ChemComm

HIGHLIGHT

View Article Online
View Journal | View Issue

Cite this: *Chem. Commun.*, 2024, **60**, 14691

New Frontiers in phosphorothioate formation: harnessing inorganic phosphorus sources

Jiawei He, Xuesi Zhou, Zixuan Wan, Hua Cao and Xiang Liu *

Received 1st November 2024,
Accepted 18th November 2024

DOI: 10.1039/d4cc05854b

rsc.li/chemcomm

Organic phosphorothioates are a class of organic compounds containing the C–S–P structural motif, known for their unique physical and chemical properties. These compounds hold significant value in various fields, including agriculture, pharmaceuticals, and materials science, particularly playing a crucial role in agrochemicals and nucleotide modification. Traditionally, phosphorothioates have been synthesized primarily through the formation of P–S bonds or direct phosphorothioation reactions from organic phosphorus sources such as P(O)H and P(O)SH. In recent years, new strategies utilizing inorganic phosphorus sources, such as P_4S_{10} and white phosphorus (P_4), have emerged as a dynamic area of research. This review highlights the latest advancements in the synthesis of phosphorothioates and phosphoropolythioates from inorganic phosphorus sources, focusing on their applicability, mechanisms, current limitations, and potential future directions.

Organophosphorothioates are a class of organic compounds characterized by the C–S–P structural motif. These compounds possess unique physical and chemical properties, making them valuable in various fields such as agriculture, pharmaceuticals, and materials science.[1–3] In particular, they exhibit potent insecticidal and acaricidal activities as pesticides and herbicides in the agrochemical industry (Scheme 1). For instance, iprobenfos (*O*,*O*-diisopropyl *S*-benzyl phosphorothioate) is a widely utilized fungicide in agriculture, valued for its efficacy and versatility in crop protection. In medicinal chemistry, phosphorothioates play a crucial role as intermediates in nucleotide synthesis, providing enhanced stability and resistance to enzymatic degradation. Moreover, these compounds are widely explored in biologically active molecules with antifungal, antibacterial, antiparasitic, and anticancer properties. The versatility and reactivity of phosphorothioates make them important subjects in both fundamental research and practical applications.

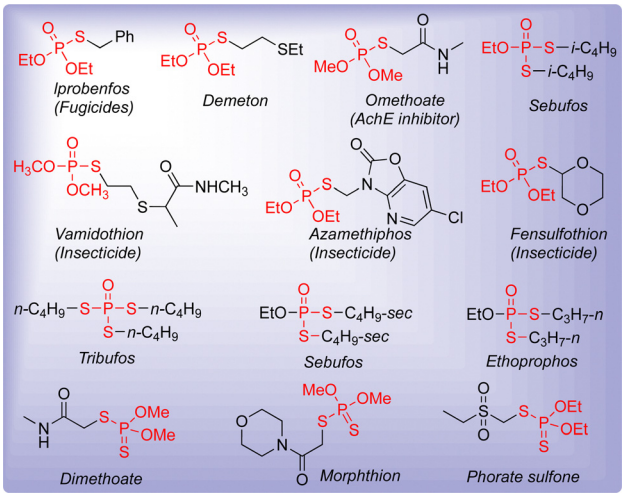
School of Chemistry and Chemical Engineering and Guangdong Cosmetics Engineering & Technology Research Center, Guangdong Pharmaceutical University, Zhongshan 528458, China. E-mail: liux96@gdpu.edu.cn

Jiawei He

Jiawei He studied applied chemistry at Guangdong Pharmaceutical University and received her bachelor's degree in 2024. She is currently pursuing for her master's degree at this university under the guidance of Associate Professor Xiang Liu. Her research interests focus on the efficient construction of N-heterocycles and the development and reaction research of new sulfurization reagents.

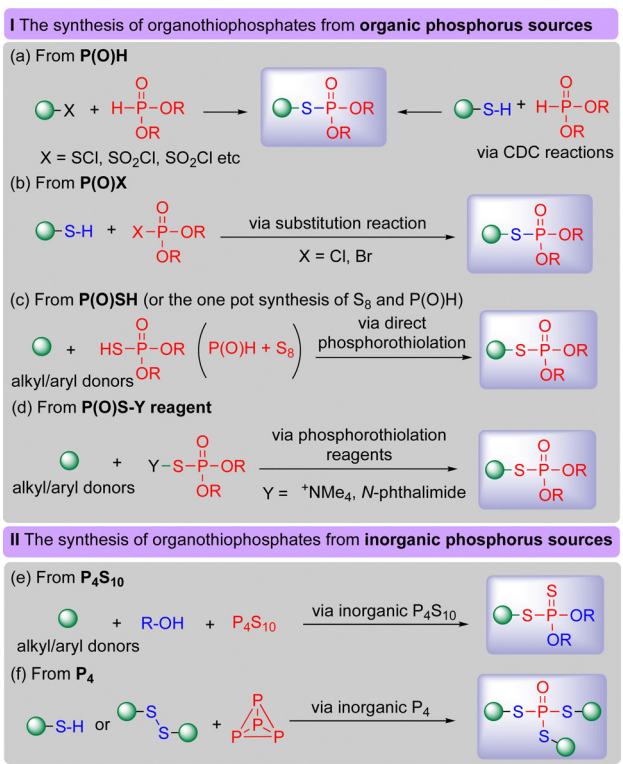
Xiang Liu

Xiang Liu is an Associate Professor at the School of Chemistry and Chemical Engineering, Guangdong Pharmaceutical University. He received his PhD degree in Organic Chemistry from Sun Yat-sen University under the supervision of Prof Xiaodan Zhao, where his research focused on asymmetric catalysis and synthesis. After completing his PhD in 2019, he joined Guangdong Pharmaceutical University to start his independent research career. During 2023 to 2024, he started as visiting scholar at the UCSD, US, where his research focused on design and synthesis of organic functional molecules. His current research interests include organic synthetic methodology and medicinal chemistry.



Scheme 1 Representative examples of bioactive phosphorothioates.

Traditionally, the synthesis of phosphorothioates has primarily relied on the formation of P–S bonds or the direct phosphorothioation from organic phosphorus sources.[4] Based on the type of phosphorus source, these methods can be classified into four main categories: (1) Arbuzov-type or cross dehydrogenation coupling reactions of P(O)H with sulfonyl halides, sulfohalides, disulfides, or thiophenols (Scheme 2(a)); (2) substitution reactions of P(O)Cl or P(O)Br with thiophenols (Scheme 2(b)).[5] One drawback of these two methods is the requirement for reagents that are sensitive to heat and moisture



Scheme 2 The synthesis of phosphorothioates from different phosphorus sources.

or emit an unpleasant odor; (3) direct phosphorothioation with alkyl or aryl donors with P(O)SH (or *in situ* generation from P(O)H and S_8), which allows the direct introduction of the –S–P(O)(OR)$_2$ group into parent molecules (Scheme 2(c));[6–8] (4) direct phosphorothiolation reactions, which utilize either electrophilic or nucleophilic phosphorothiolation reagents, are often hampered by the necessity for prior preparation of these reagents (Scheme 2(d)).[9,10]

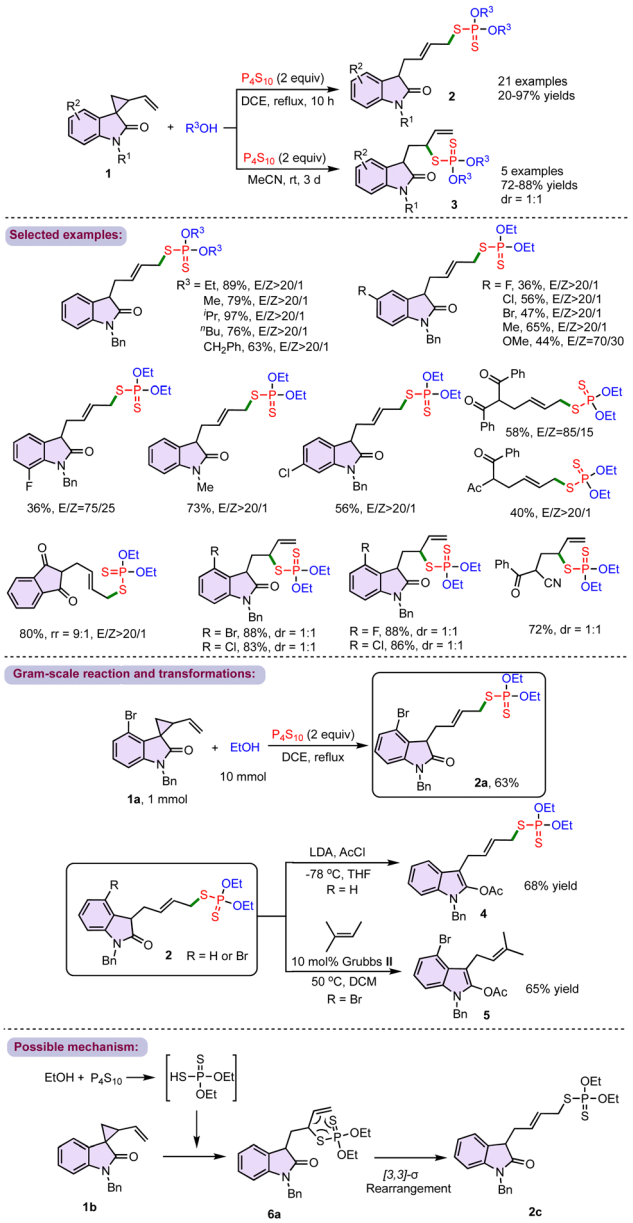
In recent years, new strategies utilizing inorganic phosphorus sources such as P_4S_{10} and P_4 have emerged, becoming an active area for the synthesis of phosphorothioates, and phosphoropolythioates (Schemes 2(e) and (f)).[11] This review presents the latest advancements in this emerging field of phosphorothioate synthesis from inorganic phosphorus sources, focusing on their applicability, mechanisms, current limitations, and potential future directions. These methods are classified based on the inorganic phosphorus source used and the structural units obtained.

