Synthesis K. Dziuba et al. Paper

Knoevenagel Condensation of Phosphinoylacetic Acids with Aldehydes: An Efficient One-Pot Strategy for the Synthesis of P-Functionalized Alkenyl Compounds

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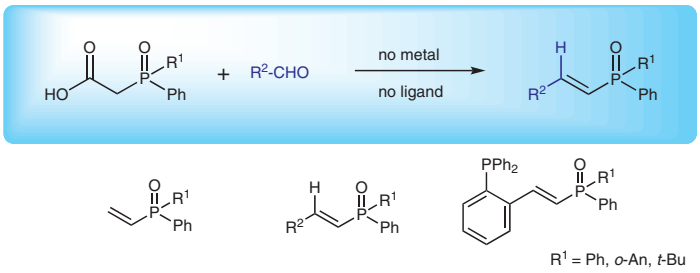
Transition-metal-free approach to alkenylphosphine oxides



>30 examples, yields up to 93%, excellent regioselectivity *E*/*Z* up to 99:1

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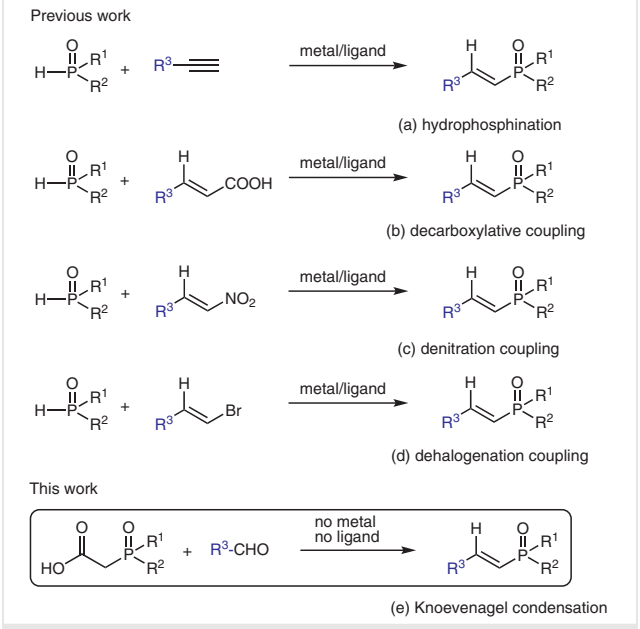
Abstract A wide range of commercially available aldehydes have been applied to Knoevenagel condensation reaction to give *E*-alkenylphosphine oxides and vinylphosphine oxides. The readily available phosphinoylacetic acids derived from P(O)–H compounds were used as the starting materials in the reaction, providing a highly stereoselective and efficient method for constructing α,β-unsaturated phosphine oxides. Moreover, this simple and practical procedure provides an alternative and more environmentally friendly synthesis strategy for this type of P-functionalized alkenyl compounds.

Key words Knoevenagel condensation, alkenylphosphine oxide, phosphinoylacetic acid, amine/acid-catalyzed, metal free

Alkenylphosphorus compounds have gained much attention in over the past several years due to their extensive applications in various fields of chemistry. This class of compounds containing C–P bonds seems extremely versatile due to their ability to undergo a wide variety of transformations affording products for applications in medicinal and agricultural chemistry.[1] Alkenylphosphine oxides (including the chiral ones) are good precursors of trivalent phosphines that have eminent metal-complexing abilities to transition metals.[2] Also, the phosphoryl oxygen might be used for complexation of metal ions and acids, and metal complexes based on phosphoryl compounds are well recognized in the scientific literature.[3] P-functionalized vinyl compounds play an important role in many synthetic applications. In the reaction with amines, phosphine oxides, and carbon species, they allow to construct precursors of bifunctional adducts.[4] In addition, alkenylphosphine oxides have wide applications in material chemistry.[5] They exhibit flame retarding properties and this unique feature of these compounds has recently been of interest.[6]

Despite the great importance of alkenylphosphorus compounds, general and effective methods to access this scaffold are quite limited.[7–17] In this context, transition-metal-catalyzed P–C bond formation reaction between P–H-type compounds and alkynes (hydrophosphination reaction; Scheme 1a) or functionalized alkenes (cross-coupling reaction; Scheme 1b–d) were established as the dominant synthetic strategies.

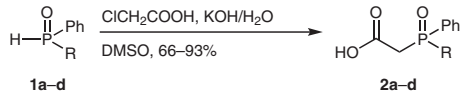


Scheme 1 Synthesis of alkenylphosphorus compounds

In 1996, Tanaka and Han reported a pioneering Pd-catalyzed hydrophosphination of alkynes.[8] Since then, many transition-metal-catalyzed methods for the synthesis of alkenylphosphine oxides based on palladium,[9] copper,[10] nickel,[11] rhodium,[12] zirconium,[13] and ytterbium[14] catalytic system have constantly appeared. Although hydrophosphination is highly atom-economy strategy, still the main disadvantage of this method remains the use of precious metals and the issues associated with the stereo- and regioselectivity of the process. There are also numerous publications describing the cross-coupling reactions of functionalized alkenes as another attractive strategy for the synthesis of alkenylphosphorus compounds (Scheme 1b–d). Significant progress has been also made in the decarboxylative coupling,[15] denitration,[16] and dehalogenation reactions.[17] However, despite the usefulness of the above methods, most of them still require well-defined ligands, specifically functionalized precursors and oxidants, which increase the overall costs and limit the practical application of these methodologies, especially for the synthesis of phosphine ligand precursors. In addition, transition metals used in these reactions are difficult to remove due to the complex formation with the reaction products. Despite this, simple and transition-metal-free methods of the synthesis of these compounds are still highly desirable due to the wide spectrum of applications.

In 2005 Krawczyk and Albrecht reported the phosphono-olefination of carbonyl compounds with dialkylphosphonoacetic acids resulting in the synthesis of α,β-unsaturated phosphonates.[18] The synthetic approach was based on the Knoevenagel condensation of diethylphosphonoacetic acid with aldehydes with subsequent decarboxylation of the acids. However, despite all these elegant methods, in our synthetic project we needed access to a different class of organophosphorus compounds, that is, vinylphosphine oxides and alkenylphosphine oxides, and therefore wanted to explore the readily available phosphinoylacetic acids as substrates. Thus, given the present achievements in organocatalytic transformations we considered Knoevenagel condensation as a powerful tool for an efficient and rapid skeleton structure modification of phosphinoylacetic acids. Knoevenagel condensation is a reaction between aldehydes or ketones and an active methylene compounds with ammonia or another amine as a catalyst that results in the formation of α,β-unsaturated compounds.[19] This classic C–C bond forming reaction occurs in two stages, the first one is the nucleophilic addition to carbonyl group and the second is the elimination of a water molecule.[20] Starting from readily available phosphinoylacetic acids a modular approach for the synthesis of alkenylphosphine oxides can be employed in which both steric and electronic properties around phosphorus moiety can be easily varied. Considering this, we report a highly efficient, and transition-metal-free synthesis of *E*-alkenylphosphine oxides from phosphinoylacetic acids and commercially available aldehydes (Scheme 1e). To the best of our knowledge this method is the first example of the efficient synthesis of alkenylphosphine oxides based on the Knoevenagel type reaction, whose advantage is the synthetic simplicity, high yields, and broad substrate scope.

