrometer or a 400 MHz & 100 MHz respectively Bruker Avance 400 spectrometer. The chemical shifts were reported in δ units (ppm) relative to the residual protonated solvent resonance, and the coupling constants (*J*) quoted in Hz.

General experimental procedure for the preparation of ester and thioester compounds (4a–4aa and 6a–6i)

To a solution of benzaldehyde (**1a**) (0.212 g, 2.00 mmol) in CH_2Cl_2 (4 mL) was added dibromoisocyanuric acid (0.287 g, 1.00 mmol). The mixture was allowed to stir at room temperature for 5 h. Benzyl alcohol (0.324 g, 3.00 mmol), DIPEA (0.388 g, 3.00 mmol), and DMAP (0.244 g, 0.200 mmol) were added to the reaction mixture. After being stirred for 20 min at room temperature, the solid (cyanuric acid) was filtered, and the filtrate was extracted with CH_2Cl_2 (2 x 30 mL). The organic layer was dried over sodium sulfate and concentrated under reduced pressure. The resulting residue was then purified by flash column chromatography on silica gel with hexane-EtOAc as eluent to afford the desired product **4a** (0.396 g, 93%).

Benzyl benzoate (4a). Purified by flash column chromatography (EtOAc:hexane = 1:50) in 93% yield (396 mg, 1.87 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.09–8.08 (m, 2H), 7.58–7.55 (m, 1H), 7.46–7.34 (m, 7H), 5.37 (s, 2H). ^{13}C NMR (150 MHz, $CDCl_3$) δ

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166.6, 136.2, 133.2, 130.2, 129.8 (2C), 128.7 (2C), 128.5 (2C), 128.4, 128.3 (2C), 66.8. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{14}H_{13}O_2$ = 213.0916, found 213.0918.

Butyl benzoate (4b). Purified by flash column chromatography (EtOAc:hexane = 1:50) in 92% yield (330 mg, 1.84 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.08–8.05 (m, 2H), 7.59–7.55 (m, 1H), 7.48–7.43 (m, 2H), 4.35 (t, *J* = 3.6 Hz, 2H), 1.80–1.74 (m, 2H), 1.54–1.48 (m, 2H), 1.01 (t, *J* = 7.4 Hz, 3H).^{13}C NMR (150 MHz, $CDCl_3$) δ 166.7, 132.8, 130.5, 129.5 (2C), 128.3 (2C), 64.8, 30.8, 19.3, 13.8. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{11}H_{15}O_2$ = 179.1072, found 179.1076 .

Cyclohexyl benzoate (4c). Purified by flash column chromatography (EtOAc:hexane = 1:90) in 84% yield (302 mg, 1.69 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.06–8.04 (m, 2H), 7.58–7.53 (m, 1H), 7.45–7.42 (m, 2H), 5.03 (tt, *J* = 9.0, 3.6 Hz, 1H), 1.96–1.93 (m, 2H), 1.82–1.77 (m, 2H), 1.62–1.55 (m, 3H), 1.49–1.42 (m, 2H), 1.38–1.32 (m, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 166.1, 132.8, 131.1, 129.7 (2C), 128.4 (2C), 73.2, 31.8 (2C), 25.6, 23.8 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{13}H_{17}O_2$ = 205.1229, found 205.1227.

Benzhydryl benzoate (4d). Purified by flash column chromatography (EtOAc:hexane = 1:90) in 83% yield (480 mg, 1.66 mmol) as a white solid, mp 83–85 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.18 (d, *J* = 7.6 Hz, 2H), 7.61 (t, *J* = 7.2 Hz, 1H), 7.49 (dd, *J* = 8.0, 3.6 Hz, 6H), 7.41 (t, *J* = 6.4 Hz, 4H), 7.34 (t, *J* = 7.2 Hz, 2H), 7.17 (s, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 165.7, 140.4 (2C), 133.3 (2C), 130.3, 129.9 (3C), 128.7 (3C), 128.6 (2C), 128.1 (2C), 127.3 (3C), 77.5. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{20}H_{17}O_2$ = 289.1229, found 289.1230.

Phenyl benzoate (4e). Purified by flash column chromatography (EtOAc:hexane = 1:30) in 84% yield (336 mg, 1.69 mmol) as a white solid, mp 70–72 °C. ^{1}H NMR (600 MHz, $CDCl_3$)

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δ 8.24 (dd, *J* = 6.8, 1.6 Hz, 2H), 7.67 (dd, *J* = 7.2, 3.6 Hz, 1H), 7.51 (t, *J* = 7.6 Hz, 2H), 7.47 (dd, *J* = 8.0, 4.0 Hz, 2H), 7.33–7.25 (m, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 165.2, 151.0, 133.6, 130.2 (2C), 129.6 (2C), 129.5, 128.6 (2C), 125.9, 121.8 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{13}H_{11}O_2$ = 199.0759, found 199.0755.