1 The synthesis of phosphorodithioates from P_4S_{10}

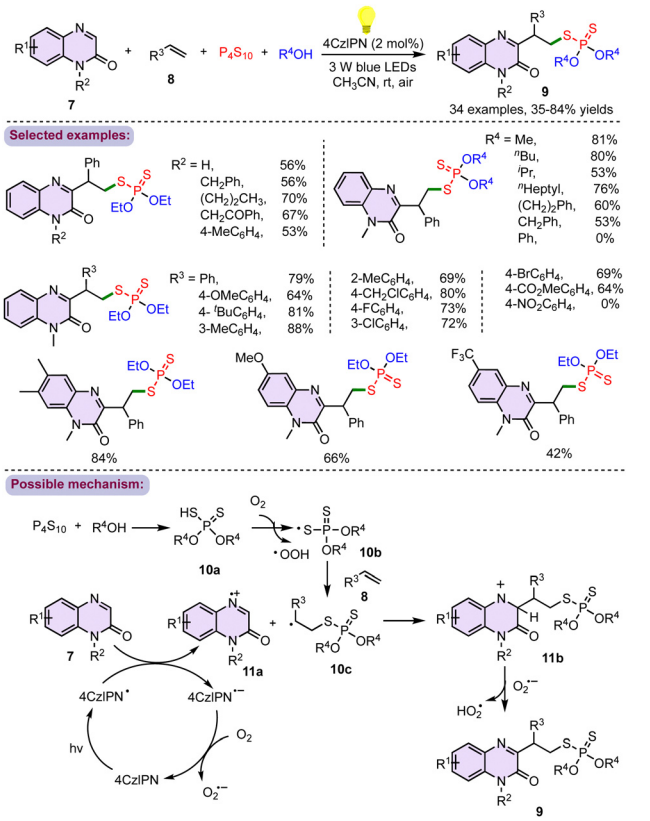
P_4S_{10} is an important inorganic compound. It is a yellow solid that has been widely utilized in organic synthesis, particularly as a precursor for synthesizing various phosphorus- and sulfur-containing molecules. P_4S_{10} is commercially available and plays a critical role in the production of various industrial chemicals, including lubricant additives, oils, flotation agents, and insecticides.[12] Its versatility and high reactivity make it an indispensable reagent in modern chemistry. Very recently, new strategies for synthesizing phosphorodithioates using P_4S_{10} as a precursor have been reported by pioneers Lu, Zhou, Wei, Li *et al.*, which has attracted widespread attention.

1.1 Phosphorodithioation with alkenes

Alkenes are widely available raw materials and are considered good alkyl donors. In 2022, Lu, Zhou, and co-authors have successfully developed a novel metal- and additive-free 1,5-addition reaction that utilizes P_4S_{10} and alcohols as nucleophiles to achieve regioselective ring-opening of spirovinylcyclopropyl oxindoles **1** under thermal condition (Scheme 3).[13] This approach enables the efficient synthesis of allylic organothiophosphates **2**, characterized by broad functional group tolerance, excellent chemo- and regioselectivity, and high *E*-selectivity. In the investigation of substrate applicability, they explored a variety of alcohols and phenols, including methanol, ethanol, propanol, isopropanol, *n*-butanol, benzyl-substituted propanol, phenol, and spirovinylcyclopropyl oxindoles with different halogens and OMe substituents. It was found that 2-vinylcyclopropane-1,1-dicarbonyl and spirovinylcyclopropyl 1,3-indanedione compounds were also compatible with the reaction. However, *N*-phenyl spirovinylcyclopropyl oxindole failed to yield the desired product. Interestingly, at room temperature, it was discovered that the reaction of spirovinylcyclopropyl oxindoles with ethanol and P_4S_{10} also produced 1,3-addition products **3** with excellent regioselectivity and high efficiency. Five examples were presented with yields ranging



Scheme 3 The metal-free, regioselective hydrophosphorodithioation of spiro[vinylcyclopropyl]oxindoles.



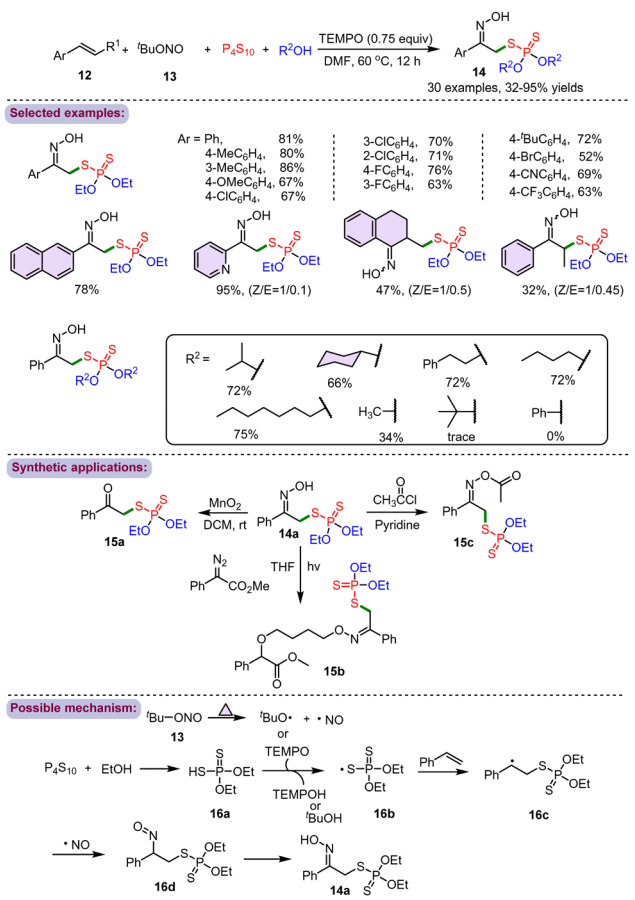
Scheme 4 Visible-light-induced four-component difunctionalization of alkenes to construct phosphorodithioate-containing quinoxalin-2(1*H*)-ones.

from 72–88% and 1 : 1 dr. A 1 mmol reaction was conducted, yielding 63% of **2a**. Additionally, synthetic transformations of oxindoles **2** *via* acetoxylation and cross-metathesis were carried out. Regarding the reaction mechanism, initially, phosphine sulfide reacts with ethanol to form diethyl phosphorodithioate; subsequently, the vinyl cyclopropane is attacked by the nucleophile to produce the intermediate **6a**; ultimately, intermediate **6a** undergoes a facile [3,3]-σ rearrangement to yield the linear 1,5-addition product **2c**.

Photocatalytic synthesis is a green chemistry method that utilizes light energy to activate a catalyst, producing reactive intermediates and enabling efficient and selective organic transformations under mild conditions.[14] In recent years, it has become a powerful tool in modern organic synthesis. In 2024, Chen, Wei, and Yi successfully developing a visible light-induced four-component cascade reaction of alkenes, quinolin-2(1*H*)-one, P_4S_{10}, and alcohols at room temperature (Scheme 4).[15] This technique uses 1,2,3,5-tetrakis(carbazole-9-yl)-4,6-dicyanobenzene (4CzIPN) as a catalyst, 3W blue LED lamp as the light source, and air as the green oxidant, delivering phosphorodithioate-containing quinoxalin-2(1*H*)-ones **9** with yields ranging from 35% to 84%. Aromatic alkenes with both electron-donating groups (such as OMe, *t*Bu, and Me) and electron-withdrawing groups (such as CH_2Cl, F, Cl, Br, and CO_2Me) on the aromatic rings proved to be suitable substrates. Notably, steric hindrance had little impact on the reaction efficiency. However, when aliphatic alkenes like 1-hexene and 1-octene were used, no corresponding products were observed. The reaction also accommodated a range of quinoxalin-2(1*H*)-ones with various *N*-protecting groups, including benzyl, propargyl, ketone, and aryl groups. Chain alcohols, phenylethanol, and phenylmethanol, as well as more sterically demanding alcohols like isopropanol, were tolerated in this reaction system. Unfortunately, the use of phenol in this multi-component reaction did not yield the desired product. To confirm the electron transfer between substrates and the photocatalyst, fluorescence quenching experiments were conducted under visible light. The results indicate that electron transfer likely occurs between quinoxalin-2(1*H*)-one and the excited photocatalyst. For the reaction

mechanism, P_4S_{10} reacts with alcohol to produce *O*,*O*-dialkyl S-hydrogen phosphorodithioate **10a**, which is further oxidized by oxygen in the air to form the thiyl radical **10b**. This thiyl radical **10b** then reacts with the alkene **8** to form the alkyl radical intermediate **10c**. Meanwhile, 4CzIPN is photo-activated to generate its excited state in the presence of visible light irradiation. Subsequently, a single-electron transfer (SET) occurs between the excited state of 4CzIPN* and quinoxalin-2(1*H*)-one, resulting in the formation of a radical cation **11a** and the release of the $4CzIPN^{\bullet -}$ radical anion. The radical anion is oxidized by O_2 to produce a superoxide anion radical and regenerate the photocatalyst. Next, the interaction between the alkyl radical intermediate **10c** and the radical cation **11a** leads to the formation of a nitrogen cation intermediate **11b**. Finally, this nitrogen cation intermediate **11b** undergoes a deprotonation process to yield the desired product **9**.

