POLYOXOMETALATES

Open Access
RESEARCH ARTICLE

Direct and green synthesis of dithioesters enabled by dispersant-collaborative semiconductor cluster photocatalysis

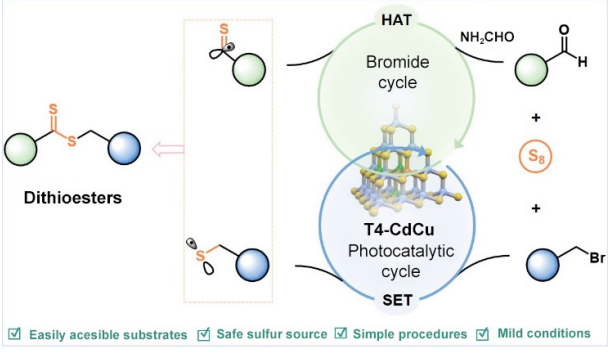
Pei-Lin Ou[1,§], Hong-Tao Gao[1,§], Chao-Li Chen[1], Hao Ma[1], Bingzhe Wang[1], Rui Zhou[1,2], Dong-Sheng Li[3], Shang-Fu Yuan[1] ✉, and Tao Wu[1] ✉

[1] *State Key Laboratory of Bioactive Molecules and Druggability Assessment, Guangdong Basic Research Center of Excellence for Natural Bioactive Molecules and Discovery of Innovative Drugs, College of Chemistry and Materials Science, and Guangdong Provincial Key Laboratory of Supramolecular Coordination Chemistry, Jinan University, Guangzhou 510632, China*
[2] *Department of Developmental and Regenerative Biology, Jinan University, Guangzhou 510632, China*
[3] *College of Materials and Chemical Engineering, Hubei Provincial Collaborative Innovation Center for New Energy Microgrid, Key Laboratory of Inorganic Nonmetallic Crystalline and Energy Conversion Materials, China Three Gorges University, Yichang 443002, China*
[§] *Pei-Lin Ou and Hong-Tao Gao contributed equally to this work.*

Cite This: *Polyoxometalates*, **2026**, *5*, 9140111

Read Online

ABSTRACT: Dithioesters, which are crucial sulfur-containing derivatives of carboxylic esters, demonstrate broad potential in organic synthesis and biomedicine. However, traditional synthetic methods remain inefficient and pose safety concerns owing to the use of toxic sulfur sources, cumbersome procedures, and/or harsh high-temperature conditions. Herein, we report a direct and green strategy for the synthesis of dithioesters using elemental sulfur, alkyl bromides, and aromatic aldehydes as raw materials. The reaction is catalyzed by metal chalcogenide clusters through single-electron transfer, in combination of hydrogen atom transfer from bromide radicals produced *in situ*. In this system, formamide acts as both a dispersant for the metal chalcogenide clusters and a promoter for acylthio radical formation. Notably, the method shows great substrate compatibility with linear alkyl bromides and aromatic aldehydes while offering advantages such as low-cost feedstocks, simple operational procedures, and mild reaction conditions. This study unveils a new approach to thiocarbonyl bond construction and holds significant promise for applications in organic and pharmaceutical synthesis.



KEYWORDS: metal chalcogenide clusters, dithioesters, single electron transfer, hydrogen atom transfer, cooperative catalysis

1 Introduction

Dithioesters represent sulfur-containing analogs of carboxylate esters, in which both oxygen atoms of the ester group are replaced by sulfur, giving rise to the distinctive –C(=S)S– functionality [1, 2]. Owing to their versatile applications, dithioesters serve as key intermediates in organic synthesis, enabling the preparation of sulfanylated *gem*-difluoroalkenes [3], sulfur-containing heterocycles, and trifluoromethylarenes via oxidative desulfuration–fluorination reactions [4]. In biomedicine, recent studies have highlighted their potential as readily modifiable, cysteine-triggered hydrogen sulfide (H_2S) donors, which mediate essential physiological processes including vasodilation and reactive oxygen species scavenging [5, 6]. In polymer science, dithioesters are crucial as reversible addition–fragmentation chain-transfer agents for controlled polymerization [7, 8]. Additionally, they hold promise in antimicrobial formulations and agrochemicals, underscoring their considerable yet untapped potential (Fig. 1(a)) [9, 10]. Owing to their broad applicability, dithioesters have drawn significant interest in the development of synthetic methodologies (Fig. 1(b)). Conventional approaches generally fall into two categories: (1) the reaction of thiols with acylating agents to produce thioesters, followed by sulfurization with Lawesson's reagent [11, 12] or P_4S_{10} [13] to form the C=S bond; (2) the reaction of Grignard reagents with electrophiles, employing carbon disulfide as the sulfur source [14, 15]. In 2020, Zhao et al. developed an innovative protocol in which thiocarboxylic acids react with ynamides to form α-thioacyloxy enamide intermediates, which subsequently undergo nucleophilic thiolysis to deliver dithioesters [16].

Despite these advances, current methods face critical limitations.

Received: October 15, 2025; **Revised:** December 6, 2025
Accepted: December 31, 2025

✉Address correspondence to Shang-Fu Yuan, sfyuan@jnu.edu.cn; Tao Wu, wutao@jnu.edu.cn