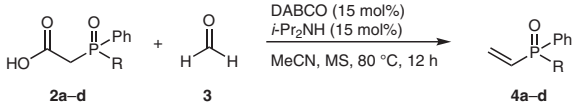
To meet our research interests, we synthesized a series of phosphinoylacetic acids and then applied them in the amine-catalyzed Knoevenagel reaction. Experimental procedure for the synthesis of phosphinoylacetic acids was adapted from the work of Kabachnik.[21] For this purpose, the corresponding secondary phosphine oxides and chloroacetic acid were subjected to a reaction in the presence of aqueous KOH solution in dimethyl sulfoxide as a solvent (Scheme 2). The target diarylphosphinoylacetic acids **2a**,**b** and alkylphenylphosphinoylacetic acids **2c**,**d** were obtained after crystallization in 66–93% yields.



Scheme 2 Synthesis of phosphinoylacetic acids

Krawczyk and Albrecht reported the reaction of the diethylphosphonoacetic acid with excess of formaldehyde performed in boiling benzene in the presence of catalytic amounts of dicyclohexylamine and DABCO. A Dean–Stark water separator was used to remove the resulting water in the reaction mixture. For the purposes of our synthesis of vinylphosphine oxides, we have adopted the synthesis conditions presented by Krawczyk and Albrecht.

Table 1 Synthesis of Vinylphosphine Oxides[a]



Entry	R	Conv. (%)[b]	**4** Yield (%)[c]
1	Ph	100	**4a** (83)
2[d]	Ph	100	**4a** (80)
3[e]	Ph	100	**4a** (82)
4[f]	Ph	60	**4a** (51)
5[g]	Ph	90	**4a** (80)
6	*o*-An	100	**4b** (87)
7	Me	100	**4c** (86)
8	*t*-Bu	100	**4d** (87)

[a] Reaction conditions: phosphinoylacetic acid **2** (0.76 mmol), formaldehyde (**3**; 1.53 mmol), DABCO (15 mol%), *i*-Pr_2NH (15 mol%), MeCN, MS 3Å, stirred at 80 °C for 12 h.
[b] Determined by ^{31}PNMR analysis of the crude reaction mixture.
[c] Isolated yield.
[d] Dicyclohexylamine (15 mol%) was used instead of *i*-Pr_2NH.
[e] Toluene was used as the solvent.
[f] No molecular sieves.
[g] Reaction carried out on a 1.5 gram scale for 48 h.

When we examined phosphinoylacetic acids **2a–d** as substrates in a condensation with formaldehyde as a route for the synthesis of vinylphosphine oxides **4a–d**, we have found a mixture of DABCO and diisopropylamine (Table 1, entry 1) or dicyclohexylamine (entry 2) as a suitable catalyst system for this reaction. We eliminated the use of benzene as a solvent from the reaction and replaced it with acetonitrile or toluene (entry 3). The reaction without the azeotropic removal of water gave the product in low yield (entry 4). However, we noticed that the addition of molecular sieves (MS 3Å) was enough to remove the water from the reaction. Molecular sieves also worked well with the 1.5 gram scale reaction (entry 5).

Thus, in a typical experimental procedure, a mixture of formaldehyde (2.0 equiv) and acid **2a–d** (1 equiv) in acetonitrile was heated at 80 °C in the presence of the catalysts for 12 hours. Standard workup and silica gel chromatography gave the pure products in high isolated yields up to 87%.

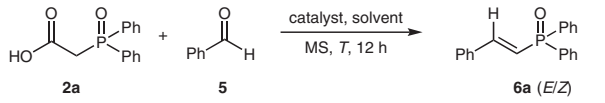
Encouraged by these results, we focused our efforts on the Knoevenagel condensation of phosphinoylacetic acids with aryl aldehydes. We commenced our study with the reaction of diphenylphosphinoylacetic acid with benzaldehyde (1.2 equiv). In the presence of DABCO/Cy_2NH in acetonitrile at 80 °C, we were pleased to note that the (*E*)-β-styryldiphenylphosphine oxide was obtained but in only 9% conversion (Table 2, entry 1). To improve the yield, we decided to perform optimization studies in order to find the most suitable conditions for the preparation of compound **6a**.

Thus, we optimized a variety of reaction conditions such as catalyst type and ratio, solvents, and reaction temperature. After screening of reaction parameters, the desired product **6a** was obtained with full conversion and in 90% isolated yield with the use of piperidine (30 mol%) and acetic acid (30 mol%) in acetonitrile as the solvent (Table 2, entry 6). The reaction proceeded smoothly only when piperidine itself or piperidine with AcOH or *p*-toluenesulfonic acid were used as the catalysts and the best ratio of these two catalysts was 1:1. In contrast, the use of DABCO with dicyclohexylamine or diisopropylamine was totally ineffective (less than 9% of conversion). Changing the solvent to methylcyclohexane gave the product with high conversion 99% (entry 13), the reaction in toluene was less effective and provided **6a** in 93% conversion, whereas in DMF it was only 37%. Fortunately, when we used non-dried, non-distilled HPLC-grade acetonitrile and the reaction was run under air, its efficiency was unchanged. We also carried out reactions on a 1.5 gram scale, obtaining the target product **6a** after 48 hours in a yield of 70% of pure *E*-isomer (entry 7).

It is important to note that the condensation reactions were highly stereospecific as the *E*/*Z* ratio of the products reached 97:3 level. The pure *E*-isomer of β-styryldiphenylphosphine oxide was simply obtained after single chromatography on silica gel. We have also noticed that under the reaction conditions the tandem process is presented, which includes modified Knoevenagel condensation of phosphinoylacetic acids with aryl aldehydes (where formic acid and water were eliminated) and then decarboxylation of the created phosphorylated acrylic acid.