Benzyl 4-methylbenzoate (4f). Purified by flash column chromatography (EtOAc:hexane = 1:70) in 76% yield (346 mg, 1.52 mmol) as a white solid, mp 39–41 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.98 (d, *J* = 8.4 Hz, 2H), 7.46–7.45 (m, 2H), 7.41–7.35 (m, 3H), 7.24 (d, *J* = 7.8 Hz, 2H), 5.36 (s, 2H), 2.41 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 166.6, 143.9, 136.3, 129.9 (2C), 129.2 (2C), 128.7 (2C), 128.3, 128.2 (2C), 127.5, 66.6, 21.8. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{15}H_{15}O_2$ = 227.1072, found 227.1073.

4-Nitrobenzyl 4-methylbenzoate (4g). Purified by flash column chromatography (EtOAc:hexane = 1:20) in 80% yield (436 mg, 1.60 mmol) as a white solid, mp 102–104 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.25 (d, *J* = 8.4 Hz, 2H), 7.98 (d, *J* = 8.4 Hz, 2H), 7.60 (d, *J* = 8.4 Hz, 2H), 7.27 (d, *J* = 8.4 Hz, 2H), 5.44 (s, 2H), 2.43 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 166.3, 147.8, 144.4, 143.7, 129.9 (2C), 129.4 (2C), 128.4 (2C), 126.8, 124.0 (2C), 65.1, 21.9. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{15}H_{14}NO_4$ = 272.0923, found 272.0925.

4-Methylbenzyl 4-methylbenzoate (4h). Purified by flash column chromatography (EtOAc:hexane = 1:70) in 83% yield (402 mg, 1.67 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.96 (d, *J* = 8.4 Hz, 2H), 7.34 (d, *J* = 7.2 Hz, 2H), 7.23 (d, *J* = 8.4 Hz, 2H), 7.20 (d, *J* = 8.4 Hz, 2H), 5.31 (s, 2H), 2.40 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 166.7, 143.8, 138.2, 133.3, 129.9 (2C), 129.4 (2C), 129.2 (2C), 128.5 (2C), 127.6, 66.6, 21.8, 21.4. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{16}H_{17}O_2$ = 241.1229, found 241.1226.

Prop-2-ynyl 4-methylbenzoate (4i). Purified by flash column chromatography

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(EtOAc:hexane = 1:70) in 81% yield (284 mg, 1.62 mmol) as a white solid, mp 44–45 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.96 (d, *J* = 7.8 Hz, 2H), 7.25 (d, *J* = 8.4 Hz, 2H), 4.91 (d, *J* = 2.4 Hz, 2H), 2.51 (t, *J* = 2.4 Hz, 1H), 2.41 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 166.0, 144.3, 130.0 (2C), 129.3 (2C), 126.8, 78.0, 75.0, 52.4, 21.8. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{11}H_{11}O_2$ = 175.0759, found 175.0761.

Benzyl 4-chlorobenzoate (4j). Purified by flash column chromatography (EtOAc:hexane = 1:80) in 90% yield (424 mg, 1.80 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.01 (d, *J* = 8.4 Hz, 2H), 7.45–7.35 (m, 7H), 5.36 (s, 2H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 165.7, 139.6, 135.9, 131.2 (2C), 128.9 (2C), 128.8 (2C), 128.7, 128.5, 128.4 (2C), 67.1. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{14}H_{12}ClO_2$ = 247.0526, found 247.0528.

4-Nitrobenzyl 4-chlorobenzoate (4k). Purified by flash column chromatography (EtOAc:hexane = 1:20) in 92% yield (592 mg, 1.84 mmol) as a white solid, mp 134–135 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.25 (d, *J* = 9.0 Hz, 2H), 8.02 (d, *J* = 8.4 Hz, 2H), 7.60 (d, *J* = 9.0 Hz, 2H), 7.44 (d, *J* = 9.0 Hz, 2H), 5.45 (s, 2H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 165.4, 147.9, 143.1, 140.1, 131.2 (2C), 129.1 (2C), 128.6 (2C), 128.0, 124.0 (2C), 65.5. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{14}H_{11}ClNO_4$ = 292.0377, found 292.0378.

4-Methylbenzyl 4-chlorobenzoate (4l). Purified by flash column chromatography (EtOAc:hexane = 1:90) in 93% yield (486 mg, 1.86 mmol) as a white solid, mp 50–51 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.00 (d, *J* = 8.4 Hz, 2H), 7.40 (d, *J* = 9.0 Hz, 2H), 7.34 (d, *J* = 8.4 Hz, 2H), 7.21 (d, *J* = 8.4 Hz, 2H), 5.32 (s, 2H), 2.37 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 165.8, 139.6, 138.4, 132.9, 131.2 (2C), 129.4 (2C), 128.83 (2C), 128.80, 128.6 (2C), 67.1, 21.4. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{15}H_{14}ClO_2$ = 261.0682, found 261.0685.