https://doi.org/10.26599/POM.2026.9140111

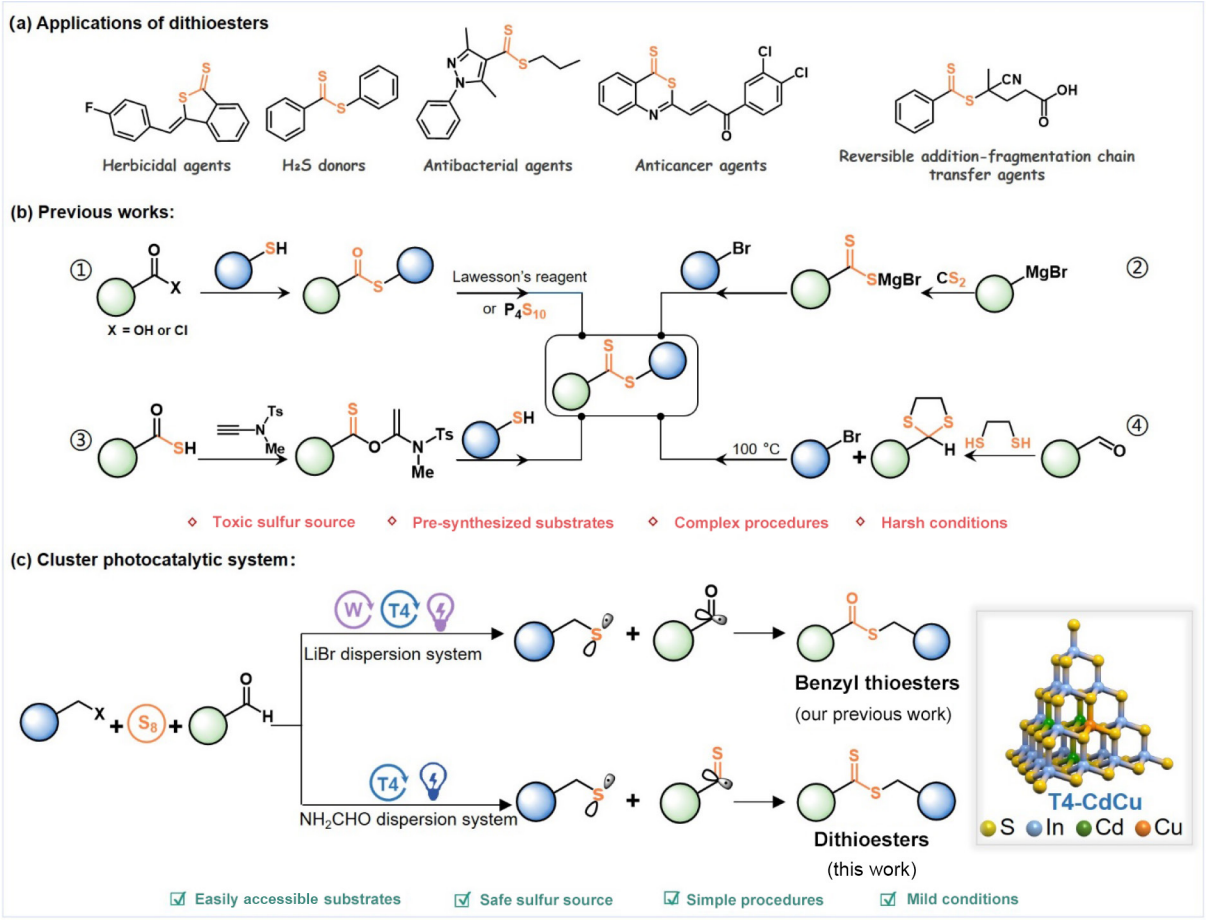


Figure 1 (a) Applications of dithioesters. (b) Previous synthesis methods of dithioesters and their associated drawbacks. (c) Semiconductor cluster photocatalytic system for the synthesis of benzyl thioesters and dithioesters using elemental sulfur, alkyl halides, and aromatic aldehydes under different dispersion conditions. W: tetrabutylammonium decatungstate; T4: T4-CdCu cluster.

The use of thiols—well known for their malodor and toxicity—or the highly flammable and explosive carbon disulfide poses serious operational hazards. Furthermore, certain protocols necessitate the presynthesis of specialized intermediates, leading to multistep procedures and cumbersome handling. Recently, Yucel et al. developed an improved one-pot synthesis strategy for the synthesis of dithioesters using 2-aryl-1,3-dithiolanes and halides [17]. While this approach addressed multiple limitations of previous methodologies, it still relies on presynthesized precursors and demands harsh high-temperature conditions. Therefore, the development of efficient and green synthetic methods for dithioesters remains a central challenge in this field.

The synthesis of dithioesters hinges on the construction of the core –C(=S)S– scaffold, which can be achieved through cross-coupling between alkyl/arylthio radicals and acylthio radicals. In our ongoing work, we have developed metal chalcogenide supertetrahedral clusters, $[Cd_3CuIn_{16}S_{35}]^{15-}$ (**T4-CdCu**), which have demonstrated broad applicability in photocatalytic organic transformations [18, 19]. These processes involve strategic cluster engineering through quantum confinement and Cu^+ doping [20–24], leading to charge-transfer states that reconcile reaction kinetics with thermodynamic feasibility based on Marcus charge-transfer theory [18]. Previous studies have shown that the hydrogen bonding and/or electrostatic interactions involving hydroxylamine ($HONH_2$), hydrazine hydrate ($N_2H_4{\cdot}H_2O$), formamide (NH_2CHO), and lithium bromide (LiBr) create strong forces that effectively stabilize and disperse **T4-CdCu** clusters [18]. Under LiBr-mediated dispersion conditions, we reported a synergistic photocatalytic system that integrates single-electron transfer (SET) from **T4-CdCu** and hydrogen atom transfer (HAT) mediated by tetrabutylammonium decatungstate (**TBADT**), enabling the green synthesis of benzyl thioesters from elemental sulfur, benzyl chlorides, and aldehydes [19]. In this system, **TBADT** functions as the HAT catalyst to generate acyl radicals. However, these acyl radicals do not react with S_8 to form thioacyl radicals, which are considered as the key intermediates in the formation of dithioesters (Fig. 1(c)).

Notably, amine have been shown to react with S_8 under alkaline conditions to form nucleophilic polysulfides, which can attack aldehydes and facilitate the conversion of C=O bonds into C=S bonds [25–27]. On this basis, we anticipated that the **T4-CdCu** photocatalyst, under NH_2CHO dispersion conditions, would promote the formation of acylthio radicals. Importantly, **T4-CdCu** possesses not only a high conduction band minimum energy level but also a strong oxidation potential (E_{ox}(**T4-CdCu**$^{+\cdot}$/**T4-CdCu**)) of +1.01 V vs. the saturated calomel electrode (SCE). Accordingly, we hypothesize that the photoexcited **T4-CdCu*** species can undergo oxidative quenching with alkyl bromide to deliver **T4-CdCu**$^{+\cdot}$, bromide ions, and alkyl radicals, which then react with S_8 to produce the corresponding alkylthio radicals. Meanwhile, single-

electron oxidation of bromide ions ($E^{1/2}_{red}$ = +0.80 V vs. SCE) by **T4-CdCu**$^{+*}$ to generate bromine radicals is thermodynamically favorable. Furthermore, the resulting electrophilic bromine radicals can readily participate in HAT with polysulfide-modified Schiff base intermediates, thereby generating acylthio radicals. Ultimately, coupling between the alkylthio radicals and the corresponding acylthio radicals affords the desired dithioester products.

Herein, we report a novel three-component strategy for dithioester synthesis via semiconductor cluster photocatalysis using readily available sulfide powder (S_8), alkyl bromides, and aromatic aldehydes (Fig. 1(c)). This protocol offers several advantages, including avoidance of highly toxic sulfur sources, elimination of specialized prefunctionalized reagents, and operation under ambient reaction conditions. Mechanistic studies indicate that the reaction proceeds through the integration of cluster photoredox SET with a bromine-involved HAT process, which is facilitated by the cooperative role of the dispersant in forming the key thiocarbonyl functionality.

2 Experimental Methods

2.1 Materials

Indium powder (In, ≥ 99.99 wt.%), sulfur powder (S_8, ≥ 99 wt.%), and copper(I) iodide (CuI, ≥ 98 wt.%) were purchased from Aladdin Industrial Corporation. Cadmium nitrate tetrahydrate ($Cd(NO)_3{\cdot}4H_2O$, AR) and formamide (NH_2CHO, ≥ 99.5 wt.%) were obtained from Macklin Biochemical Co. Ltd. 2-(2-Aminoethylamino)ethanol (AEAE, ≥ 99% wt.%), 1,8-diazabicyclo [5.4.0]undec-7-ene (DBU, 99.0 wt.%), hexamethyleneimine (HMI, 98 wt.%), *N*,*N*-dimethylformamide (DMF, ≥ 99 wt.%), *N*,*N*-dimethylaniline (DMA, ≥ 99 wt.%), ethyl alcohol (EtOH, AR), petroleum ether (PE, AR), ethyl acetate (EtOAc, AR), and tetrahydrofuran (THF, ≥ 99 wt.%) were purchased from Alfa Aesar company. All reagents and solvents were commercially available and used as received without further purification.

2.2 Synthesis of T4-CdCu crystals

The synthesis procedure was adapted from our previous work [18]. A mixture of In powder (115 mg, 1 mmol), sulfide powder (96 mg, 3 mmol), $Cd(NO_3)_2{\cdot}4H_2O$ (67.87 mg, 0.35 mmol), CuI (3.81 mg, 0.02 mmol), AEAE (2 mL), DBU (1 mL), and HMI (1.5 mL) were stirred in a 23 mL Teflon-lined stainless-steel autoclave for 30 min. The autoclave was then sealed and heated at 150 °C for 7 days. After completion of the reaction, the autoclave was allowed to cool to room temperature. The resulting product was collected, washed three times with ethanol, and vacuum-dried to yield yellow crystals (40 mg, yield: 59.5%, based on Cu).