Following the optimized reaction conditions for the construction of **6a**, we examined the scope of this synthesis using series of phosphinoylacetic acids **2a–d** and differently substituted aryl aldehydes and the results are summarized in Scheme 3. Initially, diphenylphosphinoylacetic acid (**2a**) was selected as a model substrate for the reaction with aryl

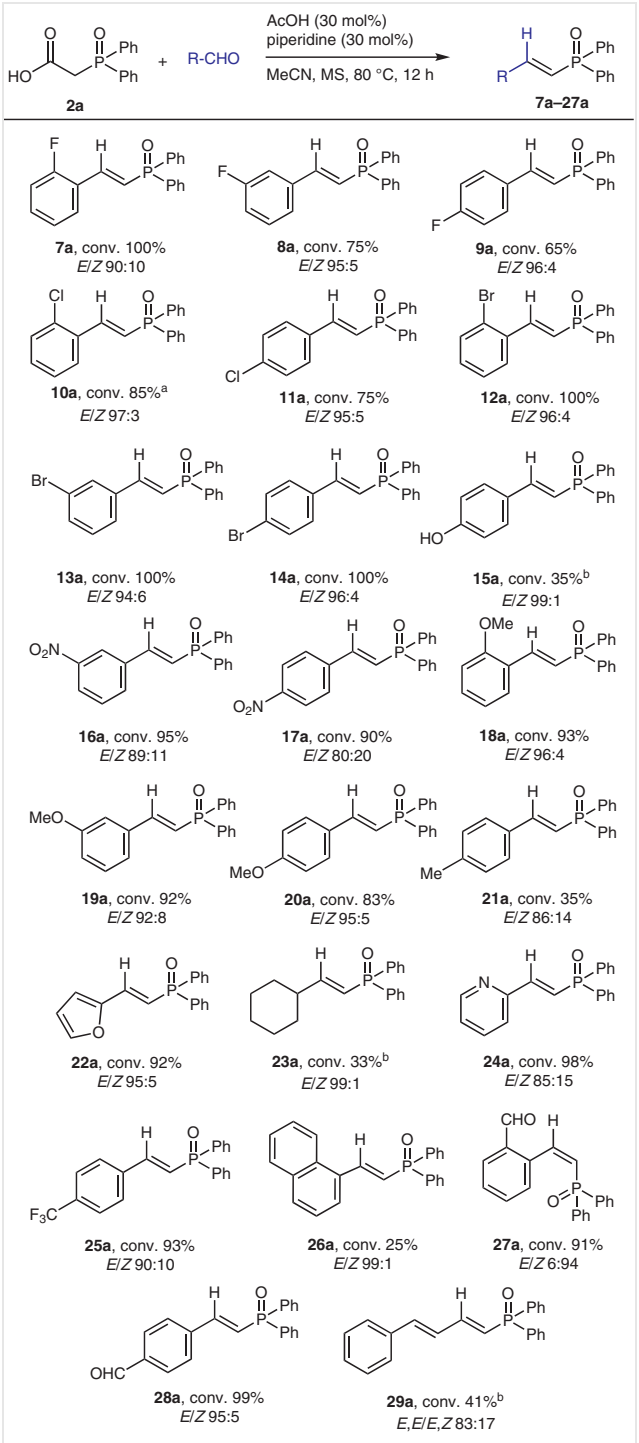
Table 2 Optimization of the Reaction Conditions[a]



2a **5** **6a** (*E*/*Z*)

Entry	Catalyst (mol %)	Solvent	Temp (°C)	Conv. (%)[b]	*E*/*Z*[b]
1	DABCO (30) Cy_2NH (30)	MeCN	80	9	nd
2	DABCO (30) *i*-Pr_2NH (30)	MeCN	80	0	nd
3	DABCO (30) *i*-Pr_2NH (30)	MeCN	80	0	nd
4	piperidine (30)	MeCN	80	81	87:13
5	piperidine (30) AcOH (30)	MeCN	80	95	97:3
6[c]	piperidine (30) AcOH (30)	MeCN	80	100[d]	96:4
7[c]	piperidine (30) AcOH (30)	MeCN	80	90[e]	96:4
8	piperidine (30) AcOH (60)	MeCN	80	33	nd
9	piperidine (60) AcOH (30)	MeCN	80	77	95:5
10	Cy_2NH (30) AcOH (30)	MeCN	80	0	nd
11	piperidine (30) *p*-TsOH (30)	MeCN	80	61	85:15
12[c]	piperidine (30) AcOH (30)	toluene	110	93	95:5
13[c]	piperidine (30) AcOH (30)	MeCy	80	99	95:5
14[c]	piperidine (30) AcOH (30)	DMF	110	37	nd
15	piperidine (30) AcOH (30)	toluene	80	21	nd

[a] Reaction conditions: diphenylphosphinoylacetic acid (**2a**; 0.76 mmol), benzaldehyde (**5**; 1.53 mmol), catalyst, MS 3Å, solvent (5.0 ml), stirred for 12 h.
[b] Reaction conversion and *E*/*Z* ratio were determined by ^{31}P NMR analysis of the crude reaction mixture. nd: Not determined.
[c] Reaction time: 48 h.
[d] Isolated yield: 90%.
[e] Reaction carried out on a 1.5 gram scale; isolated yield: 70%.



Scheme 3 Substrate scope with phosphinoylacetic acid **2a**. *Reagents and conditions*: diphenylphosphinoylacetic acid (**2a**; 0.76 mmol), aldehyde (1.53 mmol), AcOH (30 mol%), piperidine (30 mol%), MS 3Å, and MeCN (5.0 mL), stirred at 80 °C for 12 h. Reaction conversion and the *E*/*Z* ratio were determined by ^{31}P NMR analysis of the crude reaction mixture. The product was then isolated by column chromatography. The isolated yields are given in the experimental part. [a] Reaction time: 48 h. [b] Reaction temperature: 100 °C.

