# A green approach for the synthesis of $\pi$ conjugated phosphonium salts under visible-light irradiation using air as oxidant

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♦ air as green oxidant ♦ high atom economy ♦ transition-metal free ♦ suitable for gram-scale

#### Abstract:

We have developed a strategy for synthesizing  $\pi$ -conjugated phosphonium salts through visible-light-induced cyclization of aryl phosphines in the presence of air and protonic acid. The mechanism study revealed that this C–H bond activation/cyclization of aryl phosphine reaction was initiated from the homolysis of P-H bond of phosphonium salts, which is induced by visible light. This reaction is transition-metal free, exhibits good chemo-selectivity and has a high atomic economy.

#### Introduction

In the past decade, there has been a growing interest in  $\pi$  conjugated phosphonium salts due to their unique luminescence properties and strong oxidation potential under visible light. These compounds have been utilized as organocatalysts, luminescent molecules, and organogels in various fields such as organic synthesis, polymer synthesis, chromic materials, OLEDs, and cell imaging.<sup>[11]</sup> Currently, the most common methods for synthesizing these phosphonium compounds involve the ring closing of aryl phosphine using multiple amounts of Copper catalysts or the transformation of trivalent phosphopolycyclic aromatic hydrocarbons (P-PAHs) with halides.<sup>[1d, 2]</sup> Our group, as well as the groups of Yamaguchi and Hashmi, have reported the synthesis of phosphindolium salts through intramolecular cyclization of aryl

phosphines and alkynes, respectively.<sup>[3]</sup> Toste and coworkers have also demonstrated the formation of posphonium compounds through C–P reductive elimination from Gold(III) and have shown the formation of one cyclophosphonium compound under PhICl<sub>2</sub> (1 equiv) through C<sub>aryl</sub>–H activation.<sup>[4]</sup> However, compared to the research on  $\pi$  conjugated phosphine oxide, there is still a high demand for a practical and efficient approach for synthesizing  $\pi$  conjugated phosphonium salts.

In recent years, visible light-induced photocatalysis has rapidly developed due to its environmentally friendly and sustainable nature, making it an effective method for constructing C-P bonds.<sup>[5]</sup> Among them, the study of triarylphosphines as precursors for phosphorus radicals has attracted the attention of scholars. Under the mediation of photosensitizers and visible light, the phosphine molecule lost an electron to generate a corresponding phosphorus cation radical. Murakami's group has successively used this approach to develop reactions of triarylphosphine with substituted alkenes or alkynes to produce new phosphine oxides, tricyclic phosphonium salts, cyclopentane phosphonium salts and alkenyl phosphonium salts.<sup>[6]</sup> Abigail G. Doyle and Zhao groups have also achieved the generation of nitrogen free radicals by using the reaction of triarylphosphine, sulfonamide and hydroxylamine, respectively.<sup>[7]</sup> In 2022, Dilman's research group reported the use of triphenylphosphonium triflate as a key intermediate in the hydrophosphorylation of unactivated alkenes, with the producing phosphonium being directly used in the Wittig reaction.<sup>[8]</sup> Inspired by these works and our own interest in constructing phosphacycles,<sup>[9]</sup> we envisioned that  $\pi$  conjugated phosphonium salts could be synthesized from any phosphines and protonic acid directly through visible light-induced single electron transfer reactions. Herein, we report a green approach to the synthesis of five-membered and six-membered  $\pi$  conjugated phosphonium framework by C-H bond activation/cyclization of aryl phosphines with protonic acid under visible-light irradiation. The use of visible light irradiation not only avoids the addition of stoichiometric transition metals, but also enables the use of air as a green oxidant

in collaboration with photocatalysts to produce a series of  $\pi$  conjugated phosphoniums with medium to high yields.