2.3 Preparation of T4-CdCu dispersions

To a 5.0 mL glass vial, 8.0 mg of **T4-CdCu** microcrystals and 0.8 mL of formamide were added, and the mixture was stirred overnight to obtain a yellow suspension. Following centrifugation at 8,000 rpm for 5 min, a clear and transparent cluster dispersion was collected. The freshly prepared **T4-CdCu** dispersion was applied directly in subsequent catalytic reactions. For the *N*-methylformamide dispersion system, 1.3 mL of *N*-methylformamide was used instead of formamide. In the acetamide system, 1.2 g of acetamide was mixed with 2 mL of DMF as the dispersing medium, and the stirring time was extended to 24 h.

2.4 General procedures for the photocatalytic synthesis of benzyl thioesters

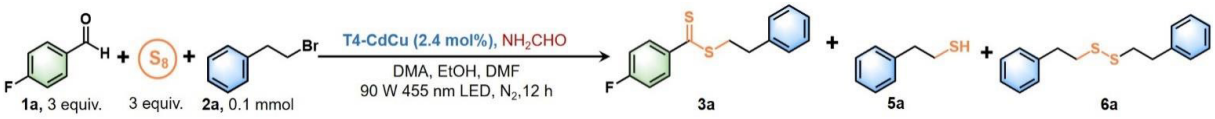
To an oven-dried, rubber-stoppered reaction tube (8.0 mL), S_8 (9.6 mg, 3 equiv), the **T4-CdCu** dispersion, DMA (10 μL, 0.08 mmol), alkyl bromide (0.1 mmol), aldehydes (0.3 mmol, 3 equiv.), and EtOH (50 μL, 8.6 mmol) were added in 2 mL of DMF. The resulting mixture was purged with N_2 for 15–20 min and then sealed. The reaction was stirred and irradiated with 90 W light-emitting diodes (LEDs) (455 nm) for 12 h. Upon completion, the reaction mixture was analyzed via gas chromatography–mass spectrometry (GC–MS). The crude product was purified via thin-layer chromatography using PE/EtOAc as the eluent, and the isolated product was characterized using ^{1}H nuclear magnetic resonance spectroscopy.

3 Results and discussion

3.1 Catalytic system setup

The **T4-CdCu** crystals were successfully synthesized according to the previously reported protocol, and their composition and purity were verified using powder X-ray diffraction, scanning electron microscopy, energy dispersive X-ray spectroscopy, and inductively coupled plasma optical emission spectroscopy (ICP-OES) (Figs. S1 and S2, and Table S1 in the Electronic Supplementary Material (ESM)). For catalyst preparation, the crystals were well-dispersed in formamide with an approximate size of 2 nm, exhibiting a clear Tyndall effect (Figs. S3 and S4 in the ESM) [28]. Herein, **T4-CdCu** was used as the photocatalyst, with S_8 serving as the sulfur source. The reaction between the model substrates 4-fluorobenzaldehyde (**1a**) and (2-bromoethyl) benzene (**2a**) led to the successful synthesis of dithioesters. After systematic optimization of the reaction conditions, the optimal parameters were determined as follows: **2a** (0.1 mmol), **1a** (3 equiv.), S_8 (3 equiv.), 2.4 mol% **T4-CdCu** as the photocatalyst, formamide as the dispersant, 10 μL of DMA, and 50 μL of EtOH in 2 mL of DMF under an N_2 atmosphere, irradiated with a 90 W, 455 nm LED lamp for 12 h. Detailed experimental procedures, a schematic diagram of the photocatalytic reaction setup, and photon flux data of the photocatalytic system are provided in the ESM (Figs. S5 and S6, and Table S2 in the ESM). Under the optimized conditions, the target product **3a** was obtained in 77% yield (Table 1, entry 1). Using a constant catalyst loading, the amounts of substrates could be scaled up fivefold relative to the parameters of the optimal conditions, achieving the highest turnover number of 53 (Table S3 in the ESM). Trace amounts of byproducts 2-phenylethanethiol (**5a**) and disulfide (**6a**), both derived from **1a**, were also detected. This suggests that the phenethylthio radical may act as an intermediate in the reaction. Control experiments showed that dithioesters were not formed in the absence of **T4-CdCu**, DMA, or light (Table 1, entries 2–4), confirming that the photocatalyst, base, and light are essential for the reaction. In addition, the reaction did not proceed under air, suggesting that reactive oxygen species have a significant inhibitory effect on the reaction (Table 1, entry 5). To rule out the potential thermal catalysis, the reaction was conducted at 100 °C without light irradiation; however, no the reaction occurred (Table 1, entry 6), implying that the reaction is driven by photocatalysis. No dithioester product **3a** was detected when the **T4-CdCu** precursor was used instead of **T4-CdCu** clusters (Table 1, entry 7), demonstrating that the inorganic salts are not catalytic.

Table 1 Optimization of the three-component coupling reaction for the synthesis of dithioesters



Entry	Deviation[a]	Yield[b]
1	Nnone	77%
2	Without T4-CdCu	0%
3	Without light	0%
4	Without DMA	0%
5	In air	0%
6	100 °C without light	0%
7	$Cd(NO_3)_2$, CuI, and In powder instead of T4-CdCu	0%
8	Ir compound or Ru compound instead of T4-CdCu	0%
9	THF instead of DMF	0%
10	2.2 equiv. S_8 instead of 3 equiv. S_8	37%
11	0.6 mol% T4-CdCu instead of 2.4 mol% T4-CdCu	32%

[a]Standard conditions: **1a** (3 equiv.), S_8 (3 equiv.), **2a** (0.1 mmol), 2.4 mol% **T4-CdCu**, 10 μL DMA, 50 μL EtOH in 2 mL DMF under the irradiation of 90 W 455 nm LED light. [b]The yield of **3a** was determined by GC-MS. Note: Byproducts phenylethanethiol **5a** and disulfide **6a** derived from alkyl bromides are detected in the reaction. Ir compound: $Ir[dF(CF_3)ppy]_2(dtbpy)PF_6$. Ru compound: $Ru(bpy)_3Cl_2$.

Furthermore, ICP-OES analysis of the solution containing the isolated product (Table S4 in the ESM) revealed metal leaching of only 0.3%. Transmission electron microscopy images of **T4-CdCu** after the reaction (Fig. S7 in the ESM) revealed a cluster size of ~ 2.2 nm, similar to that before catalysis. These results suggest that **T4-CdCu** maintains excellent dispersion and stability, confirming its behavior as a cluster catalyst. Remarkably, when **T4-CdCu** was replaced with common organic photocatalysts such as $Ir[dF(CF_3)ppy]_2(dtbpy)PF_6$ and $Ru(bpy)_3Cl_2$, the target product was not formed (Table 1, entry 8). The yield of **3a** also decreased when alternative solvents were used or when the amounts of S_8 and **T4-CdCu** were reduced (Table 1, entries 9–11). Additional optimization details are provided in Tables S5–S10 in the ESM.