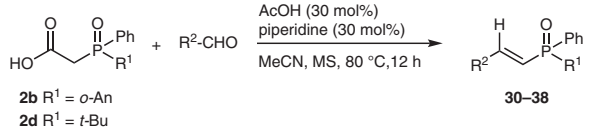
aldehydes possessing either electron-withdrawing groups (halide, trifluoromethyl, nitro) or electron-donating groups (methyl, methoxy, hydroxy). Aldehydes with halogen atom at the *ortho*-position generated the products with higher yields compared to *meta*- and *para*-substituted aldehydes. Among halogen groups, bromide was the most compatible with this transformation affording the desired products with full conversion and excellent *E*-selectivity (**12a**–**14a**). Similarly, high conversion and yields were observed with CF_3 substituted aldehyde **25a** (93%) and with *meta*- and *para*-nitrobenzaldehydes **16a** and **17a**. Aldehydes with electron-donating groups such as methoxybenzaldehyde were also amenable to this protocol and gave the products **18a**, **19a**, and **20a** with conversion up to 93% and *E*/*Z* selectivity up to 96:4. The other electron-donating substituents including methyl and hydroxy afforded products in moderate yields. The reaction conditions were also applicable to heteroaromatic substrates, such as 2-pyridyl aldehyde and furfural, furnishing the corresponding products **22a**, **24a** in good to excellent yields. Finally, the reaction with cyclohexanecarboxaldehyde, 1-naphthaldehyde, and cinnamaldehyde gave the products **23a**, **26a**, and **29a** with moderate conversion (33%, 25%, and 29%, respectively). These examples show that Knoevenagel condensation has the advantages of a wide range of substrates. Surprisingly, the reaction of diphenylphosphinoylacetic acid with 1.5 equivalents of *o*-phthalaldehyde furnished the product **27a** with 91% conversion and high *Z*-selectivity 6:94 (*E*/*Z*) while with terephthalaldehyde the yield of **28a** was 71% and the *E*-isomer was predominantly formed (*E*/*Z* = 95:5). Under the reaction conditions, in most cases the thermodynamically more stable *E*-isomer was formed. The exception was product **27a**, wherein the presence of the aldehyde group in the *ortho*-position was probably related to the preferential formation of the *Z*-isomer.

Phosphinoylacetic acids **2b** and **2d** both underwent smoothly the reaction with aryl aldehydes possessing electron-withdrawing and electron-donating groups to afford the corresponding products in high isolated yields up to 94% and with excellent *E*-selectivity (*E*/*Z* ratio up to 99:1) (Table 3). These examples again demonstrated the excellent chemoselectivity and stereoselectivity of the reaction and represented a simple and convenient protocol for the synthesis of functionalized alkenylphosphine oxides.

After examining the scope of Knoevenagel condensation of phosphinoylacetic acids with aldehydes, we sought a simple but practical application of our methodology. For this reason, we have paid a particular attention to phosphine ligands and phosphorus organocatalysts. We designed a series of simple phosphine-phosphine oxides **L1**–**L4**, which after the introduction of chirality at the phosphorus atom might become very attractive ligands for asymmetric transition metal catalysis or asymmetric organocatalysis. Following our convenient and highly efficient synthetic route for alkenylphosphorus compound we smoothly

prepared these hemilabile ligands using commercially available 2-(diphenylphosphino)benzaldehyde and diphenylphosphinoylacetic acid. Surprisingly, this *ortho*-substituted diarylphosphine was a suitable reaction partner and we isolated the pure product **L1** in 91% yield with an *E*-selectivity of >99:1 (Table 4, entry 1). Expanding this transformation we performed the coupling reaction with the other three phosphinoylacetic acids furnishing the desired products in high isolated yields and high stereoselectivity. To avoid excessive oxidation of phosphine during the reaction, anhydrous toluene was used instead of acetonitrile. The reaction proceeded smoothly in the presence of piperidine and acetic acid and the crude products **L1**–**L4** were smoothly purified by simple column chromatography.

Table 3 Knoevenagel Condensation of Phosphinoylacetic Acids **2b** and **2d** with Selected Aldehydes[a]



2b R^1 = *o*-An
2d R^1 = *t*-Bu

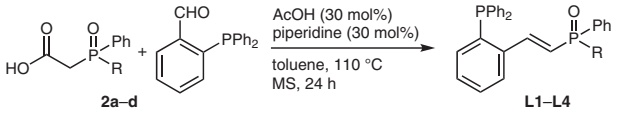
30–38

Entry	R^1	Aldehyde R^2	Conv. (%)[b]	*E*/*Z*[b]	Yield (%)[c]
1	*o*-An	2-BrC_6H_4	65	98:2	**30b** (61)
2	*o*-An	2-$MeOC_6H_4$	79	99:1	**31b** (73)
3	*o*-An	2-pyr	99	93:7	**32b** (93)
4	*o*-An	Ph	67	98:2	**33b** (62)
5	*t*-Bu	2-BrC_6H_4	75	94:6	**34d** (69)
6	*t*-Bu	2-$MeOC_6H_4$	83	96:4	**35d** (75)
7	*t*-Bu	2-pyr	99	95:5	**36d** (94)
8	*t*-Bu	Ph	66	96:4	**37d** (62)
9	*t*-Bu	2-thienyl	82	98:2	**38d** (76)

[a] Reaction conditions: phosphinoylacetic acid **2b**,**d** (0.76 mmol), aldehyde (1.53 mmol), AcOH (30 mol%), piperidine (30 mol%), MS 3Å, MeCN (5.0 mL), stirred at 80 °C for 12 h.
[b] Reaction conversion and *E*/*Z* ratio were determined by ^{31}P NMR analysis of the crude reaction mixture.
[c] Isolated yield.

In summary, our synthetic strategy toward alkenylphosphorus compound was based on Knoevenagel condensation of phosphinoylacetic acids with aldehydes. The synthesis of the products was successful and it was possible to obtain the desired products with high purity and high *E*-selectivity confirmed by NMR analysis. The influence of the catalyst and the aldehyde substituent on the reaction was evidenced. The best catalytic system for the synthesis of *E*-alkenylphosphorus derivatives was piperidine with AcOH. In turn, for the synthesis of vinylphosphine oxides DABCO with *i*-Pr_2NH was the most effective. We have also successfully realized the simple synthesis of hemilabile ligands. Ongoing research, including introduction P-chirality and further scopes, are currently underway.

Table 4 Practical Synthesis of Hemilable Ligands[a]



2a–d **L1–L4**

Entry	R	Conv. (%)[b]	*E*/*Z*[b]	Yield (%)[c]
1	Ph	97	99:1	**L1** (91)
2	*o*-An	99	98:2	**L2** (93)
3	Me	86	95:5	**L3** (79)
4	*t*-Bu	96	92:8	**L4** (87)

[a] Reaction conditions: phosphinoylacetic acid **2** (0.76 mmol), 2-(diphenylphosphino)benzaldehyde (0.95 mmol), AcOH (30 mol%), piperidine (30 mol%), MS 3Å, toluene (6.0 mL), stirred at 110 °C for 24 h.
[b] Reaction conversion and *E*/*Z* ratio were determined by ^{31}P NMR analysis of the crude reaction mixture.
[c] Isolated yield.