# **Results and discussion**

[1,1'-biphenyl]-2-yldiphenylphosphine 1a was initially chosen as the template substrate to initiate reaction optimization. As shown in Table 1 (see the ESI), a 93% isolated yield of the target product 2a could be obtained under the 4 hours of irradiation with a 10 W blue LED (430 nm) at room temperature, using oxygen in air as a green oxidant, 10 mol%  $[Acr-Mes]^+(ClO_4)^-$  as the photocatalyst (PC), and 4Å molecular sieves (4Å MS) (100 mg) as a water absorbent in EtOH (Table 1, Entry 1). Further experiments showed that when the reaction was carried out in a nitrogen atmosphere, no 2a or phosphine oxide 3a were generated, as monitored by <sup>31</sup>P NMR (Table 1, Entry 2). This indicates that the oxygen in **3a** comes from air. When there was no light irradiation, the reactants did not react (Table 1, Entry 3). If 4 Å MS was not added, the yield of 2a decreased to 45% and **3a** was got in a yield of 55% (Table 1, Entry 4). Without PC, **2a** could be furnished with a yield of 28% and more by-product **3a** (80%) was afforded (Table 1, Entry 5). When neither 4 Å MS nor PC was added, the yields of 2a and 3a were 23% and 66%, respectively (Table 1, Entry 6). When the amount of [Acr- $Mes]^+(ClO_4)^-$  was reduced by 5%, the yield of **2a** decreased to 37% and the yield of 3a increased to 56% (Table 1, Entry 7). When the amount of protonic acid HOTf was reduced to 1.5 equiv or 1.0 equiv, the yield of the target product 2a also decreased in a certain extent (Table 1, Entries 8 and 9). Later, different PCs were examined, and the experimental results showed that when PhAcr, NBI, Eosin Y, and Rose Bengal were used as PCs, the yields of 2a decreased to 26%~45% and the yields of **3a** increased (Table 1, Entries 10~13). When toluene was used as the solvent, it took up to 14 hours to complete the reaction, and ultimately obtained 2a in 90% yield. When ether (Et<sub>2</sub>O) and tetrahydrofuran (THF) were used as solvents, 2a was obtained in 70% and 50% yields, respectively, and the reactions took longer. When dichloromethane (DCM) was

used as a solvent, the main product was **3a** (88%), and no **2a** was detected. These above results indicate that this reaction can be carried out without a photocatalyst, but with low efficiency. However, the visible-light irradiation and air are necessary for the reaction. The generation of **2a** and **3a** are competitive in this reaction. Additionally, 4 Å MS, solvents, and types of PCs have different impacts on the reaction.

PF	+ HOTf	[Acr-Mes] <sup>+</sup> (ClO <sub>4</sub> ) <sup>-</sup> (10 m HOTf (2.0 equiv) 4Å MS (100 mg)	$ \xrightarrow{Ph} Ph \xrightarrow{Ph} OTf $	PPh <sub>2</sub>
1a		430 nm, 10 w LED	2a	3a
H₃C∕	CH <sub>3</sub> + CH <sub>3</sub> CH <sub>3</sub> CIC		Br HO Br Br Br Br	
	[Acr-Mes]⁺(ClO <sub>4</sub> )⁻	PhAcr	Eosin Y	NBI
hv	430 nm, 10 w	460 nm, 10 w	460 nm, 10 w	460 nm, 10 w
Entr	Variatio	ons from the standard	d Yield of	Yield of
	у	conditions	<b>2a</b> (%) <sup>b</sup>	<b>3a</b> (%) <sup>b</sup>
1		No Change	93	Trace
2	Und	ler N2 atmosphere	NR	NR
3		Without light	NR	NR
4		No 4Å MS	45	55
5		Without PC	28	80
6	No	• 4Å MS and PC	23	66
7	5 mol%	5 mol% [Acr-Mes] $+(ClO_4)^-$		56
8	1	.5 equiv TfOH	90	8
9	1	.0 equiv TfOH	71	20
10		PhACr as PC	45	50
11		NBI as PC	39	60

#### Table 1 Optimization of reaction conditions<sup>a</sup>

12	Eosin Y as PC	45	50
13	Rose Bengal as PC	16	77
14 <sup>c</sup>	toluene as solvent	90	Trace
15°	Et <sub>2</sub> O as solvent	70	10
16 <sup>c</sup>	THF as solvent	50	40
17	DCM as solvent	ND	88

<sup>a</sup> Standard Conditions: **1a** (0.2 mmol), TfOH (2.0 equiv), 4Å MS (100 mg), [Acr-Mes]<sup>+</sup>(ClO<sub>4</sub>)<sup>-</sup> (10 mol%) as PC, EtOH (1 mL) as solvent, 4 h 430 nm 10 w LED irradiation, in a 25 mL photoreactor at room temperature under air atmosphere. NR = No Reaction, ND = Not detected. <sup>b</sup> Isolated yields. <sup>C</sup> Reaction time: 14 h.