3.2 Substrate scop

With the optimized reaction conditions in hand, we explored the substrate scope of the three-component reaction for dithioesters synthesis (Fig. 2). First, the electronic effects of substituents on the aromatic ring of alkyl bromides were examined. Phenethyl bromides bearing electron-donating groups (–OCH_3, **3b**, 89%; –CH_3, **3c**, 78%) afforded high yields, while those with electron-withdrawing groups (–F, **3d**, 71%; –Br, **3e**, 77%; –CN, **3f**, 76%) provided comparable results, indicating broad substituent tolerance. In addition, linear alkyl bromides (**3g**–**3j**) produced yields ranging from moderate to good (57%–84%), whereas cycloalkane bromides (**3k** and **3l**) showed significantly reduced efficiency. To investigate whether electronic or steric effects govern the low conversion of cyclic alkyl bromides, complementary experiments were performed using 2-bromopentane and 2-bromo-2-methylbutane as branched alkyl bromide substrates. The results showed that **3m** was obtained with 61% yield, whereas no target product **3n** was detected (Fig. S8 in the ESM), suggesting a direct correlation between increased steric hindrance and low product yield. Therefore, the low reaction efficiency for cyclic alkyl bromines is primarily attributable to the substantial steric hindrance imposed by their cyclic substituents. Overall, this catalytic system effectively accommodates linear alkyl bromides with diverse substituents, although further optimization is necessary to improve reactions with cyclic alkyl bromides. In addition, when benzyl chloride was used as the substrate, nearly complete conversion to the dithioester **3o** was observed (Fig. S8 in the ESM). This enhanced reactivity is attributable to the less negative reduction potential of benzyl chloride (−1.55 V vs. SCE) compared with **2a** (−2.58 V vs. SCE) [19, 29], which facilitates the activation of benzyl chloride under the reaction conditions.

Moreover, the current photocatalytic protocol is well-suited for a series of aromatic aldehydes with diverse ring structures and substitution patterns (**4a**–**4j**, Fig. 2). Experimental results demonstrated that heteroaromatic and fused-ring aldehydes, including thiophene-2-carbaldehyde (**4a**), furan-2-carbaldehyde (**4b**), and naphthalene-1-carbaldehyde (**4c**), were efficiently converted to the corresponding target dithioesters with excellent yields (73%–84%). Further investigation of benzaldehyde derivatives unveiled effective product formation with both electron-donating substituents (**4d**: –OMe, 61%; **4e**: –^{t}Bu, 84%; **4f**: –SMe, 61%) and electron-withdrawing substituents (**4g**: –Cl, 77%; **4h**: –Br, 82%; **4i**: –I, 76%; **4j**: –CF_3, 91%). Notably, for reduction-sensitive substituents such as –Br and –I, only 5% and 9% dehalogenation were observed, and no phenylthiobenzene ester products were detected. This observation highlights notable differences in the activation thresholds between aryl and alkyl halides, consistent with our previous findings [18]. For comparison, several alkyl aldehydes, including 3-phenylpropanal, butyraldehyde, and 1-formylcyclohexane, were also investigated; however, none underwent the reaction. The lack of reactivity in alkyl aldehydes is likely owing to (1) the electron-donating nature of alkyl groups, which reduces the electrophilicity of the carbonyl carbon and impedes the formation of the iminium intermediate with formamide; (2) the resulting alkyl acylthio radicals, which lack a stabilizing conjugated system, leading to poor stability and preventing progression of the subsequent reaction. These findings collectively emphasize the remarkable compatibility of the current photocatalytic system with a wide range of aromatic aldehydes.

Traditionally, dithioesters are synthesized via two main methods: (1) thioester sulfurization through Lawesson's reagent [11] or P_4S_{10} [13]; (2) reaction of Grignard reagents with carbon disulfide [14,

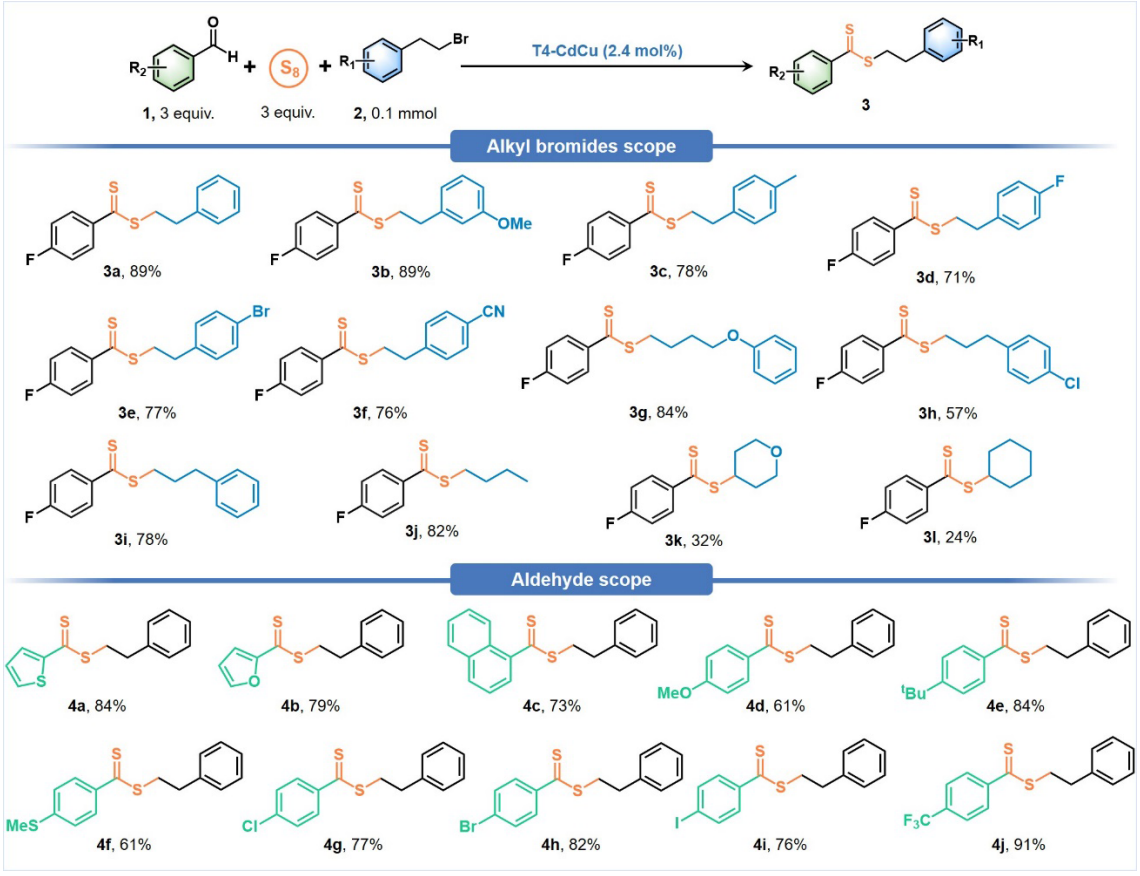


Figure 2 Substrate scope for the access of dithioesters. Standard conditions: 1 (3 equiv.), S_8 (3 equiv.), 2 (0.1 mmol), 2.4 mol% T4-CdCu, 10 μL DMA, 50 μL EtOH in 2 mL DMF under the irradiation of 90 W 455 nm LED light. Note: The yield was determined by GC-MS.