Unless noted otherwise, all starting materials and solvents were used as obtained from commercial suppliers without further purification. Not available commercially substrates were obtained by known literature procedures. The physical properties and spectra of obtained products are provided in the Supporting Information. NMR spectra were recorded on a Bruker AV500 (^1H 500 MHz, ^{31}P 202 MHz, ^{13}C NMR 126 MHz) spectrometer. All spectra were obtained in $CDCl_3$ solutions, unless mentioned otherwise, and the chemical shifts (δ) are expressed in ppm using internal reference to TMS with the solvent as an internal indicator ($CDCl_3$ 7.27 ppm for ^1H and 77 ppm for ^{13}C) and external reference to 85% H_3PO_4 in D_2O for ^{31}P. Coupling constants (*J*) are given in hertz (Hz). Standard abbreviations are used for signal patterns. Low- and high-resolution mass spectra were obtained with Shimadzu LC-MS (Kinetex® 2.6 µm Biphenyl 100 Å 50 × 2.1 mm LC-column, MeCN/H_2O with HCO_2H additive mobile phase). Flash chromatography purifications were carried out using Merck silica gel 60 (230–400 mesh particle size). TLC analyses were carried out using Merck silica gel 60 F254 plates (Merck, Kenilworth, NJ, USA). Visualization of TLC plates was performed by UV light either $KMnO_4$ or I_2 stains.

Phosphinoylacetic Acids 2a–d; General Procedure

To a stirred solution of the secondary phosphine oxide **1a–d** (22 mmol) and chloroacetic acid (2.27 g, 24 mmol) in DMSO (12 mL) was added dropwise a 56% aq KOH solution (5.6 ml, 57 mmol) at r.t. After heating for 1 h at 40–60 °C, the mixture was diluted with H_2O. The aqueous solution was acidified with dil HCl and the crude mixture was extracted with $CHCl_3$. The combined $CHCl_3$ extracts were dried ($MgSO_4$), filtered, and evaporated under vacuum. The residue was crystallized from MeCN.

Diphenylphosphinoylacetic Acid (2a)

According to the general procedure, the reaction of **1a** (4.75 g, 22 mmol) afforded product **2a** as a white solid; yield: 4.80 g (83%); mp 145–146 °C (Lit.[22] mp 146–147 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.75–7.68 (m, 4 H), 7.55–7.32 (m, 6 H), 6.81 (br s, 1 H), 3.46 (d, *J* = 14.2 Hz, 2 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 167.31 (d, *J* = 5.6 Hz), 132.44 (d, *J* = 2.8 Hz), 131.07 (d, *J* = 10.3 Hz), 130.85 (d, *J* = 105.7 Hz), 128.75 (d, *J* = 12.6 Hz), 38.36 (d, *J* = 62.2 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 30.42.

(2-Methoxyphenyl)phenylphosphinoylacetic Acid (2b)

According to the general procedure, the reaction of **1b** (5.11 g, 22 mmol) afforded product **2b** as a white solid; yield: 5.04 g (79%); mp 173–174 °C (Lit.[23] mp 176–177 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.66 (ddd, *J* = 13.7, 7.6, 1.7 Hz, 1 H), 7.61–7.50 (m, 2 H), 7.36–7.25 (m, 2 H), 7.21 (tdd, *J* = 8.2, 3.2, 1.2 Hz, 2 H), 6.85 (tdd, *J* = 7.5, 2.1, 0.9 Hz, 1 H), 6.77 (br s, 1 H), 6.71 (dd, *J* = 8.3, 5.8 Hz, 1 H), 3.56 (s, 3 H), 3.39 (dd, *J* = 14.1, 5.5 Hz, 2 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 167.51 (d, *J* = 6.2 Hz), 159.91 (d, *J* = 4.6 Hz), 134.78 (d, *J* = 2.1 Hz), 134.25 (d, *J* = 6.2 Hz), 132.14 (d, *J* = 2.9 Hz), 131.81 (d, *J* = 108.2 Hz), 130.70 (d, *J* = 10.8 Hz), 128.47 (d, *J* = 12.8 Hz), 121.35 (d, *J* = 11.7 Hz), 118.26 (d, *J* = 105.7 Hz), 110.99 (d, *J* = 7.0 Hz), 55.45, 37.46 (d, *J* = 63.2 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 30.11.

Methylphenylphosphinoylacetic Acid (2c)

According to the general procedure, the reaction of **1c** (3.08 g, 22 mmol) afforded product **2c** as a white solid; yield: 2.83 g (65%); mp 114–116 °C (Lit.[24] mp 116–117 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 9.58 (br s, 1 H), 7.77 (ddd, *J* = 12.4, 8.3, 1.4 Hz, 2 H), 7.63–7.45 (m, 3 H), 3.44–3.09 (m, 2 H), 2.02 (d, *J* = 13.6 Hz, 3 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 167.63 (d, *J* = 5.4 Hz), 132.59 (d, *J* = 2.9 Hz), 131.40 (d, *J* = 103.6 Hz), 130.78–127.03 (m), 39.80 (d, *J* = 60.3 Hz), 15.64 (d, *J* = 72.7 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 38.20.

(*tert*-Butyl)phenylphosphinoylacetic Acid (2d)

According to the general procedure, the reaction of **1d** (4.01 g, 22 mmol,) afforded product **2d** as a white solid; yield: 4.02 g (76%); mp 156–158 °C (Lit.[25] mp 160–161 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 9.46 (br s, 1 H), 7.73–7.65 (m, 2 H), 7.57–7.49 (m, 1 H), 7.48–7.42 (m, 2 H), 3.29 (dd, *J* = 14.1, 12.8 Hz, 1 H), 3.17 (dd, *J* = 14.1, 10.2 Hz, 1 H), 1.10 (d, *J* = 15.8 Hz, 9 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 167.24 (d, *J* = 6.4 Hz), 132.19 (d, *J* = 2.8 Hz), 131.77 (d, *J* = 8.7 Hz), 128.30 (d, *J* = 11.4 Hz), 127.81 (d, *J* = 93.6 Hz), 33.50 (d, *J* = 70.5 Hz), 32.22 (d, *J* = 51.8 Hz), 23.97.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 49.25.