Cyclohexyl 4-chlorobenzoate (4m). Purified by flash column chromatography

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(EtOAc:hexane = 1:90) in 84% yield (402 mg, 1.68 mmol) as a white solid, mp 38–40 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.98 (d, J = 9.0 Hz, 2H), 7.40 (d, J = 7.8 Hz, 2H), 5.01 (tt, J = 9.0, 3.6 Hz, 1H), 1.95–1.92 (m, 2H), 1.81–1.77 (m, 2H), 1.61–1.55 (m, 3H), 1.48–1.41 (m, 2H), 1.37–1.33 (m, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 162.3, 139.2, 131.1 (2C), 129.6, 128.7 (2C), 73.6, 31.7 (2C), 25.6, 23.8 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{13}H_{16}ClO_2$ = 239.0839, found 239.0838.

Butyl 4-chlorobenzoate (4n). Purified by flash column chromatography (EtOAc:hexane = 1:80) in 88% yield (376 mg, 1.76 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.97 (d, J = 9.0 Hz, 2H), 7.40 (d, J = 8.4 Hz, 2H), 4.31 (t, J = 6.6 Hz, 2H), 1.76–1.71 (m, 2H), 1.49–1.43 (m, 2H), 0.97 (t, J = 7.2 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 165.9, 139.3, 131.1 (2C), 129.1, 128.8 (2C), 65.2, 30.8, 19.4, 13.9. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{11}H_{14}ClO_2$ = 213.0682, found 213.0684.

Benzyl 4-nitrobenzoate (4o). Purified by flash column chromatography (EtOAc:hexane = 1:30) in 81% yield (420 mg, 1.62 mmol) as a white solid, mp 87–88 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.28 (d, J = 9.0 Hz, 2H), 8.24 (d, J = 9.0 Hz, 2H), 7.47–7.38 (m, 5H), 5.41 (s, 2H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 164.7, 150.7, 135.6, 135.4, 131.0 (2C), 128.9 (2C), 128.8, 128.6 (2C), 123.7 (2C), 67.8. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{14}H_{12}NO_4$ = 258.0766, found 258.0767.

Cyclopropylmethyl 4-nitrobenzoate (4p). Purified by flash column chromatography (EtOAc:hexane = 1:30) in 84% yield (374 mg, 1.68 mmol) as a white solid, mp 56–57 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.29 (d, J = 8.4 Hz, 2H), 8.23 (d, J = 7.8 Hz, 2H), 4.20 (d, J = 6.6 Hz 2H), 1.31–1.24 (m, 1H), 0.67–0.63 (m, 2H), 0.40–0.37 (m, 2H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 165.0, 150.6, 136.0, 130.9 (2C), 123.6 (2C), 70.9, 9.94, 3.57 (2C). HRMS (ESI)

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m/z $[M + H]^+$ calcd for $C_{11}H_{12}NO_4$ = 222.0766, found 222.0767.

Isobutyl 4-nitrobenzoate (4q). Purified by flash column chromatography (EtOAc:hexane = 1:30) in 87% yield (390 mg, 1.74 mmol) as a white solid, mp 70–71 ^oC. ^1H NMR (600 MHz, $CDCl_3$) δ 8.29 (d, *J* = 8.4 Hz, 2H), 8.21 (d, *J* = 9.0 Hz, 2H), 4.16 (d, 2H), 2.14–2.08 (m, 1H), 1.04 (d, *J* = 6.0 Hz, 6H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 164.8, 150.6, 136.0, 130.8 (2C), 123.7 (2C), 72.0, 28.0, 19.3 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{11}H_{14}NO_4$ = 224.0923, found 224.0921.

Allyl 4-nitrobenzoate (4r). Purified by flash column chromatography (EtOAc:hexane = 1:30) in 91% yield (408 mg, 1.82 mmol) as a colorless oil. ^1H NMR (600 MHz, $CDCl_3$) δ 8.29 (d, *J* = 9.0 Hz, 2H), 8.23 (d, *J* = 8.4 Hz, 2H), 6.08–6.01 (m, 1H), 5.45–5.42 (m, 1H), 5.35–5.33 (m, 1H), 4.88–4.86 (m, 2H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 164.5, 150.7, 135.7, 131.6, 130.9 (2C), 123.7 (2C), 119.3, 66.6. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{10}H_{10}NO_4$ = 208.0610, found 208.0613.