In 2024, Chen, Wei, and Yi developed an innovative method for the synthesis of β-oximino phosphorodithioates *via* TEMPO radical mediated four-component cascade difunctionalization reaction involving alkenes, *tert*-butyl nitrite, P_4S_{10}, and alcohols (Scheme 5).[16] Through a radical pathway, the reaction sequentially introduces phosphorodithioate and oxime functional groups, effectively synthesizing a variety of β-oximino phosphorodithioates with high efficiency and broad compatibility

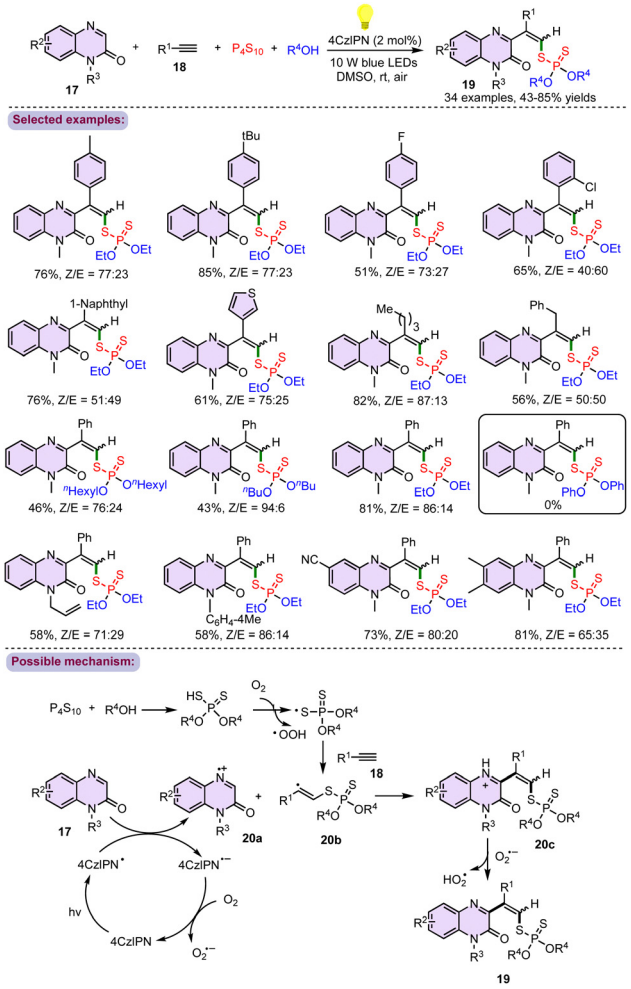


Scheme 5 TEMPO-mediated difunctionalization of alkenes with *tert*-butyl nitrite, P_4S_{10}, and alcohols.

with diverse functional groups. The method is capable of adapting to aryl alkenes with different electronic characteristic substituents. Using more sterically demanding aromatic alkenes, such as 2-methylstyrene and 2-chlorostyrene, as well as aromatic internal alkenes like 1,2-dihydronaphthalene and (*E*)-prop-1-enylbenzene in this reaction system, resulted in the formation of the corresponding products as mixtures of *Z*/*E* isomers. In contrast, no desired product was detected when the aliphatic alkene 1-hexene was employed under the same conditions. In addition, the reaction is broadly applicable to alcohol substrates, demonstrating compatibility with a range from ethanol to more sterically demanding alcohols like isopropanol, cyclohexanol, and long-chain fatty alcohols. However, its applicability is reduced with methanol and *tert*-butanol, and phenol does not react under standard conditions. The method demonstrated its scalability by maintaining a 65% isolated yield of the product when scaled up to 3 mmol. The ability to further transform β-oximino phosphorodithioates into key pharmaceutical intermediates, such as β-keto phosphorodithioates, oxime esters, and oxime ethers, underscores its potential in medicinal chemistry synthesis. Based on control experiments, the proposed reaction mechanism begins with P_4S_{10} reacting with ethanol to produce *O*,*O*-diethyl S-hydrogen phosphorodithioate (**16a**). Meanwhile, *tert*-butyl nitrite decomposes, generating *tert*-butoxy and nitric oxide radicals. These radicals, along with TEMPO, abstract a hydrogen atom from **16a**, resulting in the formation of the thiyl radical **16b**, along with TEMPOH and *tert*-butanol. The thiyl radical **16b** subsequently reacts with styrene to generate the alkyl radical **16c**, which is then captured by nitric oxide radicals to form the nitrosation intermediate **16d**. Finally, this intermediate rapidly undergoes tautomerization, catalyzed by hydrogen bonding, to yield the desired product **14a**.

1.2 Phosphorodithioation with alkynes

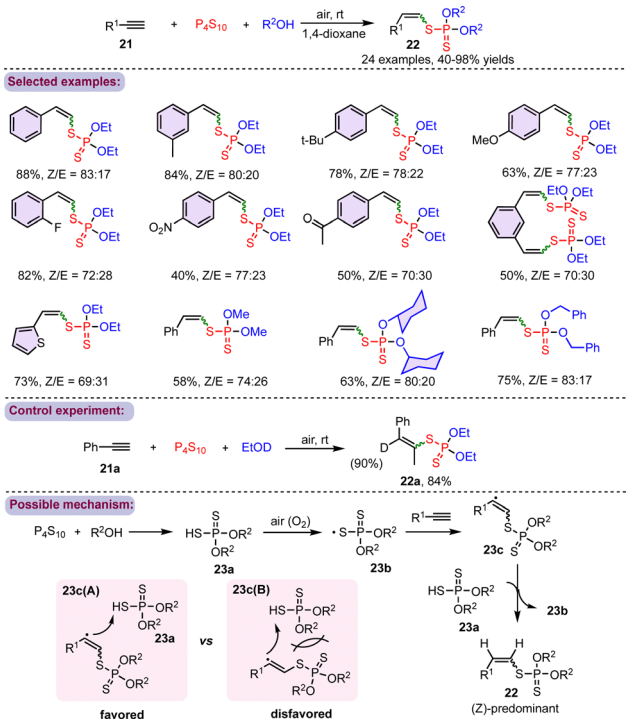
After that, You, Wei, Yi, and co-authors continued to expand this field and introduced an efficient photocatalytic synthesis strategy for the synthesis of quinoxalin-2(1*H*)-one-containing vinyl phosphorodithioates **19** through direct difunctionalization of alkynes, quinoxalin-2(1*H*)-ones, P_4S_{10}, and alcohols (Scheme 6).[17] 4CzIPN was chosen as the photocatalyst, with a mixed solvent of EtOH and DMSO selected as the optimal medium. Various quinoxalin-2(1*H*)-one containing vinyl phosphorodithioates could be produced in 35–84% yields with *Z*-isomers as the major products. It is compatible with a wide range of aromatic and aliphatic alkynes, including those with various electron-donating or electron-withdrawing substituents, as well as alkynes with significant steric hindrance or containing heteroatoms. Both *N*-unprotected and *N*-alkyl protected quinoxalin-2-(1*H*)-one were compatible with the standard conditions. In addition to ethanol, other common alcohols like *n*-butanol, isopropanol, and *n*-hexanol can also effectively participate in the reaction. Utilizing *p*-methylbenzenethiol as a substitute for conventional reagents can provided the product in 60% yield, notwithstanding the reaction's limitations when employing methanol and phenol.



Scheme 6 Visible-light-induced difunctionalization of alkynes to construct phosphorodithioate-containing quinoxalin-2(1*H*)-ones.

Control experiments and fluorescence quenching experiments provide evidence for the free radical process in the reaction and the electron transfer process between the excited state of 4CzIPN* and quinoxalin-2(1*H*)-ones. The reaction mechanism is similar to the previously reported visible light-induced alkyne difunctionalization reaction,[16] involving the reaction of P_4S_{10} with alcohol to generate a sulfur-based free radical, which reacts with alkynes to form an alkenyl free radical intermediate **20b**. Meanwhile, the excited state of 4CzIPN, under visible light excitation, undergoes a SET process with quinoxalin-2(1*H*)-ones to produce a free radical cation **20a** and anion, and finally, the target product is generated through the coupling of **20a** and **20b**.

In 2024, Wei and Yi reported a metal-, additive-free C(sp)–H hydrophosphorodithiolation of alkynes with P_4S_{10} and alcohols, synthesizing vinyl phosphorodithioates **22** in 40–98% yields with *Z*-isomer as major products under mild conditions (Scheme 7).[18] Aromatic alkynes, diynes, and alkynyl esters are suitable substrate to give the vinyl phosphorodithioates. Both chain alcohols and cyclic alcohols could undergo C(sp)–H hydrophosphorodithiolation to provide the desired products. Regrettably, attempts to incorporate aliphatic alkynes, including



Scheme 7 Direct hydrophosphorodithiolation of alkynes to vinyl phosphorodithioates.

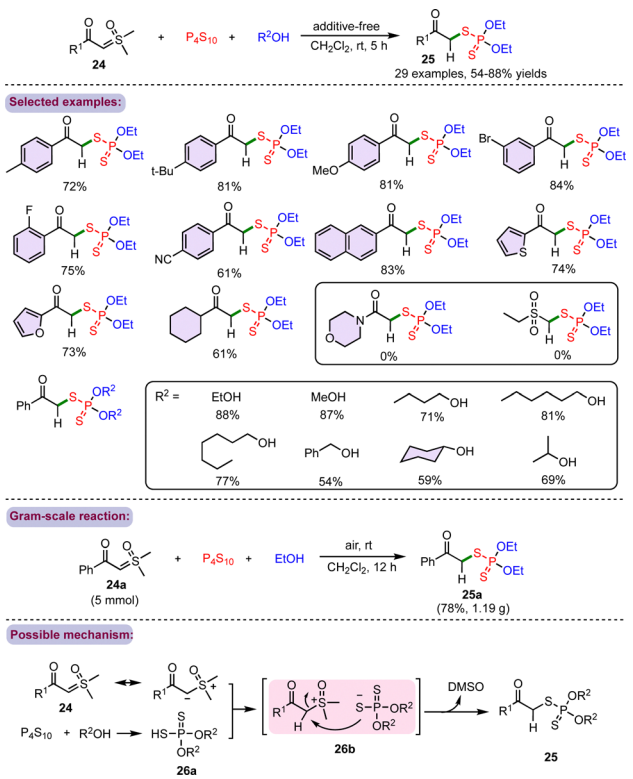
hex-1-yne and but-3-ynylbenzene, into the current reaction framework resulted in the absence of the anticipated product. Using EtOD as both the substrate and solvent led to the efficient formation of the deuterated product D-**22a**, achieving an 84% yield with 90% deuterium incorporation. This finding suggests that the vinyl hydrogen atom adjacent to the benzene ring in the product originated from EtOH. A possible reaction mechanism was proposed. Initially, the reaction of P_4S_{10} with EtOH produced compound **23a**, the dialkyl phosphorodithioate. Subsequently, under the catalysis of oxygen (O_2), compound **23a** was further oxidized to produce the thiyl radical **23b**. The thiyl radical **23b** reacted with alkyne **21** to form the alkenyl radical **23c**. The radical **23c** further reacted with compound **23a**, transferring a hydrogen atom to form the target product **22**, and regenerating the radical intermediate **23b** in the process. The *Z*-isomer of the vinyl phosphorodithioate became the main product, possibly because the abstraction of a hydrogen atom from compound **23a** by the radical intermediate **23c (A)** is more sterically favored than that by the radical intermediate **23c (B)**.