Knoevenagel Condensation between Formaldehyde (3) and Phosphinoylacetic Acids 2; General Procedure

The aldol reactions were carried out in a 15 mL vial. In a typical reaction, the vial was charged at r.t. with the reactants in the following order: the respective phosphinoylacetic acid **2** (0.76 mmol), formaldehyde (**3**; 46 mg, 1.53 mmol), MeCN (5.0 mL), catalysts (Table 1), and molecular sieves (100 mg) . The flask was capped with a stopper and sealed. Then, the reaction mixture was stirred at 80 °C for 12 h. The mixture was filtered and the filtrate concentrated under reduced pressure. The product conversion with respect to the phosphinoylacetic acids were determined by ^{31}P NMR analysis in $CDCl_3$ on the crude mixture. The crude residue was purified by column chromatography on silica gel (eluent: EtOAc/MeOH with a gradient mixture ratio from 50:1 to 20:1).

Diphenyl(vinyl)phosphine Oxide (4a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **4a** as a white solid; yield: 144 mg (83%); mp 116–117 °C (Lit.[26] mp 115–115.8 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.74–7.66 (m, 4 H), 7.57–7.50 (m, 2 H), 7.50–7.43 (m, 4 H), 6.67 (ddd, *J* = 24.6, 18.4, 12.6 Hz, 1 H), 6.39–6.20 (m, 2 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 134.86, 132.22 (d, *J* = 105.0 Hz), 131.96 (d, *J* = 2.7 Hz), 131.39 (d, *J* = 10.0 Hz), 131.09 (d, *J* = 98.3 Hz), 128.62 (d, *J* = 12.2 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 23.94.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{28}H_{26}O_2P_2Na^+$: 479.1300; found: 479.1309.

(2-Methoxyphenyl)phenyl(vinyl)phosphine Oxide (4b)

According to the general procedure, the reaction of **2b** (221 mg, 0.76 mmol) afforded product **4b** as a white solid; yield: 171 mg (87%); mp 107–109 °C (Lit.[27] mp 107–108 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.02 (ddd, *J* = 13.2, 7.5, 1.8 Hz, 1 H), 7.70–7.61 (m, 2 H), 7.56–7.50 (m, 1 H), 7.50–7.43 (m, 1 H), 7.43–7.36 (m, 2 H), 7.13 (tdd, *J* = 7.4, 1.9, 0.9 Hz, 1 H), 6.95–6.80 (m, 2 H), 6.51 (ddd, *J* = 22.6, 18.7, 1.9 Hz, 1 H), 6.28 (ddd, *J* = 41.6, 12.5, 1.9 Hz, 1 H), 3.67 (s, 3 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 160.08 (d, *J* = 4.3 Hz), 134.17, 134.12 (d, *J* = 5.8 Hz), 134.12 (d, *J* = 108.2 Hz), 134.08 (d, *J* = 2.1 Hz), 131.34, 130.93 (d, *J* = 96.3 Hz), 130.65 (d, *J* = 10.5 Hz), 128.21 (d, *J* = 12.4 Hz), 121.19 (d, *J* = 11.3 Hz), 120.06 (d, *J* = 104.1 Hz), 110.95 (d, *J* = 6.7 Hz), 55.31.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 20.89.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{30}H_{30}O_4P_2Na^+$: 539.1512; found: 539.1525.

Methylphenyl(vinyl)phosphine Oxide (4c)

According to the general procedure, the reaction of **2c** (151 mg, 0.76 mmol) afforded product **4c** as a white solid; yield: 108 mg (86%); mp 70–72 °C (Lit.[28] mp 78–79 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.93 (ddt, *J* = 12.0, 6.8, 1.6 Hz, 2 H), 7.82–7.58 (m, 3 H), 6.71–6.54 (m, 1 H), 6.54–6.29 (m, 2 H), 2.01 (dt, *J* = 13.2, 3.5 Hz, 3 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 133.08, 133.05 (d, *J* = 102.3 Hz), 132.41 (d, *J* = 95.4 Hz), 131.84 (d, *J* = 2.7 Hz), 130.12 (d, *J* = 9.8 Hz), 128.73 (d, *J* = 11.8 Hz), 16.35 (d, *J* = 74.4 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 27.09.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{18}H_{22}O_2P_2Na^+$: 355.0987; found: 355.0991.

(*tert*-Butyl)phenyl(vinyl)phosphine Oxide (4d)

According to the general procedure, the reaction of **2d** (183 mg, 0.76 mmol) afforded product **4d** as a white solid; yield: 137 mg (87%); mp 74–76 °C.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.76–7.68 (m, 2 H), 7.54–7.47 (m, 1 H), 7.44 (tdd, *J* = 8.4, 2.8, 1.1 Hz, 2 H), 6.73 (ddd, *J* = 28.2, 18.5, 12.7 Hz, 1 H), 6.47 (ddd, *J* = 19.6, 18.5, 2.0 Hz, 1 H), 6.30 (dd, *J* = 12.7, 2.0 Hz, 1 H), 1.10 (d, *J* = 15.1 Hz, 9 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 136.27, 131.75 (d, *J* = 8.1 Hz), 131.56 (d, *J* = 2.7 Hz), 130.53 (d, *J* = 93.2 Hz), 128.21 (d, *J* = 10.9 Hz), 126.90 (d, *J* = 87.8 Hz), 32.52 (d, *J* = 73.0 Hz), 24.08.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 37.99.

LCMS: *m*/*z* [2 M+ Na]$^+$ calcd for $C_{24}H_{34}O_2P_2Na^+$: 439.1923; found: 439.1926.

Knoevenagel Condensation between Aldehydes and Phosphinoylacetic Acids 2; General Procedure

The aldol reactions were carried out in a 15 mL vial. In a typical reaction, the vial was charged at r.t. with the reactants in the following order: diphenylphosphinoylacetic acid (**2a**; 198 mg, 0.76 mmol), respective aldehyde (1.53 mmol), solvent (5.0 mL), catalysts (Table 2 and Scheme 3), and molecular sieves (50 mg). The flask was capped with a stopper and sealed. Then, the reaction mixture was stirred at the desired temperature for 12 h. The mixture was filtered and the filtrate concentrated under reduced pressure. The product conversion with respect to the diphenylphosphinoylacetic acid and the *E*/*Z* ratio were determined by ^{31}P NMR analysis in $CDCl_3$ on the crude mixture. The crude residue was purified by column chromatography on silica gel (eluent: EtOAc/MeOH with a gradient mixture ratio from 50:1 to 20:1).