Benzyl cyclohexanecarboxylate (4s). Purified by flash column chromatography (EtOAc:hexane = 1:50) in 91% yield (400 mg, 1.83 mmol) as a colorless oil. ^1H NMR (600 MHz, $CDCl_3$) δ 7.38–7.30 (m, 5H), 5.11 (s, 2H), 2.36 (tt, *J* =11.4, 3.6 Hz, 1H), 1.95–1.92 (m, 2H), 1.78–1.74 (m, 2H), 1.65–1.64 (m, 1H), 1.50–1.44 (m, 2H), 1.31–1.21 (m, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 176.1, 136.4, 128.6 (2C), 128.2, 128.1 (2C), 66.0, 43.3, 29.1 (2C), 25.9, 25.6 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{14}H_{19}O_2$ = 219.1385, found 219.1384.

4-Chlorobenzyl cyclohexanecarboxylate (4t). Purified by flash column chromatography (EtOAc:hexane = 1:50) in 84% yield (426 mg, 1.68 mmol) as a colorless oil. ^1H NMR (600 MHz, $CDCl_3$) δ 7.32 (d, *J* = 8.4 Hz, 2H), 7.27 (d, *J* = 8.4 Hz, 2H), 5.06 (s, 2H), 2.34 (tt, *J* = 11.4, 3.6 Hz, 1H), 1.93–1.90 (m, 2H), 1.76–1.73 (m, 2H), 1.65–1.62 (m, 1H), 1.48–1.42 (m,

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2H), 1.31–1.20 (m, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 175.9, 135.0, 134.1, 129.5 (2C), 128.8 (2C), 65.2, 43.3, 29.1 (2C), 25.8, 25.5 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{14}H_{18}ClO_2$ = 253.0995, found 253.0997.

4-Methoxyphenyl cyclohexanecarboxylate (4u). Purified by flash column chromatography (EtOAc:hexane = 1:40) in 77% yield (364 mg, 1.55 mmol) as a white solid, mp 66–68 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 6.97 (d, *J* = 9.0 Hz, 2H), 6.88 (d, *J* = 9.0 Hz, 2H), 3.79 (s, 3H), 2.53 (tt, *J* = 11.4, 3.6 Hz, 1H), 2.06–2.04 (m, 2H), 1.83–1.80 (m, 2H), 1.70–1.68 (m, 1H), 1.61–1.55 (m, 2H), 1.39–1.25 (m, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 175.1, 157.2, 144.5, 122.4 (2C), 114.5 (2C), 55.7, 43.3, 29.1 (2C), 25.9, 25.5 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{14}H_{19}O_3$ = 235.1334, found 235.1337.

Benzyl butyrate (4v). Purified by flash column chromatography (EtOAc:hexane = 1:80) in 88% yield (316 mg, 1.76 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.39–7.32 (m, 5H), 5.13 (s, 2H), 2.35 (t, *J* = 7.5 Hz, 2H), 1.69 (qt, *J* = 7.4 Hz, 2H), 0.96 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 173.6, 136.2, 128.6 (2C), 128.3 (3C), 66.1, 36.3, 18.6, 13.8. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{11}H_{15}O_2$ = 179.1072, found 179.1073.

2-Bromophenyl butyrate (4w). Purified by flash column chromatography (EtOAc:hexane = 1:70) in 85% yield (414 mg, 1.70 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.61–7.60 (m, 1H), 7.34–7.31 (m, 1H), 7.13–7.10 (m, 2H), 2.61 (t, *J* = 7.8 Hz, 2H), 1.83 (qt, *J* = 7.4 Hz, 2H), 1.07 (t, *J* = 7.8 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 171.3, 148.4, 133.5, 128.6, 127.4, 124.0, 116.4, 36.1, 18.5, 13.9. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{10}H_{12}BrO_2$ = 243.0021, found 243.0023.

***p*-Tolyl butyrate (4x).** Purified by flash column chromatography (EtOAc:hexane = 1:80) in 90% yield (324 mg, 1.85 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.17 (d, *J* =

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8.4 Hz, 2H), 6.96 (d, *J* = 8.4 Hz, 2H), 2.53 (t, *J* = 7.2 Hz, 2H), 2.35 (s, 3H), 1.79 (qt, *J* = 7.4 Hz, 2H), 1.05 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 172.5, 148.6, 135.4, 130.0 (2C), 121.4 (2C), 36.4, 21.0, 18.6, 13.8. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{11}H_{15}O_2$ = 179.1072, found 179.1071.

Benzyl 3-methylbutanoate (4y). Purified by flash column chromatography (EtOAc:hexane = 1:80) in 90% yield (348 mg, 1.80 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.38–7.31 (m, 5H), 5.12 (s, 2H), 2.25 (d, *J* = 7.8 Hz, 2H), 2.15–2.11 (m, 1H), 0.96 (d, *J* = 6.6 Hz, 6H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 173.1, 136.3, 128.7 (2C), 128.35, 128.26 (2C), 66.1, 43.5, 25.9, 22.6 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{12}H_{17}O_2$ = 193.1229, found 193.1230.