1.3 The phosphorodithioation with sulfoxonium ylides and sulfonium salts

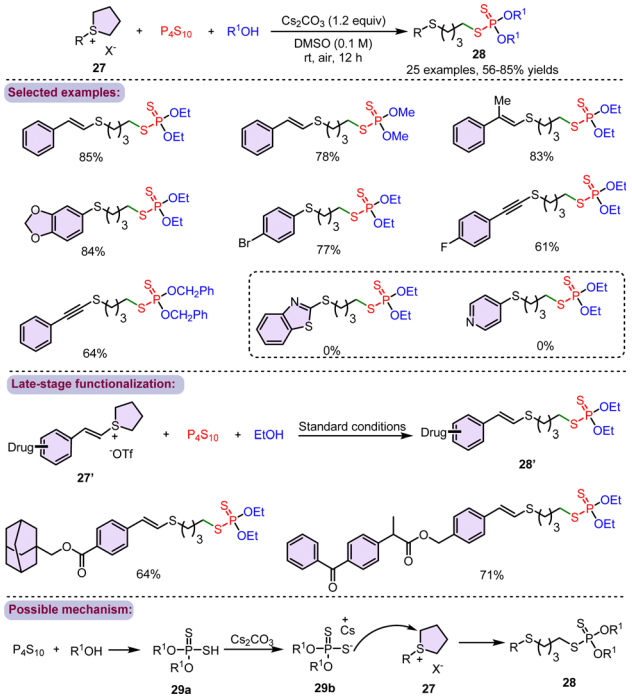
Sulfoxonium ylides are important reagents in synthetic chemistry due to their versatility in forming carbon–carbon and carbon–heteroatom bonds, enabling efficient and selective transformations.[19] In 2024, the Lv, Wei, and Yi group developed a simple and additive-free protocol for the preparation of β-keto phosphorodithioates **25** *via* the three-component reaction of

easily available sulfoxonium ylides **24**, P_4S_{10}, and alcohols at room temperature (Scheme 8).[20] The procedure demonstrates excellent compatibility with a variety of functional groups on sulfoxonium ylides, including halogens, trifluoromethyl, nitro, cyano groups, naphthalene, furan, and thiophene rings. α,β-Unsaturated carbonyl sulfoxonium ylides and aliphatic sulfoxonium ylides are also suitable for this reaction. However, when other sulfoxonium ylides containing amino or sulfonyl groups were used, no desired products were observed. Different alcohols, including methanol, *n*-butanol, *n*-hexanol, *n*-heptanol, benzyl alcohol, and cyclohexanol all produced the target products in moderate to good yields. In a gram-scale reaction under standard conditions (5 mmol scale) for the model reaction of benzoyl sulfoxonium ylide **24a** with P_4S_{10} and ethanol, the reaction efficiency remained high, yielding 1.19 g of β-keto phosphorodithioate **25a** with a 78% yield. To further investigate the reaction mechanism, the author carried out a series of control experiments. These experiments revealed that the reaction of P_4S_{10} with alcohol yielded dialkyl phosphorodithioate **26a**, which served as a crucial intermediate. Following this, intermediate **26a** protonated the sulfoxonium ylide, resulting in the formation of an active sulfoxonium ionic pair **26b**. Finally, the desired product **25** was successfully synthesized through the nucleophilic substitution of DMSO by either a free or contact ion pair of phosphorodithioate.

Sulfonium salts constitute an important class of readily accessible, bench-stable sulfur-containing reagents. Owing to their versatile reactivity, they have garnered significant interest



Scheme 8 Phosphorodithiolation of sulfoxonium ylides with P_4S_{10} and alcohols.



Scheme 9 The synthesis of *S*-alkyl phosphorodithioates from cyclic sulfonium salts, P_4S_{10}, and alcohols.

from chemists and are highly valued as intermediates in organic synthesis. Very recently, Peng and Xie developed a mild and practical three-component ring-opening reactions of sulfonium salts with S_8, P_4S_{10}, and alcohols for the preparation of *S*-alkyl phosphorodithioates **28** (Scheme 9).[21] While the reaction of cyclic sulfonium salts, S_8/Se, and H-phosphonates enabling the synthesis of *S*-alkyl phosphorothioates. This methodology allows for the synthesis of a diverse range of phosphorothioate/phosphorodithioate containing compounds (up to 93 examples) in satisfactory yields. A wide range of sulfonium salts, including alkenyl, aryl, and alkynyl variants, exhibited excellent reactivity with P_4S_{10} and ethanol, yielding the corresponding ring-opening products in 55–85% yields. Additionally, various alcohols, such as methanol, isopropyl alcohol, butanol, cyclohexanol, and benzyl alcohol, were found to be compatible with the reaction conditions. Heteroaryl sulfonium salts, including those containing benzofuran, pyridine, and benzothiazole moieties, were also employed; however, pyridyl and 2-benzothiazolyl sulfonium salts proved unsuitable for this transformation. Furthermore, the methodology was effective with four alkene sulfonium salts modified by 1-adamantanemethanol and ketoprofen, affording the desired products **28′** in 64% and 71% yields, respectively. The reaction involves a nucleophilic ring-opening process, where the nucleophile **29b** is formed *in situ* by the reaction of P_4S_{10} and R^1OH in the presence of Cs_2CO_3.

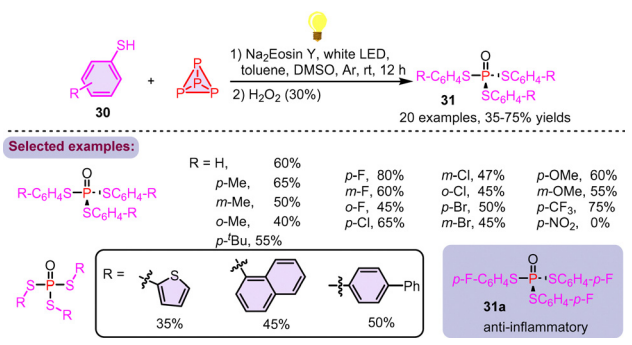
2 The synthesis of phosphorotrithioates from P_4

P_4, commonly known as white phosphorus, is a highly reactive and toxic allotrope of the element phosphorus. P_4 is one of the

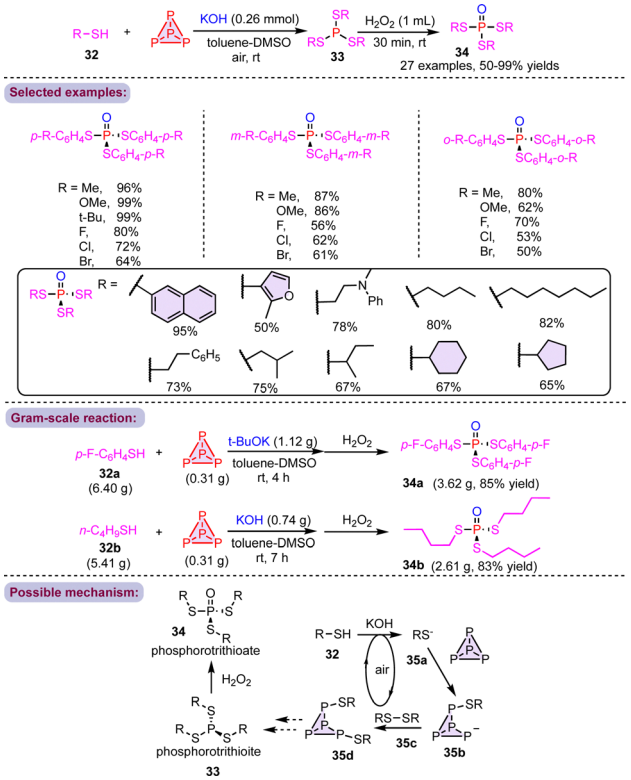
most important synthetic raw materials in modern chemical industry, with an annual production exceeding 10^6 tons.[11] Due to its high reactivity, white phosphorus is prone to spontaneous combustion in air, necessitating its storage underwater to prevent contact with oxygen. Despite its hazardous nature, white phosphorus serves as a crucial precursor in the production of various phosphorus-containing compounds, including fertilizers, insecticides, and certain chemicals used in pharmaceuticals and specialized materials. In recent years, Tang, Zhao, and colleagues have developed a series of pioneering methods for synthesizing phosphorodithioate and phosphorotrithioate derivatives from P_4.

In 2019, Tang and his colleagues pioneeringly reported a novel synthetic strategy for the synthesis of phosphorotrithioates **31** from white phosphorus and arylthiols *via* a visible-light-mediated radical reaction (Scheme 10).[22] This method utilizes Na_2-eosin Y as a photocatalyst, white LEDs as the light source, and DMSO as the key oxidant. The results demonstrate that arylthiols, bearing either electron-donating or electron-withdrawing groups, can react with white phosphorus under these mild conditions to achieve moderate yields. Heterocyclic thiols, such as thiophene-2-thiol and naphthalene-2-thiol, can also participate in the reaction, whereas thiols with strongly electron-withdrawing nitro groups and alkyl thiols are unsuitable for this reaction. Notably, the synthesized compound **31a** exhibited excellent anti-inflammatory activity and low cytotoxicity in RAW264.7 cells, highlighting its potential as an anti-inflammatory therapeutic agent. Investigations into the reaction mechanism revealed that the use of TEMPO as a radical scavenger significantly reduced the reaction activity, suggesting that radical intermediates may play a key role in the reaction process. Additionally, control experiments indicated that, under standard conditions or in the dark at 80 °C, the reaction of *p*-methylphenyl disulfide with white phosphorus produced only a trace amount of phosphorotrithioate, implying that this disulfide compound may not be the main intermediate but rather a byproduct of a competitive reaction.