15]. Although these methods are widely used, they present challenges such as complex operations and safety concerns. Alternative methods involve thioacylating reagents and transesterification reactions, which offer more convenient synthetic routes [30, 31]. Nonetheless, most thioacylating reagents are highly unstable and require complicated, multistep presynthesis. Herein, a general strategy was proposed for the direct conversion of aromatic aldehydes into the corresponding dithioesters using sulfer powder in a semiconductor cluster-based photocatalytic system. The present approach offers several advantages: (1) It employs S_8, an abundant, nontoxic, and odorless sulfur source; (2) it operates under mild conditions, with visible-light (455 nm) irradiation at room temperature; (3) it is compatible with simple, commercially available chemicals (alkyl bromides and aromatic aldehydes) as coupling partners [32, 33]; (4) it provides access to a wide range of dithioesters with high functional-group tolerance and impressive yields (up to 91%) in a one-pot reaction. Overall, this study provides a direct and green alternative for dithioester synthesis via photocatalysis using readily available feedstocks (e.g., S_8, alkyl bromides, and aromatic aldehydes).

3.3 Mechanistic study

To elucidate the mechanism of photocatalytic dithioester synthesis, several trapping experiments were conducted. No target product **3a** was formed when the electron acceptor 2,3-dichloro-5,6-dicyano-1,4-benzoquinone was added to the model reaction system, suggesting that an electron transfer process is involved in the reaction. In addition, the introduction of 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO), a radical scavenger, completely suppressed the reaction, reinforcing the conclusion that radical intermediates play a key role in the crucial reaction steps (Fig. 3(a)). The dual inhibition observed suggests that the photocatalytic process proceeds via a composite mechanism, involving contributions from both electron transfer and radical transfer. Meanwhile, the apparent quantum efficiency (AQE) of the model reaction using substrates **1a** and **2a** was determined to be 0.4%. This low AQE value excludes the possibility of a radical chain mechanism and demonstrates the inherent challenges of the reaction [34].

To identify the specific intermediates involved in the photocatalytic reaction, control experiments were conducted from multiple perspectives. The absence of **1a** in the reaction system resulted in the detection of phenylethanethiol **5a** via GC–MS (Fig. 3(b)), implying that the phenethyl radical, generated after debromination of **2a**, was intercepted by sulfur powder, leading to the formation of the phenethylthio radical intermediate **II** (Fig. 4(c)). To verify that the activation of the aldehyde substrate in the system depends on the presence of bromide ions, **5a** was used in place of **2a** as the reaction precursor (Fig. 3(c)). Under these conditions, neither the target product nor the characteristic signals of thio derivatives **7a**, **8a**, or other products of aldehydes were detected. This confirms that in the absence of a bromide source, aldehydes remain unactivated. However, when LiBr reagent was incorporated into the above reaction (Fig. 3(d)), both products **3a** and **9a** were detected simultaneously, indicating that the reaction activity was restored. These results confirm the crucial role of Br^- in the catalytic cycle and imply the formation of the thioacyl radical

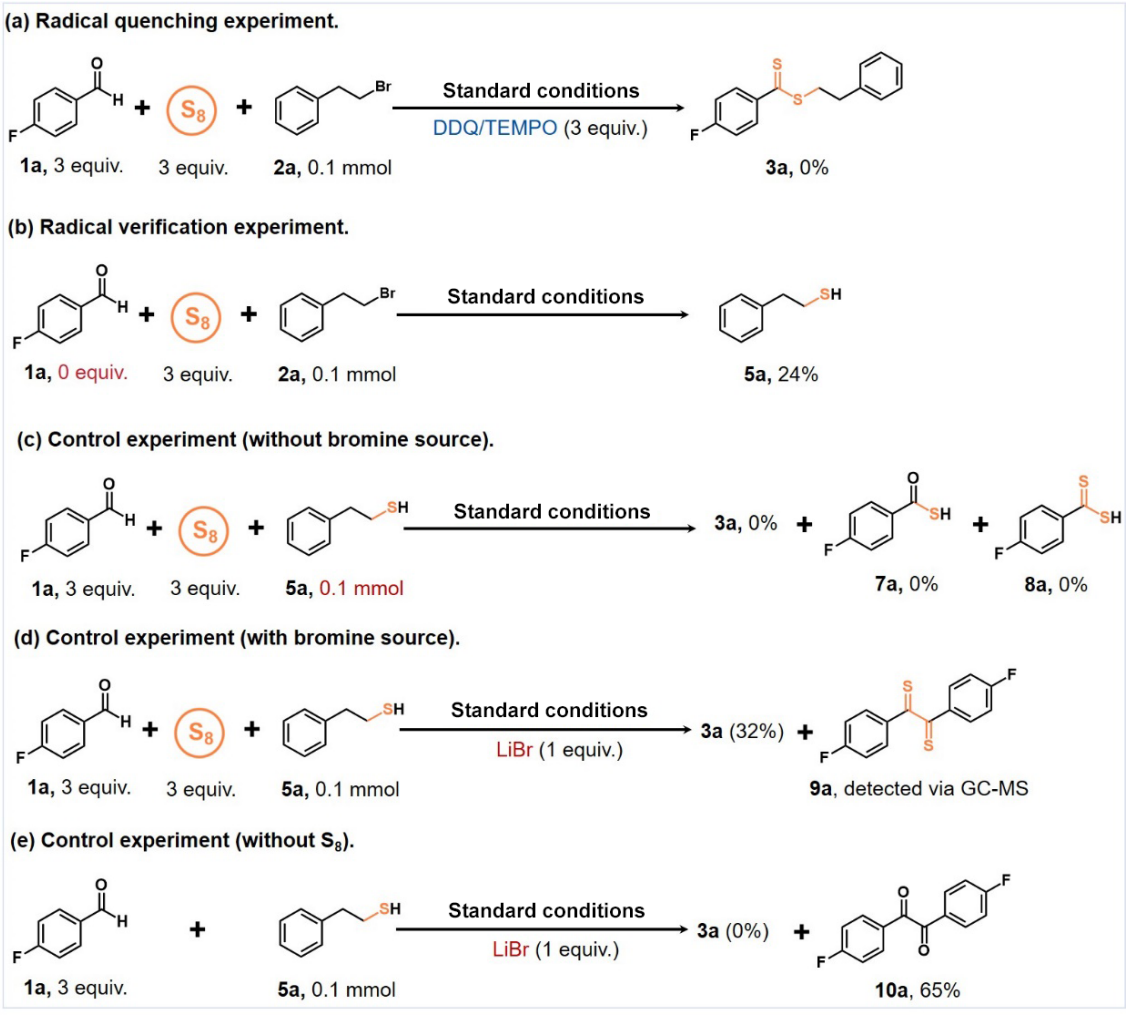


Figure 3 Experiments for mechanism validation. (a) Radical quenching experiment. (b) Radical verification experiment. (c) Controlled experiment (without bromine source). (d) Control experiment (with bromine source). (e) Control experiment (without S_8). DDQ: 2,3-dichloro-5,6-dicyano-1,4-benzoquinone. TEMPO: 2,2,6,6-tetramethyl-1-piperidinyloxy.

intermediate **VII** during the reaction (Fig. 4(c)). To further verify the role of S_8, the experiment in Fig. 3(d) was repeated without S_8. Under these conditions, only product **10a** was detected (Fig. 3(e)), demonstrating that S_8 is an indispensable sulfur source for constructing the thiocarbonyl (C=S) moiety in this system.