4-Chlorophenyl 3-methylbutanoate (4z). Purified by flash column chromatography (EtOAc:hexane = 1:70) in 83% yield (354 mg, 1.66 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.34 (d, *J* = 8.4 Hz, 2H), 7.02 (d, *J* = 9.0 Hz, 2H), 2.43 (d, *J* = 6.6 Hz, 2H), 2.24–2.22 (m, 1H), 1.05 (d, *J* = 7.2 Hz, 6H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 171.5, 149.3, 131.2, 129.6 (2C), 123.1 (2C), 43.4, 26.0, 22.5 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{11}H_{14}ClO_2$ = 213.0682, found 213.0681.

4-Methoxybenzyl 3-methylbutanoate (4aa). Purified by flash column chromatography (EtOAc:hexane = 1:70) in 80% yield (358 mg, 1.60 mmol) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.29 (d, *J* = 9.0 Hz, 2H), 6.89 (d, *J* = 9.0 Hz, 2H), 5.05 (s, 2H), 3.81 (s, 3H), 2.21 (d, *J* = 6.6 Hz, 2H), 2.14–2.07 (m, 1H), 0.94 (d, *J* = 6.0 Hz, 6H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 173.2, 159.7, 130.2 (2C), 128.4, 114.0 (2C), 65.9, 55.4, 43.6, 25.9, 22.5 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{13}H_{19}O_3$ = 223.1334, found 223.1335.

Benzyl octanoate (4ab). Purified by flash column chromatography (EtOAc:hexane = 1:70)

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in 91% yield (428 mg, 1.82 mmol) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42-7.30 (m, 5H), 5.14 (s, 2H), 2.38 (t, *J* = 7.6 Hz, 2H), 1.72-1.62 (m, 2H), 1.40-1.20 (m, 8H), 0.90 (t, *J* = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.7, 136.2, 128.5 (2C), 128.2 (3C), 66.0, 34.3, 31.6, 29.1, 28.9, 25.0, 22.6, 14.1. HRMS (ESI) *m/z* $[M + H]^+$ cacld for $C_{15}H_{23}O_2$ = 235.1698, found 235.1699.

Heptyl pivalate (4ac). Purified by flash column chromatography (EtOAc:hexane = 1:70) in 92% yield (370 mg, 1.84 mmol) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.06 (t, *J* = 6.4 Hz, 2H), 1.64 (quint, *J* = 6.8 Hz, 2H), 1.40-1.25 (m, 8H), 1.21 (s, 9H), 0.90 (t, *J* = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.6, 64.5, 38.7, 31.7, 28.9, 28.6, 27.2 (3C), 25.9, 22.6, 14.0. HRMS (ESI) *m/z* $[M + H]^+$ cacld for $C_{12}H_{25}O_2$ = 201.1855, found 201.1857.

Thiophen-2-ylmethyl 3-methylbutanoate (4ad). Purified by flash column chromatography (EtOAc:hexane = 1:70) in 90% yield (359 mg, 1.80 mmol) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (dd, *J* = 4.2, 1.2 Hz, 1H), 7.11 (dd, *J* = 2.8, 0.4 Hz, 1H), 7.00 (dd, *J* = 4.2, 3.2 Hz, 1H), 5.29 (s, 2H), 2.24 (d, *J* = 6.8 Hz, 2H), 2.13 (nontet, *J* = 6.4 Hz, 1H), 0.96 (d, *J* = 6.8 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.8, 138.2, 128.0, 126.8, 126.7, 60.2, 43.3, 25.7, 22.4 (2C). HRMS (ESI) *m/z* $[M + H]^+$ cacld for $C_{10}H_{15}O_2S$ = 199.0793, found 199.0798.

Butyl thiophene-2-carboxylate (4ae). Purified by flash column chromatography (EtOAc:hexane = 1:70) in 85% yield (315 mg, 1.70 mmol) as a light yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (dd, *J* = 3.6, 1.2 Hz, 1H), 7.56 (dd, *J* = 4.8, 1.2 Hz, 1H), 7.11 (dd, *J* = 4.8, 3.6 Hz, 1H), 4.32 (t, *J* = 6.4 Hz, 2H), 1.76 (quint, *J* = 6.4 Hz, 2H), 1.49 (sextet, *J* = 7.2 Hz, 2H), 0.99 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.3, 134.1, 133.2, 132.1, 127.7, 65.0, 30.8, 19.2, 13.7. HRMS (ESI) *m/z* $[M + H]^+$ cacld for $C_9H_{13}O_2S$ = 185.0636, found 185.0638.