Subsequently, the Tang group employed KOH or K_2CO_3 as a base and a DMSO–toluene mixture as the solvent, successfully achieving a general and high-yielding synthesis of phosphorothioate esters **33** ($P(SR)_3$) and phosphorothioate esters **34** ($P(O)(SR)_3$) from P_4 and thiols (Scheme 11).[23] Compared to



Scheme 10 Direct synthesis of phosphorotrithioates from white phosphorus mediated by visible light.

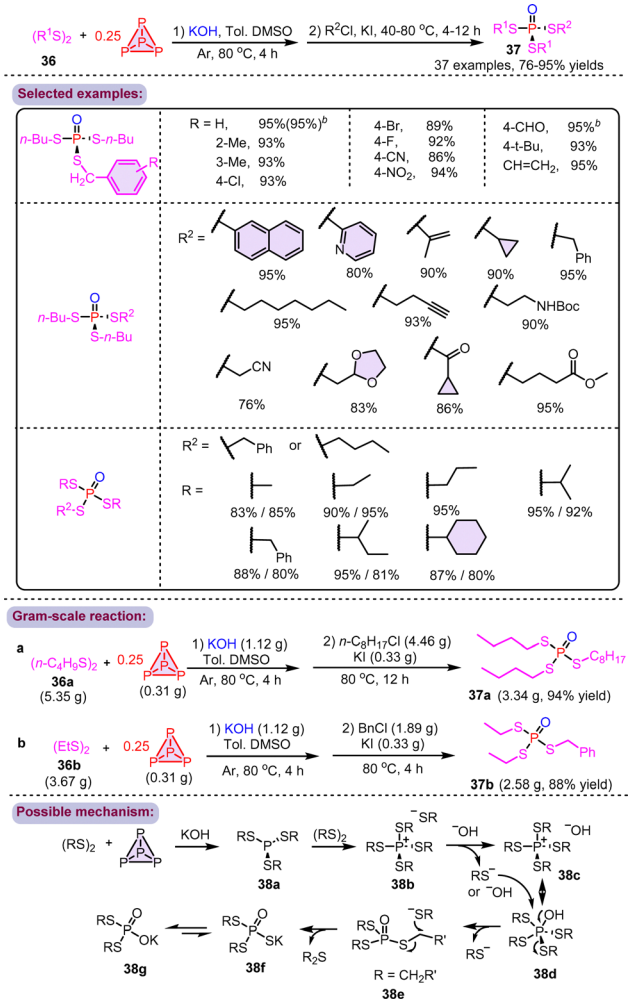


Scheme 11 Direct synthesis of phosphorotrithioites and phosphorotrithioates from white phosphorus and thiols.

the previous photo-induced strategy, this base-promoted reaction significantly enhances efficiency. The method is compatible with a wide range of arylthiols, including halogen-substituted aromatic thiols, larger aromatic thiols, and thiols containing reactive furan rings such as 5-methylfuran-2-thiol. Additionally, aliphatic thiols are effectively incorporated into the reaction, yielding phosphorothioate esters, including tribufos, a known plant growth regulator. Reactions of P_4 on a 10.0 mmol scale with 4-fluorobenzenethiol and 1-butanethiol yielded compounds **34a** and **34b** in 85% and 83% yields, respectively. Control experiments indicated that both disulfides and thiols play crucial roles in driving the transformation. The oxidation of thiolates, leading to the formation of thiolyl intermediates and subsequently disulfides, likely represents a key mechanistic step in the overall process. Thus, the generation of disulfides emerges as one of the primary pathways integral to the transformation. In the absence of DMSO, KOH, or air, only trace amounts of disulfide were obtained, underscoring the essential role of DMSO in promoting the transformation. Based on these findings, a reaction mechanism was proposed. Initially, thiols are deprotonated by KOH to form thiolate species **35a**, while simultaneously undergoing oxidative coupling in the presence of KOH and oxygen to yield disulfide **35c**. The thiolate then nucleophilically attacks the phosphorus atom in white phosphorus, leading to the cleavage of the P_4 tetrahedron and the formation of phosphorus-based anion **35b**. This anion subsequently engages in a nucleophilic attack on disulfide **35c**, generating intermediate **35d** and

regenerating the thiolate **35a**. The overall reaction culminates in the formation of phosphorothioate **33**, which is further oxidized to phosphorothiolate **34**. This mechanistic pathway not only illustrates precise control over reaction conditions but also highlights a thorough understanding of the underlying reaction dynamics.

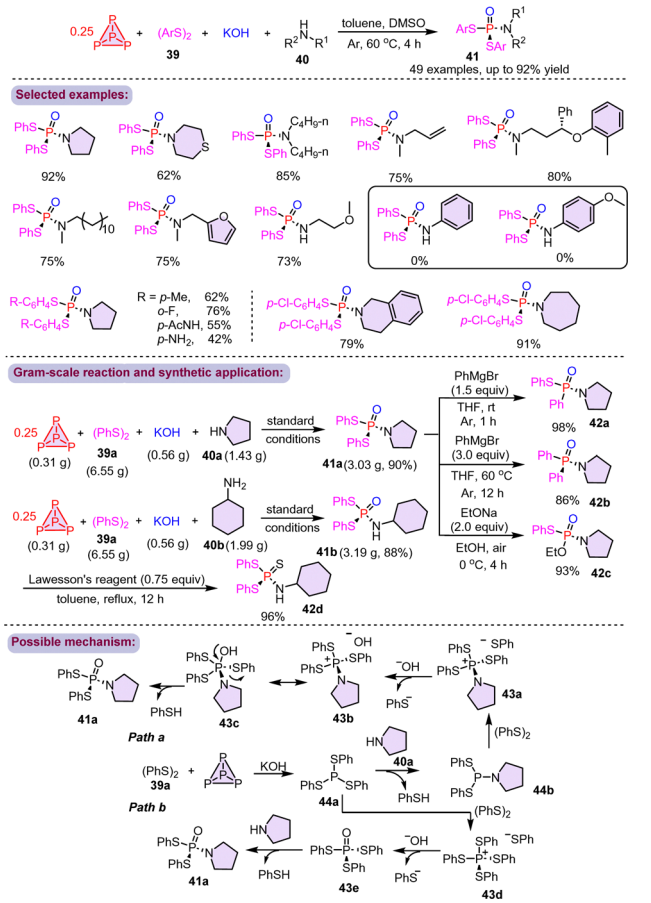
In 2020, Tang further developed an efficient pathway that allows for the synthesis of a series of mixed phosphorothioate phosphate esters **37** ($(R^1S)_2P(O)SR^2$) from white phosphorus, disulfides, and alkyl halides (Scheme 12).[24] This synthetic process uses KOH as an additive and DMSO–toluene as the reaction medium, successfully prompting the reaction between disulfides and white phosphorus to form the intermediate product *O*-potassium *S*,*S*-dialkyl phosphorothioate ($(R^1S)_2P(S)OK$), which then undergoes Michaelis–Arbuzov reaction and alkylation to produce the desired target compounds. Under optimized reaction conditions, alkyl halides with alkyl, vinyl, electron-withdrawing groups (such as aldehydes, nitriles, nitro groups), or halogen atoms on the benzene ring can efficiently form the target products. In addition, modified conditions for benzyl halides and other alkyl halides containing terminal alkynes, amides, nitriles, acetals, ketones, and ester groups can also participate in the reaction smoothly. Although alkyl disulfide performs well, the use of diphenyl disulfide as a substrate failed to synthesize the expected *O*-potassium *S*,*S*-diphenyl phosphorothioate. On a gram scale, utilizing 2.5 mmol of P_4 (0.31 g), two compounds **37a** and **37b** were synthesized with yields of 94% and 88%, respectively. Under an argon atmosphere, disulfides and P_4 first form the phosphorothioate phosphate ester [P(III), **38a**] in the presence of KOH, which then reacts with disulfides to generate the pentavalent ion species **38b**. This species undergoes further reaction with KOH to form intermediates **38c** and **38d**. The elimination through the nonpolar pentavalent intermediate **38d** results in the formation of phosphorothioate phosphate ester [P(V), **38e**]. Subsequently, alkyl halides attack the phosphorothioate phosphate ester **38e**, cleaving the C–S bond in a dealkylation process akin to the Michaelis–Arbuzov reaction, yielding salts **38f**/**38g** and releasing R_2S. The final alkylation step of salts **38f**/**38g** completes the synthesis of the mixed phosphorothioate phosphate esters.



Scheme 12 Synthesis of mixed phosphorotrithioates from white phosphorus.

In 2022, Tang successfully developed a four-component reaction using white phosphorus, PhSSPh, pyrrolidine, and KOH to prepare phosphoramidodithioates **41** containing both P–N, P–S, and P═O bonds (Scheme 13).[25] At 60 °C, under an argon atmosphere, and employing a mixed solvent system of toluene and DMSO, the target phosphoramidodithioate product was synthesized with yields reaching up to 90%. This synthetic approach not only demonstrates high efficiency but also exhibits excellent substrate versatility, accommodating a broad spectrum of secondary amines, including both cyclic amines containing heteroatoms (such as O and S) and acyclic amines. Notably, commercially available drugs like Atomoxetine and Fluoxetine also produced the corresponding products. Additionally, similar yields were achieved for primary amines and benzyl amines bearing heterocyclic groups. However, anilines with low nucleophilicity did not participate in the reaction, despite the complete consumption of white phosphorus. In gram-scale experiments, utilizing 10 mmol of white phosphorus, disulfides, and amines, products were obtained in yields of 90%, 88%, and 87%. Further synthetic transformations of phosphoramidodithioates were also explored. For instance, the *S*,*S*-diphenyl pyrrolidin-1-ylphosphonodithioate synthesized on a gram scale was readily converted into the desired products with yields of 98% and 86% upon treatment with 1.5 and 3.0 equivalents of PhMgBr, respectively. The transesterification of the P(O)–S bond was easily achieved by treating the compound with EtONa in EtOH, resulting in the desired product **42c** with a 93% yield. Additionally, Lawsone's reagent, typically used to convert C═O to C═S, was shown to effectively convert P═O (**41b**) to P═S (**42d**), achieving a 96% yield.