(*E*)-Diphenyl(styryl)phosphine Oxide (6a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **6a** as a white solid; yield: 214 mg (90%); mp 167–168 °C (Lit.[29] mp 162–163 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.80–7.72 (m, 4 H), 7.58–7.45 (m, 9 H), 7.45–7.34 (m, 3 H), 6.84 (dd, *J* = 22.3, 17.4 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 147.63 (d, *J* = 3.6 Hz), 135.10 (d, *J* = 17.8 Hz), 132.88 (d, *J* = 105.9 Hz), 131.94 (d, *J* = 2.7 Hz), 131.41 (d, *J* = 10.0 Hz), 130.16, 128.88, 128.66 (d, *J* = 12.2 Hz), 127.80, 119.15 (d, *J* = 104.5 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.51.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{34}O_2P_2Na^+$: 631.1919; found: 631.1926.

(2-Fluorostyryl)diphenylphosphine Oxide (7a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **7a** as a yellow solid; yield: 236 mg (96%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 90:10).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.95–7.87 (m, 2 H), 7.81–7.72 (m, 4 H), 7.71–7.45 (m, 11 H), 7.39–7.30 (m, 2 H), 7.16 (td, *J* = 7.6, 1.1 Hz, 1 H), 7.09 (ddd, *J* = 10.9, 8.2, 1.1 Hz, 1 H), 7.00 (dd, *J* = 22.7, 17.6 Hz, 1 H); the only assigned signals of *Z*-isomer in the mixture: 8.92 (d, *J* = 14.1 Hz) 7.70–7.58 (m).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 162.17, 160.16, 159.10 (d, *J* = 13.6 Hz), 155.36, 153.98 (d, *J* = 4.9 Hz), 140.35 (dd, *J* = 4.4, 2.6 Hz), 134.17, 133.13, 132.47 (d, *J* = 2.8 Hz), 132.29, 132.05 (d, *J* = 10.8 Hz), 131.97 (d, *J* = 2.7 Hz), 131.52 (d, *J* = 8.9 Hz), 131.39 (d, *J* = 9.9 Hz), 130.53 (d, *J* = 110.4 Hz), 129.46, 129.29 (d, *J* = 2.9 Hz), 128.62, 128.46, 125.01, 124.44 (d, *J* = 3.6 Hz), 123.21 (d, *J* = 11.3 Hz), 123.05 (d, *J* = 6.4 Hz), 122.23 (d, *J* = 6.8 Hz), 121.58 (d, *J* = 102.2 Hz), 118.49 (d, *J* = 10.3 Hz), 116.77, 116.21 (d, *J* = 21.8 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.28 (*E*), 23.16 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{42}F_2O_2P_2Na^+$: 667.1738; found: 667.1734.

(3-Fluorostyryl)diphenylphosphine Oxide (8a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **8a** as a yellow solid; yield: 170 mg (69%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 95:5).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.80–7.70 (m, 4 H), 7.58–7.45 (m, 7 H), 7.45–7.27 (m, 2 H), 7.23 (dt, *J* = 9.8, 2.1 Hz, 1 H), 7.06 (td, *J* = 8.3, 2.5 Hz, 1 H), 6.87 (dd, *J* = 22.1, 17.4 Hz, 1 H); the only assigned signals of *Z*-isomer in the mixture: 8.02–7.83 (m) 6.59–6.19 (m).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 163.02 (d, *J* = 246.7 Hz), 146.18 (t, *J* = 3.2 Hz), 137.34 (dd, *J* = 18.2, 7.4 Hz), 132.59 (d, *J* = 106.2 Hz), 132.05 (d, *J* = 2.7 Hz), 131.37 (d, *J* = 10.0 Hz), 130.46 (d, *J* = 8.2 Hz), 128.77, 123.89 (d, *J* = 2.8 Hz), 120.93 (d, *J* = 103.1 Hz), 116.97 (d, *J* = 21.4 Hz), 113.99 (d, *J* = 22.0 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.14 (*E*), 19.68 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{42}F_2O_2P_2Na^+$: 667.1738; found: 667.1730.

(4-Fluorostyryl)diphenylphosphine Oxide (9a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **9a** as a yelow solid; yield: 142 mg (58%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 96:4).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.78–7.68 (m, 4 H), 7.55–7.41 (m, 9 H), 7.04 (t, *J* = 8.6 Hz, 2 H), 6.75 (dd, *J* = 22.1, 17.4 Hz, 1 H); the only assigned signals of *Z*-isomer in the mixture: 8.08 (dd, *J* = 8.6, 5.7 Hz), 7.90 (dd, *J* = 12.2, 7.5 Hz), 7.37–7.16 (m), 6.84 (d, *J* = 8.8 Hz), 6.87–6.81 (m), 6.51–6.18 (m).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 163.76 (d, *J* = 251.0 Hz), 146.29 (d, *J* = 3.9 Hz), 132.78 (d, *J* = 106.1 Hz), 131.98 (d, *J* = 2.8 Hz), 131.37 (d, *J* = 10.0 Hz), 129.68 (d, *J* = 8.4 Hz), 128.68 (d, *J* = 12.2 Hz), 118.87 (dd, *J* = 104.5, 2.4 Hz), 115.96 (d, *J* = 22.0 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.56 (*E*), 20.26 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{42}F_2O_2P_2Na^+$: 667.1738; found: 667.1747.

(*E*)-(2-Chlorostyryl)diphenylphosphine Oxide (10a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **10a** as a white solid; yield: 208 mg (81%); mp 163–165 °C (Lit.[29] mp 161–162 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.76–7.65 (m, 5 H), 7.59–7.52 (m, 1 H), 7.51–7.37 (m, 6 H), 7.30 (dt, *J* = 7.4, 3.1 Hz, 1 H), 7.25–7.14 (m, 2 H), 6.80 (dd, *J* = 20.7, 17.4 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 143.67 (d, *J* = 5.4 Hz), 134.54, 133.44 (d, *J* = 18.3 Hz), 132.38 (d, *J* = 106.1 Hz), 132.05 (d, *J* = 2.9 Hz), 131.51 (d, *J* = 10.0 Hz), 130.88, 130.15, 128.69 (d, *J* = 12.2 Hz), 127.74, 127.07, 122.94 (d, *J* = 103.1 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.61.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{32}Cl_2O_2P_2Na^+$: 699.1147; found: 699.1139.

(*E*)-(4-Chlorostyryl)diphenylphosphine Oxide (11a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **11a** as a white solid; yield: 180 mg (70%); mp 181–183 °C (Lit.[29] mp 179–180 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.78–7.69 (m, 4 H), 7.59–7.41 (m, 9 H), 7.35 (d, *J* = 8.3 Hz, 2 H), 6.82 (dd, *J* = 22.0, 17.3 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 146.07 (d, *J* = 3.6 Hz), 135.97, 133.62 (d, *J* = 18.0 Hz), 132.78 (d, *J* = 106.0 Hz), 131.99 (d, *J* = 2.7 Hz), 131.36 (d, *J* = 10.0 Hz), 129.04 (d, *J* = 15.9 Hz), 128.69 (d, *J* = 12.2 Hz), 120.08 (d, *J* = 103.6 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.43.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{32}Cl_2O_2P_2Na^+$: 699.1147; found: 699.1147.