Previous studies have established that sulfur powder cannot directly react with acyl radicals to generate intermediate **VII** [35], prompting us to investigate the key role of the dispersant (formamide) in promoting the formation of **VII** in the reaction system. Specifically, formamide plays two pivotal functions: 1) Upon deprotonation by a base, it reacts with S_8 to form polysulfide species **III** [25–27]; 2) it can also react with the aromatic aldehyde (e.g., **1a**) to generate an electron-deficient iminium species **IV** [36], which undergoes nucleophilic addition by the polysulfide ion, facilitating the formation of key intermediate **V**. Then, intermediate **V** can readily undergo a HAT process with the bromine radical to generate the acylthio radical intermediate **VII**. To validate this hypothesis, control experiments were performed using acetamide and *N*-methylformamide as alternative dispersants. Remarkably, both substituted dispersants effectively promoted the reaction, affording the target product **3a** in yields of 67% and 86%, respectively (Table S11 in the ESM). Additionally, the ultraviolet–visible absorption spectrum of the reaction mixture showed no significant peaks in the range of 550–650 nm (Fig. S9 in the ESM). Combined with the absence of trisulfur anion radical signals in the electron paramagnetic resonance spectrum (Fig. S10 in the ESM), these results confirm that the reaction does not involve the participation of the trisulfur anion radical [37, 38].

In emission titration experiments, **2a** effectively quenched the photoluminescence (PL) of **T4-CdCu** in DMF (Fig. 4(a)). Using the Stern–Volmer equation, the quenching constant (K_q) was determined to be 2.78×10^6 $M^{-1}\cdot s^{-1}$ (Fig. 4(b)) [39]. This suggests that the excited-state **T4-CdCu*** species can reduce **2a** to generate alkyl radical **I** and Br^-, a process that is thermodynamically feasible. Based on the Tauc plot and cyclic voltammogram of **T4-CdCu** (Figs. S11 and S12 in the ESM), the reduction potential (E_{red}) of **T4-CdCu** is –2.70 V vs. SCE, and its oxidation potential (E_{ox}(**T4-CdCu$^{+\cdot}$/T4-CdCu**)) is +1.01 V vs. SCE. Because this oxidation potential is more positive than the one-electron oxidation of Br^- (+0.80 V vs. SCE), the generation of bromine radical is thermodynamically favorable [40]. Therefore, oxidated **T4-CdCu$^{+\cdot}$** can abstract electrons from Br^-, thereby oxidizing Br^- to $Br^\cdot$.

Based on the above results, a plausible mechanism is proposed in Fig. 4(c). Upon photoexcitation, **T4-CdCu** is first excited to generate the **T4-CdCu*** state. This excited species then donates an electron to **1a** through a SET process, resulting in the cleavage of

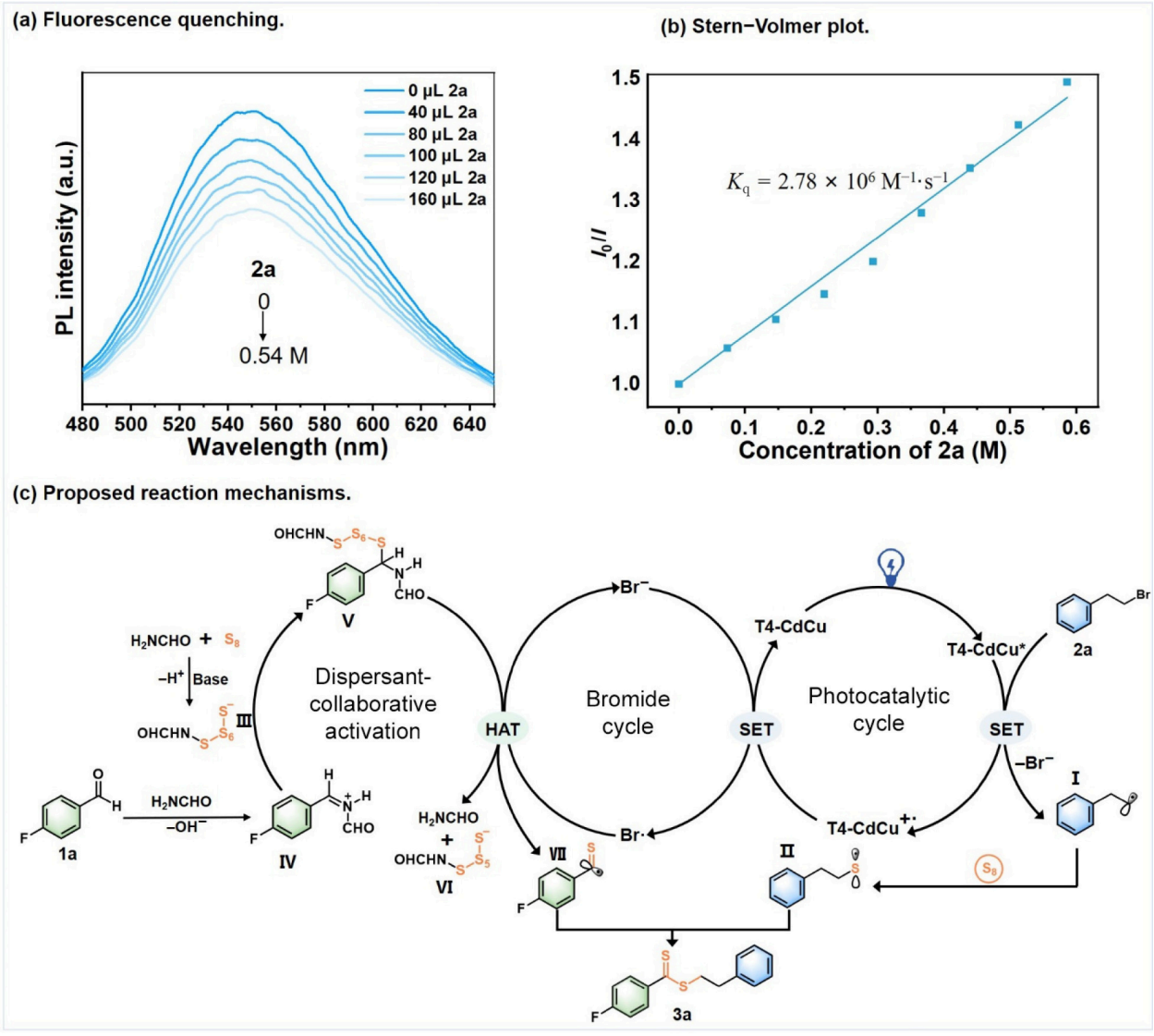


Figure 4 (a) Fluorescence quenching. (b) Stern–Volmer plot. (c) Proposed reaction mechanism.

the C–Br bond in **1a** and the formation of the phenethyl radical **I** and Br^-, along with the simultaneous generation of the oxidized intermediate **T4-CdCu**$^{+\bullet}$. A second SET occurs between the oxidized **T4-CdCu**$^{+\bullet}$ and Br^-, producing $Br^\bullet$ and regenerating **T4-CdCu**. The generated phenethyl radical **I** triggers the ring-opening of the sulfur chain via nucleophilic addition with S_8, forming the phenethylthio radical intermediate **II**. Concurrently, formamide reacts with S_8 and loses one proton under base conditions to generate the polysulfide anion **III**, while substrate **1a** reacts with formamide to form the iminium intermediate **IV**. In this case, the nucleophilic polysulfide **III** undergoes an addition reaction with **IV**, yielding intermediate **V**. Afterward, a HAT process occurs between intermediate **V** and $Br^\bullet$, converting $Br^\bullet$ back to Br^- and leading to the elimination of NH_2CHO and polysulfide **VI**, which produces the acylthio radical intermediate **VII**. Finally, intermediate **VII** undergoes a cross-coupling reaction with alkylthio radical **II** to yield the target dithioester product **3a**.