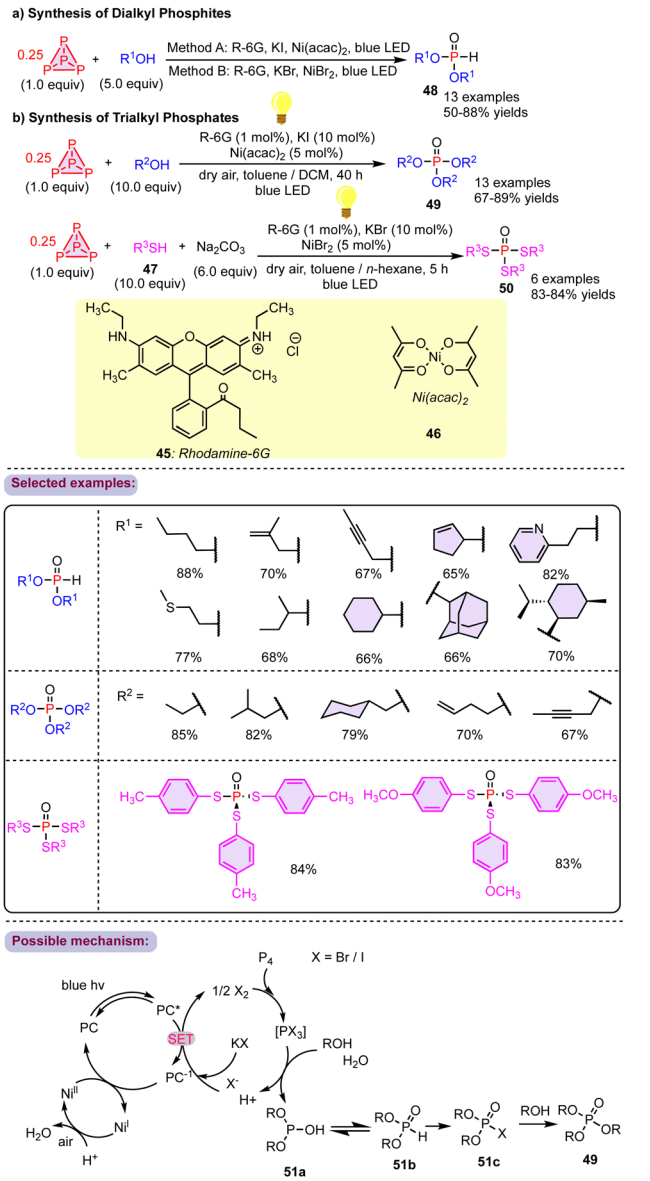
Two potential reaction mechanisms were proposed: in pathway a, P_4 and disulfide **39a** form P(III) **44a** in the presence of KOH under argon, which then reacts with amine **40a** to generate P(III) **44b**. This intermediate subsequently reacts with PhSSPh to form the pentavalent ionic species **43a**. Through anion exchange with



Scheme 13 The formation of N–P(O)–S bonds through a four-component reaction.

KOH, **43b** and **43c** are produced, and the elimination of the nonpolar pentavalent intermediate **43c** leads to product **41a**. In pathway b, P(III) **44a** first reacts with disulfide **39a**, forming **43d**, which undergoes anion exchange and elimination reactions to form P(V) **43e**. The final step involves an amidation reaction with amine to yield product **41a**.

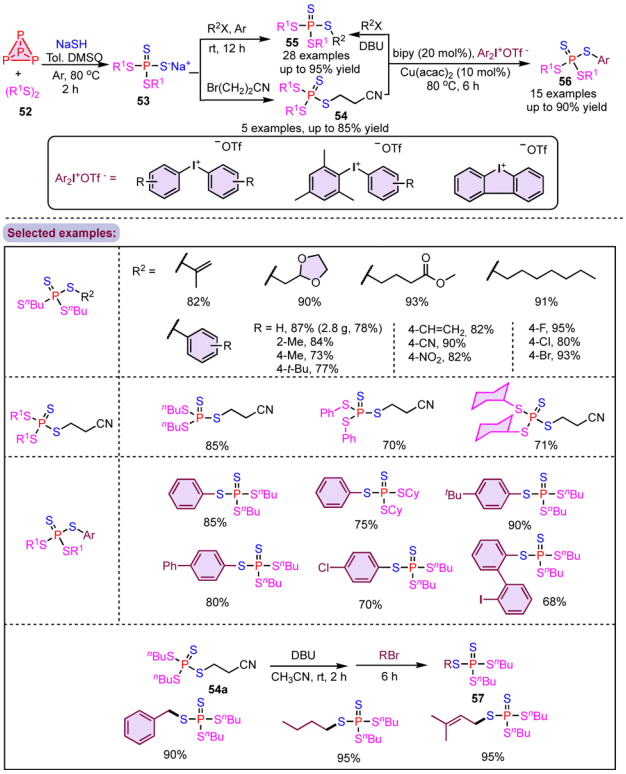
In 2023, Tang reported a green photocatalytic technology that uses white phosphorus and a variety of alcohols as raw materials to efficiently synthesize dialkyl phosphites **48** (DAPIs) and trialkyl phosphates **49** (TAPAs) (Scheme 14).[26] This method can avoid the use of Cl_2 and PCl_3, and directly convert white phosphorus into DAPI *via* a combination of photoredox catalyst, nickel catalyst, and halide anion, effectively avoiding the problems of high waste generation and toxic reaction conditions. This photocatalytic strategy is suitable for coupling various alcohols. Notably, when using thiophenols and adding Na_2CO_3 as an additive, this method can be employed for the synthesis of triaryl phosphorotrithioates **50**. Unfortunately, the system has limited applicability for alkyl thiols, aliphatic amines, and aromatic amines. Based on mechanistic studies, authors suggest the photocatalyst rhodamine 6G (R-6G) absorbs light to form an excited state and transfers an electron to a halide anion, producing X_2 and the R-6G anion. This X_2 then reacts with P_4 to create the intermediate PX_3, which



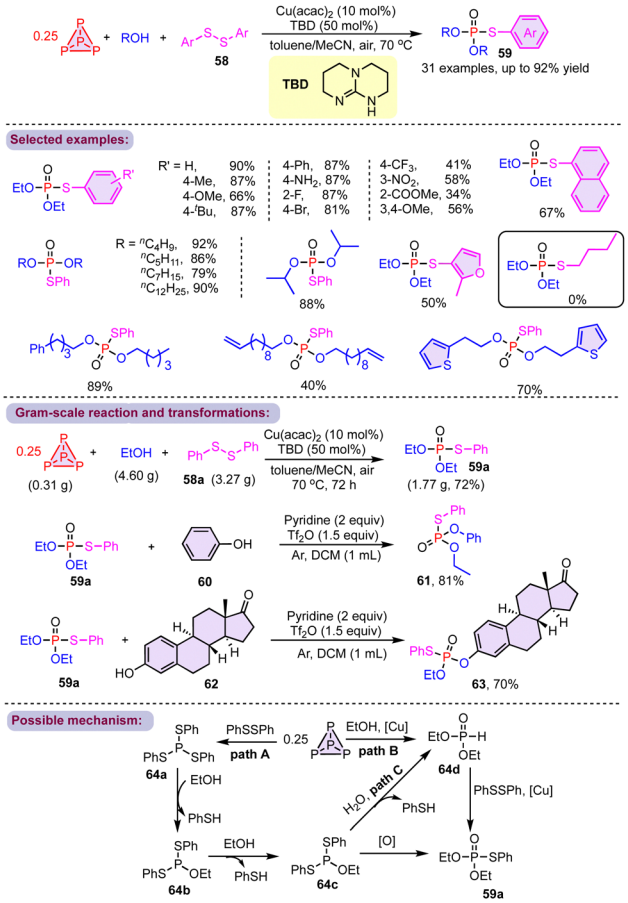
Scheme 14 Ternary photoredox/nickel/halide catalysis for the phosphorylation of alcohols with white phosphorus.

undergoes nucleophilic substitution with two alcohol molecules (ROH) and *in situ*-formed water to yield $(RO)_2P(O)H$ **51a**, releasing a proton. The photocatalyst is regenerated by oxidation with Ni(II), and the resulting Ni(I) is reoxidized to Ni(I) by air and a proton, closing the catalytic cycle and generating water. Furthermore, $(RO)_2P(O)H$ **51b** can react with X_2 to form $(RO)_2P(O)$–X **51c**, which then reacts with ROH to produce $(RO)_3P(O)$, broadening the synthetic potential.

Compared to the extensive research and application of thiophosphates, dithiophosphates, and trithiophosphates, tetrathiophosphates, which contain four P–S bonds, have been less explored. In 2023, Tang reported a transition-metal-free, one-pot direct synthesis of tetrathiophosphates **54–56** $(R^1S)_2P(S)SR^2$ from P_4, NaSH, dialkyl disulfides (Scheme 15).[27] In the presence of NaSH, various disulfides such as diaryl and



Scheme 15 The synthesis of tetrathiophosphates from white phosphorus.