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_S_-Cyclohexyl benzothioate (6a). Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 91% yield (403 mg, 1.82 mmol) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (dd, J = 8.4, 1.2 Hz, 2H), 7.57 (tt, J = 7.6, 1.2 Hz, 1H), 7.45 (t, J = 8.0 Hz, 2H), 3.79–3.73 (m, 1H), 2.07–2.03 (m, 2H), 1.79 (m, 2H), 1.65 (m, 1H), 1.57 (m, 4H), 1.30 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.8, 137.5, 133.1, 128.5 (2C), 127.1 (2C), 42.5, 33.2 (2C), 26.0 (2C), 25.6. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{13}H_{17}OS$ = 221.1000, found 221.1005.

_S_-Phenyl benzothioate (6b). Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 83% yield (357 mg, 1.66 mmol) as a white solid, mp 56–58 ^{o}C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.01 (dd, J = 6.8, 1.2 Hz, 2H), 7.64 (tt, J = 7.2, 1.6 Hz, 1H), 7.52 (m, 7H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.1, 136.7, 135.1 (2C), 133.7, 129.5, 129.3 (2C), 128.8 (2C), 127.5 (2C), 127.4. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{13}H_{11}OS$ = 215.0531, found 215.0534.

_S_-Benzyl 4-methylbenzothioate (6c). Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 86% yield (420 mg, 1.73 mmol) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, J = 8.0 Hz, 2H), 7.41 (d, J = 8.4 Hz, 2H), 7.34 (t, J = 7.2 Hz, 2H), 7.28 (m, 3H), 4.34 (s, 2H), 2.43 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.9, 144.3, 137.6, 134.3, 129.3 (2C), 129.0 (2C), 128.6 (2C), 127.4 (2C), 127.3, 33.3, 21.7. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{15}H_{15}OS$ = 243.0844, found 243.0842.

_S_-Benzyl 4-chlorobenzothioate (6d). Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 89% yield (470 mg, 1.79 mmol) as a white solid, mp 50–52 ^{o}C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 (d, J = 8.4 Hz, 2H), 7.44 (d, J = 8.8 Hz, 2H), 7.40 (d, J = 7.2 Hz, 2H), 7.35 (t, J = 6.8 Hz, 2H), 7.28 (t, J =8.4 Hz, 1H), 4.35 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.1, 139.8, 137.2, 135.1, 128.98 (2C), 128.95 (2C), 128.7 (2C), 128.6

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(2C), 127.4, 33.5. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{14}H_{12}ClOS$ = 263.0297, found 263.0299.

***S*-Butyl 4-chlorobenzothioate (6e).** Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 86% yield (394 mg, 1.72 mmol) as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$) δ 7.92 (d, *J* = 8.8 Hz, 2H), 7.43 (d, *J* = 8.8 Hz, 2H), 3.10 (t, *J* = 7.2 Hz, 2H), 1.68 (quint, *J* = 7.6 Hz, 2H), 1.49 (sextet, *J* = 7.6 Hz, 2H), 0.97 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.9, 139.6, 135.6, 128.8 (2C), 128.5 (2C), 31.6, 28.9, 22.1, 13.6. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{11}H_{14}ClOS$ = 229.0454, found 229.0455.

***S*-Phenyl butanethioate (6f).** Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 94% yield (341 mg, 1.88 mmol) as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$) 7.46–7.42 (m, 5H), 2.67 (t, *J* = 7.2 Hz, 2H), 1.79 (sextet, *J* =7.2 Hz, 2H), 1.03 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.4, 134.5 (2C), 129.3, 129.2 (2C), 128.0, 45.6, 19.1, 13.5. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{10}H_{13}OS$ = 181.0687, found 181.0688.

***S*-4-Chlorophenyl butanethioate (6g).** Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 91% yield (392 mg, 1.82 mmol) as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$) 7.40 (d, *J* = 8.4 Hz, 2H), 7.35 (d, *J* = 8.4 Hz, 2H), 2.67 (t, *J* = 7.2 Hz, 2H), 1.79 (sextet, *J* =7.6 Hz, 2H), 1.03 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.8, 135.7 (3C), 129.4 (2C), 126.4, 45.6, 19.1, 13.5. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{10}H_{12}ClOS$ = 215.0297, found 215.0299.

***S*-Benzyl 3-methylbutanethioate (6h).** Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 84% yield (352 mg, 1.68 mmol) as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$) δ 7.32–7.28 (m, 5H), 4.15 (s, 2H), 2.47 (d, *J* = 7.2 Hz, 2H), 2.21

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(nontet, J = 6.8 Hz, 1H), 0.98 (d, J = 6.8 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.3, 137.8, 128.8 (2C), 128.6 (2C), 127.2, 52.6, 33.2, 26.5, 22.3 (2C). HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{12}H_{17}OS$ = 209.1000, found 209.1002.