4 Conclusions

Herein, a simple and efficient protocol for the straightforward construction of dithioesters was developed via the three-component coupling of S_8, aromatic aldehydes, and alkyl bromides using the **T4-CdCu** photocatalyst. The system allows for the efficient synthesis of diverse dithioesters with excellent functional-group compatibility and impressive yields (up to 91%) in a one-pot reaction under mild conditions. The collaborative activation of the dispersant NH_2CHO facilitates the generation of key thiocarbonyl intermediates. This study pioneers a sustainable photocatalytic approach for dithioester synthesis through cooperative SET and HAT catalysis using economical and environmentally friendly feedstocks. We anticipate that this strategy will inspire the development of additional novel sulfur-containing compounds through semiconductor cluster photocatalysis.

Electronic Supplementary Material: Supplementary material (physical measurements, catalyst characterization, optimization of photocatalytic systems, apparent quantum efficiency measurement, ^{1}H NMR, ^{13}C NMR, and ^{19}F NMR spectra) is available in the online version of this article at https://doi.org/10.26599/POM.2026.9140111.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

Acknowledgments

We acknowledge the National Natural Science Foundation of China (Nos. 92261205, 92461309, 22201103, 22571121, and U22A20432) and the 111 Project (No. D20015). This work was supported by Science and Technology Project in Guangzhou (No. 202102070001).

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

P.-L. O. and H.-T. G.: Data curation, project administration, validation, writing manuscript, experimental design. C.-L. C. and H. M.: Experimental design and data collection. B. Z. W., R. Z., D.-S. L., S.-F. Y., and T. W.: Project administration, funding acquisition, and writing manuscript. All the authors have approved the final manuscript.

Use of AI statement

During the preparation of this work, the authors used ChatGPT in order to revise the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

[1] Sun, Q.; Xu, Y.; Yang, L.; Zheng, C. L.; Wang, G. W.; Wang, H. B.; Fang, Z.; Wang, C. S.; Guo, K. Direct C−H sulfuration: Synthesis of disulfides, dithiocarbamates, xanthates, thiocarbamates and thiocarbonates. *Chem.—Asian J.* **2024**, *19*, e202400124.

[2] Hazra, G.; Masarwa, A. Synthesis and functionalization of thiophosphonium salts: A divergent approach to access thioether, thioester, and dithioester derivatives. *Org. Lett.* **2023**, *25*, 6396–6400.

[3] Takayama, R.; Yamada, A.; Fuchibe, K.; Ichikawa, J. Synthesis of sulfanylated difluoroalkenes: Electrophilic difluoromethylidenation of dithioesters with difluorocarbene. *Org. Lett.* **2017**, *19*, 5050–5053.

[4] Döbele, M.; Wiehn, M. S.; Bräse, S. Traceless solid-phase synthesis of trifluoromethylarenes. *Angew. Chem., Int. Ed.* **2011**, *50*, 11533–11535.

[5] Cerda, M. M.; Newton, T. D.; Zhao, Y.; Collins, B. K.; Hendon, C. H.; Pluth, M. D. Dithioesters: Simple, tunable, cysteine-selective H_2S donors. *Chem. Sci.* **2019**, *10*, 1773–1779.

[6] Urquhart, M. C.; Dao, N. V.; Ercole, F.; Boyd, B. J.; Davis, T. P.; Whittaker, M. R.; Quinn, J. F. Polymers with dithiobenzoate end groups constitutively release hydrogen sulfide upon exposure to cysteine and homocysteine. *ACS Macro Lett.* **2020**, *9*, 553–557.

[7] Huang, Y.; Sun, Y.; Weng, Y. Y.; Zhang, W. D. A simple and green oxygen-tolerant RAFT polymerization without additional catalyst and initiator. *ChemistrySelect* **2022**, *7*, e202201583.

[8] Chen, M.; Zhang, W. G.; Li, J. W.; Hong, C. Y.; Zhang, W. J.; You, Y. Z. Preparation of pH-and reductive-responsive prodrug nanoparticles via polymerization-induced self-assembly. *Sci. China Chem.* **2018**, *61*, 1159–1166.

[9] Giofrè, S. V.; Mancuso, R.; Araniti, F.; Romeo, R.; Iannazzo, D.; Abenavoli, M. R.; Gabriele, B. Microwave-assisted synthesis of sulfurated heterocycles with herbicidal activity: Reaction of 2-alkynylbenzoic acids with Lawesson's reagent. *ChemPlusChem* **2019**, *84*, 942–950.

[10] Majed, H.; Johnston, T.; Kelso, C.; Monachino, E.; Jergic, S.; Dixon, N. E.; Mylonakis, E.; Kelso, M. J. Structure-activity relationships of pyrazole-4-carbodithioates as antibacterials against methicillin-resistant *Staphylococcus aureus*. *Bioorg. Med. Chem. Lett.* **2018**, *28*, 3526–3528.

[11] Khatoon, H.; Abdulmalek, E. A focused review of synthetic applications of Lawesson's reagent in organic synthesis. *Molecules* **2021**, *26*, 6937.

[12] He, L. T.; Jiang, Q.; Gao, R. Z.; Yang, X. S.; Feng, W.; Luo, S. Z.; Yang, Y. Q.; Yang, L.; Yuan, L. H. Crescent aromatic oligothioamides as highly selective receptors for copper(II) ion. *Sci. China Chem.* **2014**, *57*, 1246–1256.

[13] Sudalai, A.; Kanagasabapathy, S.; Benicewicz, B. C. Phosphorus pentasulfide: A mild and versatile catalyst/reagent for the preparation of dithiocarboxylic esters. *Org. Lett.* **2000**, *2*, 3213–3216.

[14] Cortez-Lemus, N. A.; Salgado-Rodríguez, R.; Licea-Claveríe, A. Preparation of α,ω-telechelic hexyl acrylate polymers with –OH, –COOH, and $–NH_2$ functional groups by RAFT. *J. Polym. Sci. Part A Polym. Chem.* **2010**, *48*, 3033–3051.

[15] Gonzalo-Barquero, A.; Lepoittevin, B.; Rouden, J.; Baudoux, J. Synthesis and reactivity of fluorinated dithiocarboxylates to prepare thioamides-effective access to a 4-styrenylthioamide-cinchona alkaloid monomer. *Molecules* **2023**, *28*, 7333.

[16] Yao, C. C.; Yang, J. H.; Lu, X. B.; Zhang, S. Y.; Zhao, J. F. Ynamide-mediated thionoester and dithioester syntheses. *Org. Lett.* **2020**, *22*, 6628–6631.

[17] Pelit, H.; Sinmaz, M. A.; Ildem, O. A.; Mert, Z.; Turhan, Y. E.; Aydin, E.; Yilmaz, S. D.; Mentese, A.; Yucel, B. Synthesis of dithioester derivatives by base-mediated fragmentation of 1,3-dithiolanes. *Org. Lett.* **2025**, *27*, 4135–4139.

[18] Ma, H.; Han, C. K.; Liu, J. X.; Xu, Y. L.; Chen, C. L.; Zhong, X. H.; Chen, L. Y.; Zhou, R.; Wang, B. Z.; Wang, J. H. et al. Semiconductor cluster with high reduction potential and efficient charge transfer enables visible-light-driven activation of inert organic substrates. *Angew. Chem., Int. Ed.* **2025**, *64*, e202509764.

[19] Gao, H. T.; Ou, P. L.; Ma, H.; Zhang, H.; Zhang, L. M.; Xu, Y. L.; Guo, Y. Z.; Hao, D. B.; Chen, C. L.; Li, D. S. et al. Single electron transfer/hydrogen atom transfer synergistic catalysis for green synthesis of benzyl thioesters. *Green Chem.* **2025**, *27*, 9768–9776.