Scheme 16 The synthesis of phosphorothioates *via* three-component coupling of P_4, alcohols, and diaryl disulfides.

dialkyl disulfides are easily coupled with P_4 to give sodium alkyltetrathiophosphates $(R^1S)_2P(S)SNa$ in nearly quantitative yield, identified as key intermediates. These intermediates subsequently react with a range of alkyl halides in one pot to generate $(R^1S)_2P(S)SR^2$. A variety of functionalized halides, including benzyl halides, halides with terminal olefins, nitriles, acetals, esters, were found to be compatible. Additionally, *S*-(2-cyanoethyl)-substituted tetrathiophosphates $(R^1S)_2P(S)SCH_2CH_2CN$ **54a** are successfully designed as a kind of tetrathiophosphorylation reagent, reacting with alkyl halides and both symmetrical and unsymmetrical diaryl iodonium salts to produce tetrathiophosphates *via* a deprotection-dealkylation process. This method can be scaled up to gram quantities, significantly expanding the application of P_4 in tetrathiophosphate synthesis.

In 2024, Tang developed a novel, high-yielding method for synthesizing various phosphorothioates with diverse substituents directly from white phosphorus, disulfides, and alcohols in a one-step reaction (Scheme 16).[28] This innovative approach employed $Cu(acac)_2$ as a catalyst and 1,5,7-triazabicyclo-[4.4.0]dec-5-ene (TBD) as a base, using a mixture of toluene and acetonitrile as solvents, and operated under an air atmosphere at 70 °C, eliminating the need for harmful reagents like PCl_3. The method was versatile, tolerating a wide range of aryl disulfides with varying electronic properties, as well as simple primary and secondary alcohols. When conducted on a gram scale, the reaction proceeded smoothly, yielding product **59a** in 72% after 72 h reaction time. Further activation of product **59a** with triflic anhydride generated a reactive electrophilic phosphorus species, which enabled phenol derivatives to attack the phosphonium intermediate, leading to the formation of mixed thiophosphates **61** and **63**.

The reaction mechanism for synthesizing phosphorothioate **59a** was elucidated through control experiments. Initially, disulfide **58a** couples with P_4 to produce triphenyl phosphorothioate trisulfide (**64a**). Ethanol is then introduced as a nucleophile, cleaving the P–S bond and forming a P–O bond, yielding intermediate **64b**. Ethanol undergoes further nucleophilic substitution with intermediate **64b**, producing intermediate **64c**, which is oxidized by air to form the desired phosphorothioate **59a**.

Preliminary ^{31}P NMR studies revealed the involvement of bis(ethoxy)phosphine(O) compound (**64d**) in this transformation. Consequently, two alternative reaction pathways cannot be excluded. One possibility is that H-phosphonate **64d** is formed directly *via* ethanol-induced cleavage of the P–P bond in P_4 under copper salt catalysis. Alternatively, intermediate **64c** may undergo nucleophilic substitution with water molecules from the atmosphere, resulting in the formation of H-phosphonate **64d**. In either pathway, compound **64d** subsequently couples with disulfide **58a** under copper catalysis to produce the desired product **59a**.

3 Conclusions

Organophosphorothioates and phosphoropolythioates are a class of attractive organic molecules with significant applications in agriculture, pharmaceuticals, and materials science. Currently, numerous research groups have developed a variety of methods for synthesizing phosphorothioate derivatives from organic phosphorus sources such as P(O)H, P(O)X, and toxic PCl_3. In recent years, new strategies for synthesizing phosphorothioate derivatives from inorganic phosphorus sources like P_4S_{10} and P_4 have emerged. P_4S_{10} can undergo radical or ionic reactions with alkenes, alkynes, and sulfonium ylides in the presence of alcohols, generating dithiophosphate derivatives under mild conditions. Tang's group has pioneered a series of methods for preparing phosphorotrithioates and phosphorotetrathioates from P_4 with disulfides or thiols. These strategies offer the advantages of mild conditions, minimal use of excessive metal catalysts, avoidance of large amounts of toxic and highly reactive reagents, and reduced waste generation, aligning with the principles of atom-economic green synthetic chemistry. These new technologies are a perfect complement to the synthesis of phosphorothioate derivatives from organic phosphorus sources, and they have also opened a new door for the synthesis of this class of compounds.

Despite the emergence of various new approaches for synthesizing phosphorodithioate derivatives from inorganic phosphorus sources, there is still much space for further development in this system: (1) the synthesis of a variety of phosphorothioate derivatives utilizing alternative inorganic phosphorus sources remains a promising area for development. For instance, Cummins has innovatively synthesized a precursor phosphorylating reagent, tetrametaphosphate reagent ($[PPN]_2[P_4O_{11}]$).[29] The treatment of this reagent with benzylmercaptan and triethylamine yielded a phosphorothioate anion, which subsequently underwent ring-opening with [TBA][OH] to form the TBA salt of tetraphosphate. When considering other phosphorus sources, significant challenges include: (a) the availability and stability of the phosphorus source, and (b) achieving good reactivity and chemical diversity. (2) The breakthroughs described in this review are still in their early stages, and significantly more research is clearly needed if any of them are to truly threaten the current state of the industrial art. The phosphorothiolation processes are currently confined to the laboratory setting, with the synthesis scale being relatively diminutive. The feasibility of scaling up to industrial-grade synthesis while maintaining high conversion efficiency is yet to be ascertained. Furthermore, the absence of substantial industrial demand for the resultant phosphorothioates has mitigated the progress of industrializing the direct conversion of inorganic phosphorus sources into phosphorothioates. (3) The types of direct functionalization reactions of inorganic phosphorus sources such as P_4S_{10} and P_4 are still limited, with some examples having low yields, and there is still a need to develop more efficient new systems. (4) There is currently a lack of successful cases for the asymmetric catalysis and synthesis of chiral phosphorothioate derivatives, despite the fact that research on chiral phosphorothioate derivatives has been very scarce.

We hope that this review will provide some reference for scholars engaged in the development of new methods for the synthesis of sulfur-containing organophosphorus compounds, especially experts in the field of phosphorothioates synthesis. We would be deeply gratified if this work attracts the interest of more practitioners or provides inspiration for the synthesis and development of phosphorothioate derivatives.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by a Start-up Grant from Guangdong Pharmaceutical University (grant no. 51304043005) and Guangdong Cosmetics Engineering & Technology Research Center.

Notes and references

1 (*a*) M. D. McReynolds, J. M. Dougherty and P. R. Hanson, *Chem. Rev.*, 2004, **104**, 2239–2258; (*b*) T. Ozturk, E. Ertas and O. Mert, *Chem. Rev.*, 2010, **110**, 3419–3478; (*c*) T. S. Kumar, T. Yang, S. Mishra, C. Cronin, S. Chakraborty, J.-B. Shen, B. T. Liang and K. A. Jacobson, *J. Med. Chem.*, 2013, **56**, 902–914; (*d*) R. Xie, Q. Zhao, T. Zhang, J. Fang, X. Mei, J. Ning and Y. Tang, *Bioorg. Med. Chem.*, 2013, **21**, 278–282; (*e*) A. M. Lauer, F. Mahmud and J. Wu, *J. Am. Chem. Soc.*, 2011, **133**, 9119–9123; (*f*) D. J. Jones, E. M. O'Leary and T. P. O'Sullivan, *Adv. Synth. Catal.*, 2020, **362**, 1825–1830; (*g*) Y. Xu, J. Gao, C. Wang, Y. Ma, J. Zhou and G. Wu, *Org. Chem. Front.*, 2021, **8**, 3457–3462.

2 (*a*) L. D. Quin, *A guide to organophosphorus chemistry*, John Wiley & Sons, 2000; (*b*) P. J. Murphy, *Organophosphorus Reagents*, 2004, 1–14; (*c*) S. Cogoi, V. Rapozzi, F. Quadrifoglio and L. Xodo, *Biochem.*, 2001, **40**, 1135–1143; (*d*) T. Kasagami, T. Miyamoto and I. Yamamoto, *Pest Manage. Sci.*, 2002, **58**, 1107–1117.

3 (*a*) N.-S. Li, J. K. Frederiksen and J. A. Piccirilli, *Acc. Chem. Res.*, 2011, **44**, 1257–1269; (*b*) J. Wang, X. Huang, Z. Ni, S. Wang, J. Wu and Y. Pan, *Green Chem.*, 2015, **17**, 314–319.

4 (*a*) H. Zheng, J. Peng, X. Liu and P. Zhao, *Adv. Synth. Catal.*, 2024, **366**, 3739–3760; (*b*) X. Liu, L. Zhou, R. Yang, X. R. Song and Q. Xiao, *Adv. Synth. Catal.*, 2023, **365**, 2280–2298.

5 (*a*) D. J. Jones, E. M. O'Leary and T. P. O'Sullivan, *Tetrahedron Lett.*, 2018, **59**, 4279–4292; (*b*) D. J. Jones, E. M. O'Leary and T. P. O'Sullivan, *Adv. Synth. Catal.*, 2020, **362**, 2801–2846.

6 (*a*) Z. Zheng, S. Shi, Q. Ma, Y. Yang, Y. Liu, G. Tang and Y. Zhao, *Org. Chem. Front.*, 2021, **8**, 6845–6850; (*b*) Z. Zheng, J. He, Q. Ma, Y. Zhang, Y. Liu, G. Tang and Y. Zhao, *Green Chem.*, 2022, **24**, 4484–4489; (*c*) S. Shi, H. Chen, M. Zhao, S. Yang, P. Li, X. Wang, J. Zhu, Q. Fang, W. Xu and G. Tang, *Org. Lett.*, 2023, **25**, 8296–8301; (*d*) J. Xu, L. Zhang, X. Li, Y. Gao, G. Tang and Y. Zhao, *Org. Lett.*, 2016, **18**, 1266–1269; (*e*) S. Shi, J. Chen, S. Zhuo, Z. A. Wu, M. Fang, G. Tang and Y. Zhao, *Adv. Synth. Catal.*, 2019, **361**, 3210–3216; (*f*) S. Shi, P. Zhang, C. Luo, S. Zhuo, Y. Zhang, G. Tang and Y. Zhao, *Org. Lett.*, 2020, **22**, 1760–1764; (*g*) Y. Guo, Y. Luo, S. Mu, J. Xu and Q. Song, *Org. Lett.*, 2021, **23**, 6729–6734; (*h*) B. Wang, L. Sun, Q. Cao, X. Li, J. Chen, S. Wang, M. Ke and F. Chen, *Chin. Chem. Lett.*, 2024, **35**, 109617.