***S*-*p*-Tolyl 3-methylbutanethioate (6i).** Purified by flash column chromatography (dichloromethane:hexane = 1:2) in 95% yield (398 mg, 1.90 mmol) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 (d, J = 8.0 Hz, 2H), 7.24 (d, J = 8.0 Hz, 2H), 2.55 (d, J = 6.8 Hz, 2H), 2.40 (s, 3H), 2.25 (nontet, J = 6.8 Hz, 1H), 1.03 (d, J = 6.4 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.4, 139.5, 134.4 (2C), 130.0 (2C), 124.5, 52.3, 26.5, 22.3 (2C), 21.3. HRMS (ESI) *m/z* $[M + H]^+$ calcd for $C_{12}H_{17}OS$ = 209.1000, found 209.1003.

Electronic supplementary material

Electronic Supplementary Material (ESI) available: ^{1}H and ^{13}C NMR spectra of all compounds. See DOI:

Conflicts of interest

There are no conflicts to declare.

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Notes and references

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DOI: 10.1039/C8NJ01085D

1. (*a*) M. R. Attwood, C. H. Hassall, A. Krohn, G. Lawton and S. Redshaw, *J. Chem. Soc., Perkin Trans. 1 (1972-1999)*, 1986, **0**, 1011; (*b*) K. Takao, K. Toda, T. Saito and Y. Sugita, *Chem. Pharm. Bull.*, 2017, **65**, 1020; (*c*) Y. Sun, Y. Bai, X. He, Y. Bai, P. Liu, Z. Zhao, X. Chen and X. Zheng, *Molecules*, 2017, **22**, 1739.

2. (*a*) S. Bommagani, J. Ponder, N. R. Penthala, V. Janganati, C. T. Jordan, M. J. Borrelli and P. A. Crooks, *Eur. J. Med. Chem.*, 2017, **136**, 393; (*b*) J. Chen, T. Wang, S. Xu, P. Zhang, A. Lin, L. Wu, H. Yao, W. Xie, Z. Zhu and J. Xu, *Eur. J. Med. Chem.*, 2017, **135**, 414.

3. M. S. Kabir, O. A. Namjoshi, R. Verma, R. Polanowski, S. M. Krueger, D. Sherman, M. A. Rott, W. R. Schwan, A. Monte and J. M. Cook, *Bioorg. Med. Chem.*, 2010, **18**, 4178.

4. F. Del Bello, A. Bonifazi, G. Giorgioni, R. Petrelli, W. Quaglia, A. Altomare, A. Falcicchio, R. Matucci, G. Vistoli and A. Piergentili, *Eur. J. Med. Chem.*, 2017, **137**, 327.

5. (*a*) U. R. Awodi, J. L. Ronan, J. Masschelein, E. L. C. de los Santos and G. L. Challis, *Chem. Sci.*, 2017, **8**, 411; (*b*) H. Peng, E. Wei, J. Wang, Y. Zhang, L. Cheng, H. Ma, Z. Deng and X. Qu, *ACS Chem. Biol.*, 2016, **11**, 3278; (*c*) H. Fuwa, S. Matsukida, T. Miyoshi, Y. Kawashima, T. Saito and M. Sasaki, *J. Org. Chem.*, 2016, **81**, 2213; (*d*) J. M. Winter, D. Cascio, D. Dietrich, M. Sato, K. Watanabe, M. R. Sawaya, J. C. Vederas, Y. Tang, *J. Am. Chem. Soc.*, 2015, **137**, 9885.

6. (*a*) J. Otera and J. Nishikido, *Esterification: Methods, Reactions, and Applications, Second Edition*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2009; (*b*) J. Xun, H. Huang, K. W. Vogel and D. G. Drueckhammer, *Bioorg. Chem.*, 2005, **33**, 90.

7. (*a*) A. K. Verma, T. Aggarwal, V. Rustagi and R. C. Larock, *Chem. Commun.*, 2010, **46**, 4064; (*b*) S. B. Bandgar, B. P. Bandgar, B. L. Korbad and S. S. Sawant, , *Tetrahedron Lett.*, 2007, **48**, 1287.

8. B. R. Travis, M. Sivakumar, G. O. Hollist and B. Borhan, *Org. Lett.*, 2003, **5**, 1031.

View Article Online
DOI: 10.1039/C8NJ01085D

9. R. Tank, U. Pathak, M. Vimal, S. Bhattacharyya and L. K. Pandey, *Green Chem.*, 2011, **13**, 3350.

10. S. D. Guggilapu, S. K. Prajapti and B. N. Babu, *Tetrahedron Lett.*, 2015, **56**, 889.

11. S. Mahmood, T. Li, B.-H. Xu, Y.-F. Guo and S.-J. Zhang, *Asian J. Org. Chem.*, 2017, **6**, 768.

12. (*a*) Y. Zhu and Y. Wei, *RSC Adv.*, 2013, **3**, 13668; (*b*) S. K. Rout, S. Guin, K. K. Ghara, A. Banerjee and B. K. Patel, *Org. Lett.*, 2012, **14**, 3982; (*c*) C.-L. Yi, Y.-T. Huang and C.-F. Lee, *Green Chem.*, 2013, **15**, 2476.