[20] Zhang, J. X.; Feng, P. Y.; Bu, X. H.; Wu, T. Atomically precise metal chalcogenide supertetrahedral clusters: Frameworks to molecules, and structure to function. *Natl. Sci. Rev.* **2022**, *9*, nwab076.

[21] Zhang, J. X.; Bu, X. H.; Feng, P. Y.; Wu, T. Metal chalcogenide supertetrahedral clusters: Synthetic control over assembly, dispersibility, and their functional applications. *Acc. Chem. Res.* **2020**, *53*, 2261–2272.

[22] Wu, T.; Zhang, Q.; Hou, Y.; Wang, L.; Mao, C. Y.; Zheng, S. T.; Bu, X. H.; Feng, P. Y. Monocopper doping in Cd–In–S supertetrahedral nanocluster via two-step strategy and enhanced photoelectric response. *J. Am. Chem. Soc.* **2013**, *135*, 10250–10253.

[23] Grandhi, G. K.; Tomar, R.; Viswanatha, R. Study of surface and bulk electronic structure of II-VI semiconductor nanocrystals using Cu as a nanosensor. *ACS Nano* **2012**, *6*, 9751–9763.

[24] Xu, Q. H.; Gong, X. K.; Zhao, Z. X.; Wang, L.; Sun, J.; He, J. L.; Li, S. M.; Shen, H. Comprehensive and practical guidelines for reduction synthesis of atomically precise coinage-metal nanoclusters. *Polyoxometalates* **2025**, *4*, 9140075.

[25] Jin, H.; Ge, X.; Zhou, S. D. General construction of thioamides under mild conditions: A stepwise proton transfer process mediated by EDTA. *Eur. J. Org. Chem.* **2021**, *2021*, 6015–6021.

[26] Li, X. T.; Pan, Q.; Hu, R. H.; Wang, X.; Yang, Z.; Han, S. Q. S_8-mediated one-pot synthesis of thioamides from benzyl chlorides and amines. *Asian J. Org. Chem.* **2016**, *5*, 1353–1358.

[27] Nguyen, T. B.; Retailleau, P. Sulfur-promoted decarboxylative sulfurative hexamerization of phenylacetic acids: Direct approach to hexabenzylidyne tetrasulfides. *Org. Lett.* **2019**, *21*, 279–282.

[28] Xue, C. Z.; Zhang, L.; Wang, X.; Hu, D. D.; Wang, X. L.; Zhang, J. X.; Zhou, R.; Li, D. S.; Su, H. F.; Wu, T. Enhanced water dispersibility of discrete chalcogenide nanoclusters with a sodalite-net loose-packing pattern in a crystal lattice. *Inorg. Chem.* **2020**, *59*, 15587–15594.

[29] Connell, T. U.; Fraser, C. L.; Czyz, M. L.; Smith, Z. M.; Hayne, D. J.; Doeven, E. H.; Agugiaro, J.; Wilson, D. J. D.; Adcock, J. L.; Scully, A. D. et al. The tandem photoredox catalysis mechanism of $[Ir(Ppy)_2(Dtb\text{-}Bpy)]^+$ enabling access to energy demanding organic substrates. *J. Am. Chem. Soc.* **2019**, *141*, 17646–17658.

[30] Yeo, S. K.; Choi, B. G.; Kim, J. D.; Lee, J. H. A convenient method for the synthesis of thiobenzamide derivatives and O-thiobenzoates by use of 2-benzothiazolyl dithiobenzoate as effective thiobenzoylation reagent. *Bull. Korean Chem. Soc.* **2002**, *23*, 1029–1030.

[31] Newton, J. J.; Britton, R.; Friesen, C. M. Base-catalyzed transesterification of thionoesters. *J. Org. Chem.* **2018**, *83*, 12784–12792.

[32] Nguyen, T. B. Recent advances in organic reactions involving elemental sulfur. *Adv. Synth. Catal.* **2017**, *359*, 1066–1130.

[33] Zheng, N.; Gao, H.; Jiang, Z. H.; Song, W. Z. Multicomponent polymerization of sulfur, chloroform and diamine toward polythiourea. *Sci. China Chem.* **2023**, *66*, 870–877.

[34] Yang, Q. N.; Li, X. Y.; Chen, L.; Han, X. Y.; Wang, F. R.; Tang, J. W. Effective activation of strong C−Cl bonds for highly selective photosynthesis of bibenzyl via homo-coupling. *Angew. Chem., Int. Ed.* **2023**, *135*, e202307907.

[35] Tang, H. D.; Zhang, M. L.; Zhang, Y. C.; Luo, P. H.; Ravelli, D.; Wu, J. Direct synthesis of thioesters from feedstock chemicals and elemental sulfur. *J. Am. Chem. Soc.* **2023**, *145*, 5846–5854.

[36] Wu, J. Y.; Liao, Y. Y.; Pan, M. Y.; Song, T. T.; Zhang, J.; Li, L.; Lu, J. M.; Jiang, X. F. Synthesis of alkyl thioamides by three-component reactions of allyl alcohols, elemental sulfur and amines: Elemental sulfur as a mild oxidant and a sulfur source. *Green Chem.* **2025**, *27*, 12160–12165.

[37] Tan, W.; Wang, C. H.; Jiang, X. F. Green carbon disulfide surrogate via a combination of potassium sulfide and chloroform for benzothiazine-thione and benzothiazole-thione construction. *Org. Chem. Front.* **2018**, *5*, 2390–2394.

[38] Tan, W.; Jänsch, N.; Öhlmann, T.; Meyer-Almes, F. J.; Jiang, X. F. Thiocarbonyl surrogate via combination of potassium sulfide and chloroform for dithiocarbamate construction. *Org. Lett.* **2019**, *21*, 7484–7488.

[39] Ye, C.; Zhang, D. S.; Chen, B.; Tung, C. H.; Wu, L. Z. Interfacial charge transfer regulates photoredox catalysis. *ACS Cent. Sci.* **2024**, *10*, 529–542.

[40] Sun, Z. Z.; Huang, H. W.; Wang, Q. L.; Huang, C. Y.; Mao, G. J.; Deng, G. J. Visible light-mediated radical-cascade addition/cyclization of arylacrylamides with aldehydes to form quaternary oxindoles at room temperature. *Org. Chem. Front.* **2022**, *9*, 3506–3514.

Peilin Ou is currently studying at the School of Chemistry and Chemical Engineering of Jinan University, pursuing a master's degree. Her main research area is cluster organic photocatalysis.

Hongtao Gao is a 2025 master's graduate from the College of Chemistry and Materials at Jinan University. His research mainly focuses on cluster and polyoxometalate cooperative catalysis.

Shangfu Yuan graduated from Xiamen University in 2018. From 2018 to 2020, he conducted postdoctoral research at Tsinghua University under the guidance of Professor Wang Quanming. In 2021, he joined Jinan University and was appointed as a specially-appointed professor. His research interests mainly lie in the controlled synthesis of atomic-precise metal nanoclusters and the study of their photocatalytic properties.

Tao Wu graduated from the University of California, Riverside in 2011. From 2011 to 2012, he continued his postdoctoral research at this institution. From 2012 to 2021, he served as a professor at Soochow University. Subsequently, since 2021, he has been a professor at the College of Chemistry and Materials of Jinan University. His research mainly focuses on the creation of metal chalcogenide nanoclusters and the study of their electro/photo-catalytic properties, with particular attention to the photocatalytic conversion of organic molecules with inert bonds and energy-containing small molecules.