7 (*a*) P. Zhang, W. Li, W. Qu, Z. Shu, Y. Tao, J. Lin and X. Gao, *Org. Lett.*, 2021, **23**, 9267–9272; (*b*) P. Zhang, W. Li, X. Zhu, Y. Li, X. Zhao, S. Shi, F. Zhu, J. Lin and X. Gao, *Adv. Synth. Catal.*, 2022, **364**, 3316–3320; (*c*) P. Zhang, W. Li, S. Yang, W. Qu, L. Wang, J. Lin and X. Gao, *J. Org. Chem.*, 2024, **89**, 4947–4957; (*d*) P. Zhang, G. Yu, W. Li, Z. Shu, L. Wang, Z. Li and X. Gao, *Org. Lett.*, 2021, **23**, 5848–5852; (*e*) A. Kumar Ghosh, S. Neogi, P. Ghosh and A. Hajra, *Adv. Synth. Catal.*, 2023, **365**, 2271–2278; (*f*) P. Ghosh and A. Hajra, *Adv. Synth. Catal.*, 2022, **364**, 4157–4165; (*g*) B. Sarkar and A. Hajra, *Org. Lett.*, 2023, **26**, 5141–5145; (*h*) C. Qu, R. Liu, Z. Wang, Y. Lv, H. Yue and W. Wei, *Green Chem.*, 2022, **24**, 4915–4920.

8 (*a*) X. Liu, W. Jiang, C. Huang, S. Ma, Q. Wang and H. Cao, *Org. Chem. Front.*, 2023, **10**, 5198–5204; (*b*) B. Zhang, Z. Fu, H. Yang, D. Liu, Y. Sun, Y. Xu, F. Yu and S. J. Yan, *Adv. Synth. Catal.*, 2022, **364**, 1602–1606; (*c*) S. Jiang, S. Du, J. Bai, X. Chen, M. Liang, S. Lin, M.-J. Luo, X.-R. Song and Q. Xiao, *J. Org. Chem.*, 2023, **88**, 14571–14586; (*d*) M. Bai, S. Liu, H. Xin, X. Yang, X.-H. Duan and L.-N. Guo, *Org. Biomol. Chem.*, 2023, **21**, 5855–5860; (*e*) Z.-Y. Meng, C.-T. Feng, L. Zhang, Q. Yang, D.-X. Chen and K. Xu, *Org. Lett.*, 2021, **23**, 4214–4218; (*f*) S. Du, S. Jiang, R. Yang, F. Jin, H. Huang, W.-F. Tian, Z.-Z. Zhou, X.-R. Song and Q. Xiao, *Org. Lett.*, 2023, **25**, 1263–1267; (*g*) S. Peng, L. H. Yang, X. Q. Xu and L. Y. Xie, *Adv. Synth. Catal.*, 2024, **366**, 2758–2763; (*h*) G. Guo, J. Ma, Y. Dong, Q. Wu, J. Lv, Y. Shi and D. Yang, *Org. Lett.*, 2024, **26**, 8382–8388.

9 (*a*) D. J. Jones, E. M. O'Leary and T. P. O'Sullivan, *Adv. Synth. Catal.*, 2020, **362**, 1825–1830; (*b*) X. Y. Chen, M. Pu, H. G. Cheng, T. Sperger and F. Schoenebeck, *Angew. Chem., Int. Ed.*, 2019, **58**, 11395–11399; (*c*) S. Mishra and N. T. Patil, *Chem. Sci.*, 2023, **14**, 13134–13139; (*d*) S. Sarkar and M. Kalek, *Org. Lett.*, 2023, **25**, 671–675; (*e*) L.-Y. Wu, T. Huang, Z.-Y. Tian, X.-Q. Xu, S. Peng and L.-Y. Xie, *Org. Biomol. Chem.*, 2024, **22**, 2409–2413.

10 (*a*) S. Kovacs, B. Bayarmagnai, A. Aillerie and L. J. Gooßen, *Adv. Synth. Catal.*, 2018, **360**, 1913–1918; (*b*) Z.-Y. Ma, M. Xiao, C.-K. Li, A. Shoberu and J.-P. Zou, *Chin. Chem. Lett.*, 2024, **35**, 109076; (*c*) P. Zhang, W. Qu, S. Yang, L. Wang, L. Zhang, X. Zhu and X. Gao, *Org. Chem. Front.*, 2024, **11**, 5841–5846.

11 (*a*) D. J. Scott, *Angew. Chem., Int. Ed.*, 2022, **61**, e202205019; (*b*) F. Chen, J. Peng, Y. Ying, Y. Cao, P. Xu, G. Tang and Y. Zhao, *Green Chem.*, 2023, **25**, 6629–6634; (*c*) D. J. Scott, J. Cammarata, M. Schimpf and R. Wolf, *Nat. Chem.*, 2021, **13**, 458–464.

12 T. Ozturk, E. Ertas and O. Mert, *Chem. Rev.*, 2010, **110**, 3419–3478.

13 J. Wang, F. Han, S. Hao, Y.-J. Tang, C. Xiong, L. Xiong, X. Li, J. Lu and Q. Zhou, *J. Org. Chem.*, 2022, **87**, 12844–12853.

14 (*a*) A. Y. Chan, I. B. Perry, N. B. Bissonnette, B. F. Buksh, G. A. Edwards, L. I. Frye, O. L. Garry, M. N. Lavagnino, B. X. Li and Y. Liang, *Chem. Rev.*, 2021, **122**, 1485–1542; (*b*) C.-S. Wang, P. H. Dixneuf and J.-F. Soulé, *Chem. Rev.*, 2018, **118**, 7532–7585; (*c*) N. E. S. Tay, D. Lehnherr and T. Rovis, *Chem. Rev.*, 2022, **122**, 2487; (*d*) J. M. R. Narayanam and C. R. J. Stephenson, *Chem. Soc. Rev.*, 2011, **40**, 102.

15 X.-M. Chen, L. Song, J. Pan, F. Zeng, Y. Xie, W. Wei and D. Yi, *Chin. Chem. Lett.*, 2024, **35**, 110112.

16 X.-M. Chen, J. Huang, J. Pan, Y. Xie, F. Zeng, W. Wei and D. Yi, *Org. Lett.*, 2024, **26**, 3883–3888.

17 L. Song, C. Ma, J. Huang, Y. Lv, H. Yue, J. You, W. Wei and D. Yi, *J. Org. Chem.*, 2024, **89**, 10974–10986.

18 C. Qu, Y. Wang, Y. Lv, H. Yue, W. Wei and D. Yi, *Org. Chem. Front.*, 2024, **11**, 171–175.

19 (*a*) M.-Y. Huang and S.-F. Zhu, *Chem. Sci.*, 2021, **12**, 15790–15801; (*b*) B. D. Bergstrom, L. A. Nickerson, J. T. Shaw and L. W. Souza, *Angew. Chem., Int. Ed.*, 2021, **60**, 6864–6878; (*c*) J. Vaitla, A. Bayer and K. H. Hopmann, *Angew. Chem., Int. Ed.*, 2017, **56**, 4277–4281; (*d*) W. Xie, X. Chen, J. Shi, J. Li and R. Liu, *Org. Chem. Front.*, 2019, **6**, 2662–2666; (*e*) S.-Y. Chen, Y.-F. Zeng, W.-X. Zou, D.-T. Shen, Y.-C. Zheng, J.-L. Song and S.-S. Zhang, *Org. Lett.*, 2023, **25**, 4286–4291; (*f*) H. Xie, M. Zhong, H. J. Kang, B. Shu and S. S. Zhang, *Adv. Synth. Catal.*, 2021, **363**, 1436–1442.

20 J. Hao, Y. Lv, S. Tian, C. Ma, W. Cui, H. Yue, W. Wei and D. Yi, *Chin. Chem. Lett.*, 2024, **35**, 109513.

21 L.-H. Yang, L. Chen, B. Li, Y.-X. Jin, Y. Liu, S. Peng and L.-Y. Xie, *Org. Chem. Front.*, 2024, **11**, 5731–5740.

22 G. Lu, J. Chen, X. Huangfu, X. Li, M. Fang, G. Tang and Y. Zhao, *Org. Chem. Front.*, 2019, **6**, 190–194.

23 X. Huangfu, Y. Wang, G. Lu, Y. Cao, G. Tang and Y. Zhao, *Green Chem.*, 2020, **22**, 5303–5309.

24 X. Huangfu, Y. Zhang, P. Chen, G. Lu, Y. Cao, G. Tang and Y. Zhao, *Green Chem.*, 2020, **22**, 8353–8359.

25 Y. Zhang, Y. Cao, Y. Chi, S. Chen, X. Zeng, Y. Liu, G. Tang and Y. Zhao, *Adv. Synth. Catal.*, 2022, **364**, 2221–2226.

26 Z. Cai, Y. Zhang, Y. Cao, Y. Liu, G. Tang and Y. Zhao, *ACS Catal.*, 2023, **13**, 8330–8335.

27 J. He, S. Shi, Y. Zhang, Y. Zhang, P. Xu, G. Tang and Y. Zhao, *Chin. J. Chem.*, 2023, **41**, 2311–2316.

28 Y. Cao, M. Bai, J. Huang, F. Chen, Y. Liu, G. Tang and Y. Zhao, *Green Chem.*, 2024, **26**, 477–482.

29 (*a*) S. M. Shepard, H. Kim, Q. X. Bang, N. Alhokbany and C. C. Cummins, *J. Am. Chem. Soc.*, 2021, **143**, 463–470; (*b*) S. M. Shepard, I. W. Windsor, R. T. Raines and C. C. Cummins, *J. Am. Chem. Soc.*, 2019, **141**, 18400–18404; (*c*) G. Park, E. C. Wralstad, N. Faginas-Lago, K. Qian, R. T. Raines, G. Bistoni and C. C. Cummins, *ACS Cent. Sci.*, 2024, **10**, 1415–1422.