13. (*a*) F. Rajabi, R. A. D. Arancon and R. Luque, *Catal. Commun.*, 2015, **59**, 101; (*b*) X.-F. Wu and C. Darcel, *Eur. J. Org. Chem.*, 2009, **8**, 1144; (*c*) Y.-T. Huang, S.-Y. Lu, C.-L. Yi and C.-F. Lee, *J. Org. Chem.*, 2014, **79**, 4561.

14. M. Penhoat, T. Vanbésien, A. Cocud, A. Addad, H. Vezin and C. Rolando, *New J. Chem.*, 2016, **40**, 9460.

15. (*a*) G. A. Heropoulos and C. Villalonga-Barber, *Tetrahedron Lett.*, 2011, **52**, 5319. (*b*) B. A. Tschaen, J. R. Schmink and G. A. Molander, *Org. Lett.*, 2013, **15**, 500.

16. (*a*) K. A. Ogawa and A. J. Boydston, *Org. Lett.*, 2014, **16**, 1928; (*b*) M. T. Berry, D. Castrejon and J. E. Hein, *Org. Lett.*, 2014, **16**, 3676; (*c*) S. Iwahana, H. Iida and E. Yashima, *Chem. - Eur. J.*, 2011, **17**, 8009; (*d*) T. Uno, T. Inokuma and Y. Takemoto, *Chem. Commun.*, 2012, **48**, 1901.

17. (*a*) F. E. A. Van Waes, J. Drabowicz, A. Cukalovic and C. V. Stevens, *Green Chem.*,2012, **14**, 2776; (*b*) S. Gaspa, A. Porcheddu and L. De Luca, *Org. Lett.*, 2015, **17**, 3666; (*c*) C. Simiona, I. Hashimotob, Y. Mitomac, A. M. Simiona and N. Egashirac, *Phosphorus, Sulfur Silicon Relat. Elem.*, 2010, **185**, 2480; (*d*) H. Cui, G. F. Ruda, J. Carrero-Lérida, L. M. Ruiz-Pérez, I. H. Gilbert and D. González-Pacanowska, *Eur. J. Med. Chem.*, 2010, **45**, 5140.

View Article Online
DOI: 10.1039/C8NJ01085D

18. (*a*) W. D. Brown and A. H. Gouliaev, *Synthesis*, 2002, **1**, 83; (*b*) Z. P. Demko, M. Bartsch and K. B. Sharpless, *Org. Lett.*, 2000, **2**, 2221.

19. (*a*) Y.-F. Cheung, *Tetrahedron Lett.*, 1979, **20**, 3809; (*b*) D. A. Wiebe and D. J. Burton, *J. Fluorine Chem.*, 2012, **139**, 4; (*c*) R. Knorr, K.-O. Hennig, B. Schubert and P. Böhrer, *Eur. J. Org. Chem.*, 2010, **34**, 6651.

20. (*a*) A. Sakakura, K. Kawajiri, T. Ohkubo, Y. Kosugi and K. Ishihara, *J. Am. Chem. Soc.*, 2007, **129**, 14775; (*b*) S. Xu, I. Held, B. Kempf, H. Mayr, W. Steglich and H. Zipse, *Chem. Eur. J.*, 2005, **11**, 4751.

21. (*a*) S. R. Wilson, S. Tofigh and R. N. Misra, *J. Org. Chem.*, 1982, **47**, 1360; (*b*) D. Ginsburg, *J. Am. Chem. Soc.*, 1951, **73**, 702.

View Article Online
DOI: 10.1039/C8NJ01085D

<Table of Contents>

Esters and thioesters were successfully prepared through oxidative esterification and thioesterification of corresponding aldehydes in the presence of dibromoisocyanuric acid.

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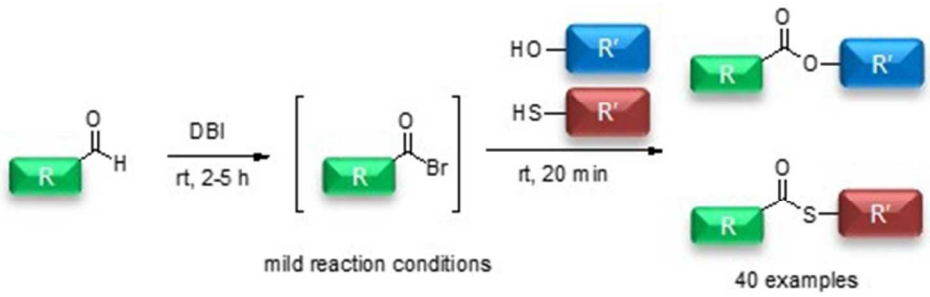

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