To investigate the scope of this intramolecular cyclization reaction, several series of aryl phosphines were synthesized and examined under optimal conditions (Table 1, entry 1). The effects of steric hindrance of the substituent on the  $Ar^1$ part on the reaction were firstly explored. Methyl groups were introduced at the ortho, meta, and para positions of the  $Ar^1$  group respectively, and the results showed that the reaction proceeded in all cases. After reacting for 4 hours, the isolated yields of the corresponding products were 60% (2b), 83% (isomer mixtures 2c + 2c'), and 83% (2d). It can be seen that the yield of 2b was significantly reduced when the methyl group was in the ortho position. This could be due to the presence of the methyl group reducing the reaction sites, thereby decreasing the formation rate of the desired product 2b. This was further confirmed by the yield of **3b**, which reached only 32%. The influence of the electronic properties of the substituent on the reaction was then investigated then. When the substituent was an electron-donating methoxy group, the reaction performed well, and 2e was produced in 88% yield. However, when the substituent was an electron-withdrawing group F, the yield of the product 2f was only moderate at 60%, and the yield of the by-product 3f increased to 36%. When  $Ar^1$  was biphenyl, the yield of the target product 2g was 50%. Heterocyclic aromatic hydrocarbons were also suitable for this reaction; when the thiophene-



Scheme 2 Substrate scope for the synthesis of  $\pi$  conjugated phosphonium salts <sup>a,b</sup>

<sup>a</sup> Standard reaction conditions:**1** (0.2 mmol), TfOH (2.0 equiv), 4Å MS (100 mg), [Acr-Mes]<sup>+</sup>(ClO<sub>4</sub>)<sup>-</sup> (10 mol%), EtOH (1 mL) as solvent, 4 h 430 nm 10 w LED irradiation, in a 25 mL photoreactor at room temperature under air atmosphere. <sup>b</sup> Isolated yields. <sup>c</sup> Toluene (1 mL) as solvent.

containing substrate 1h was used, 2h was afforded with a yield of 70%. Substrates with two p-methoxy phenyl or p-fluoro phenyl groups on the phosphorus atom also yielded the target products 2i and 2j in good yields. But when the substrate was changed to 2-dicyclohexylbiphenylphosphine, no target product was formed, and only its oxide was generated in 85% yield. When the Ar<sup>1</sup> group was replaced by naphthalene, anthracene, and pyrene, the reaction selectively produced six-membered phosphopolycyclic aromatic hydrocarbons with yields of 86% (2k), 85% (2l), and 84% (2m), respectively. This is consistent with our previous report on the synthesis of heterocyclic phosphine oxides through a free radical process [8]. The structure of  $2\mathbf{k}$  was further confirmed by X-ray diffraction analysis. When the arylphosphine containing a binaphthyl skeleton was introduced, the corresponding phosphonium salt 2n was constructed with a yield of 90%. When carbazole was incorporated into the starting material, the reaction proceeded well, and the product 20 was produced with a of 83%. Subsequently, three other carbazole derivatives were examined, and 2p, 2q and 2r were obtained in medium to high yields (55%~80%). Three thiophene-containing products 2s, 2t and 2u were got in high yields ( $\geq 90\%$ ) in toluene with higher selectivity than in EtOH. Finally, different protonic acids were investigated in this reaction. Among them, trifluoroacetic acid was found to be suitable, and the corresponding phosphonium 2a' was successfully obtained with a yield of 60%.

#### Scheme 3 Large-scale synthesis of 2a



To demonstrate the practicality of this approach, a gram-scale reaction was carried out to synthesize **2a**, and 1.68 g of **2a** was obtained in yield of 70% when a more

powerful 40 W blue light was used. This reaction can also be performed in toluene with 68% yield (Scheme 3).

#### Scheme 4 Control experiments.



In order to gain insight into the reaction mechanism, several control experiments were conducted. Instead of using visible light irritation, the reaction system was placed in an oil bath at 70 °C for 6 hours. However, the reaction did not proceed (Scheme 4a), indicating that it is not a Friedel-Crafts reaction. When free radical scavengers 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) or 2,6-di-tert-butyl-4-methylphenol (BHT) were added into the reaction system under the standard conditions, the formation of **2a** was partially inhibited, resulting in a decrease in yield to 27% or 30%, respectively. In contrast, the yields of **3a** increased to 65% or 70%, respectively (Scheme 4b and 4c). This suggests that the addition of TEMPO or BHT captured phosphorus radicals, which then generated **3a**. Finally, we carried out a fluorescence quenching experiment, and the results are depicted in Figure S1-S2. As the concentration of **A** increased, the fluorescence intensity of the PC diminished. And the relationship between these two variables adheres to the Stern-Volmer equation. These results suggest that the reaction process is possibly initiated by the reaction of excited state of the photocatalyst and **A**.

Scheme 5 Proposed mechanism.



Based on previous literature and the experimental results, a plausible catalytic pathway for this reaction was proposed (Scheme 5). Firstly, 1a reacted with HOTf to produce phosphonium salt **A**, which was characterized by <sup>31</sup>P NMR ( $\delta$ = 0.49 ppm,  $J_{P-H} = 540$  Hz) spectrum, and high-resolution mass spectrometry. Under the presence of PC and blue light irritation, phosphonium salt A underwent the homolysis of its P-H bond to generate a hydrogen radical and a phosphorus positive radical **B**. The hydrogen radical was then captured by PC\* to release a proton and form PC<sup>--</sup>. PC<sup>--</sup> was subsequently oxidized by oxygen in the air, releasing PC and a superoxide radical anion  $O_2^{-}$  to complete the catalytic cycle. In the presence of protonic acid,  $O_2^{-\bullet}$  was converted into a HOO• radical. The phosphorus positive radical **B** attacked the intramolecular aromatic ring to form a new radical intermediate C. C then lost an electron and aromatized by deprotonation to generate the final product 2a, while HOO• was converted to HOOH. The hydrogen peroxide decomposed under light to produce water and oxygen, completing the cycle of half oxygen. This is consistent with the experimental result that the amount of oxygen in the air in the photoreactor was 0.5 equivalent of 1a. If there was not enough air, the reaction could not proceed completely. The addition of 4Å MS in the reaction system could trap the generated water, shift the reaction equilibrium, and promote the formation of 2a, which was also consistent with the experimental results. When intermediate **A** reacted with superoxide anion  $O_2^{--}$ , intermediate **D** was generated, which reacted with another **1a** to produce two molecules of **3a**.

#### Conclusions

In summary, we have established a novel green protocol for producing fivemembered and six-membered  $\pi$  conjugated phosphonium salts under visible light irradiation by using triaryl phosphine and protonic acid as starting materials, cheap and easily available organic dye [Acr-Mes]<sup>+</sup>(ClO4)<sup>-</sup> as a photocatalyst, and air as a sustainable oxidant. This reaction is applicable on variety substrates, which are not only suitable for polyphenyl systems, such as naphthalene, anthracene and pyrene, but also for hetero aromatic systems containing sulphur and nitrogen. This method is transition metal free, exhibits good chemoselectivity and has a high atomic economy. Furthermore, gram-scale model reactions were proceeded well, which laid a foundation for the subsequent research of  $\pi$  conjugated phosphonium salts.

### **Supporting Information**

Experimental procedures, characterization data for all new compounds including <sup>1</sup> H, <sup>31</sup> P, and <sup>13</sup> C NMR spectra, and Crystallographic data for **2m** (CCDC 2257370).

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#### **Conflicts of interest**

There are no conflicts to declare.

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