(*E*)-(2-Bromostyryl)diphenylphosphine Oxide (12a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **12a** as a white solid; yield: 274 mg (94%); mp 162–164 °C (Lit.[29] mp 160–161 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.83–7.74 (m, 4 H), 7.74–7.53 (m, 5 H), 7.53–7.47 (m, 4 H), 7.32 (td, *J* = 7.7, 1.0 Hz, 1 H), 7.21 (td, *J* = 7.7, 1.7 Hz, 1 H), 6.82 (dd, *J* = 20.0, 17.4 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 146.31 (d, *J* = 5.7 Hz), 135.26 (d, *J* = 18.3 Hz), 133.37, 132.24 (d, *J* = 105.9 Hz), 132.07 (d, *J* = 2.8 Hz), 131.56 (d, *J* = 10.0 Hz), 131.05, 128.69 (d, *J* = 12.2 Hz), 127.85 (d, *J* = 1.7 Hz), 127.72, 124.85, 123.21 (d, *J* = 102.7 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.93.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{32}Br_2O_2P_2Na^+$: 699.1147; found: 699.1147.

(*E*)-(3-Bromostyryl)diphenylphosphine Oxide (13a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **13a** as a white solid; yield: 274 mg (94%); mp 165–167 °C (Lit.[29] mp 164–165 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.79–7.71 (m, 4 H), 7.67 (t, *J* = 1.8 Hz, 1 H), 7.59–7.52 (m, 2 H), 7.52–7.47 (m, 5 H), 7.46–7.40 (m, 1 H), 7.26 (t, *J* = 7.8 Hz, 2 H), 6.85 (dd, *J* = 22.0, 17.4 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 145.79 (d, *J* = 3.6 Hz), 137.17 (d, *J* = 18.0 Hz), 132.88, 132.59 (d, *J* = 106.2 Hz), 132.06 (d, *J* = 2.7 Hz), 131.36 (d, *J* = 10.0 Hz), 130.44, 130.23, 128.73 (d, *J* = 12.2 Hz), 126.70, 123.02, 121.18 (d, *J* = 102.7 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.02.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{32}Br_2O_2P_2Na^+$: 787.0136; found: 787.0149.

(*E*)-(4-Bromostyryl)diphenylphosphine Oxide (14a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **14a** as a white solid; yield: 236 mg (92%); mp 188–190 °C (Lit.[29] mp 186–187 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.79–7.70 (m, 4 H), 7.57–7.46 (m, 8 H), 7.46–7.36 (m, 3 H), 7.26 (s, 37 H), 6.83 (dd, *J* = 22.0, 17.4 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 146.17 (d, *J* = 3.8 Hz), 134.02 (d, *J* = 18.0 Hz), 132.68 (d, *J* = 106.2 Hz), 132.08, 132.02 (d, *J* = 2.8 Hz), 131.36 (d, *J* = 10.0 Hz), 129.22, 128.66, 124.34, 120.17 (d, *J* = 103.5 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.10.

LCMS: *m*/*z* [2 M + Na]$^+$calcd for $C_{40}H_{32}Br_2O_2P_2Na^+$: 787.0136; found: 787.0119.

(*E*)-(4-Hydroxystyryl)diphenylphosphine oxide (15a)

(**15a**): According to the general procedure, the reaction of **2a** (0.76 mmol, 198 mg) affords product **15a** as a white solid; yield: 70 mg (29%).

^{1}H NMR (500 MHz, CD_3OD): δ = 7.75–7.61 (m, 4 H), 7.57–7.41 (m, 6 H), 7.37 (d, *J* = 8.1 Hz, 2 H), 7.23 (dd, *J* = 20.3, 17.5 Hz, 1 H), 6.82–6.73 (m, 2 H), 6.61 (ddd, *J* = 21.8, 17.9, 7.6 Hz, 1 H), 4.65 (bs, 1 H).

^{13}C NMR (126 MHz, DMSO d_6): δ = 159.77, 146.42 (d, *J* = 3.2 Hz), 135.01 (d, *J* = 103.2 Hz), 132.00 (d, *J* = 2.6 Hz), 131.08 (d, *J* = 9.7 Hz), 130.28, 129.13 (d, *J* = 11.6 Hz), 126.80 (d, *J* = 18.3 Hz), 116.27 (d, *J* = 104.2 Hz), 116.05.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 29.34.

LCMS: *m*/*z* [2 M+ Na]$^+$ calcd for $C_{40}H_{34}O_4P_2Na^+$: 633.1824; found: 633.1887.

(3-Nitrostyryl)diphenylphosphine Oxide (16a)

According to the general procedure, the reaction of **2a** (0.76 mmol, 198 mg) afforded product **16a** as a white solid; yield: 215 mg (81%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 89:11).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.38 (dt, *J* = 15.6, 2.0 Hz, 1 H), 8.21 (dd, *J* = 8.1, 2.2 Hz, 1 H), 7.86–7.69 (m, 5 H), 7.66–7.47 (m, 8 H), 7.02 (dd, *J* = 21.6, 17.3 Hz, 1 H); the only assigned signals of *Z*-isomer in the mixture: 8.16 (d, *J* = 7.8 Hz), 8.05–8.02 (m), 6.58 (dd, *J* = 18.9, 14.0 Hz).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 148.67, 144.84 (d, *J* = 3.7 Hz), 136.78 (d, *J* = 18.3 Hz), 134.00, 132.32 (d, *J* = 2.7 Hz), 131.97 (d, *J* = 106.3 Hz), 131.39 (d, *J* = 10.1 Hz), 130.06, 128.86 (d, *J* = 12.3 Hz), 124.43, 121.82.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 23.88 (*E*), 19.49 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{32}N_2O_6P_2Na^+$: 721.1628; found: 721.1621.

(4-Nitrostyryl)diphenylphosphine Oxide (17a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **17a** as a white solid; yield: 167 mg (63%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 80:20).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.22 (d, *J* = 8.7 Hz, 2 H), 7.75 (ddd, *J* = 12.3, 8.2, 1.4 Hz, 4 H), 7.67 (d, *J* = 8.7 Hz, 2 H), 7.64–7.54 (m, 3 H), 7.53–7.47 (m, 4 H), 7.04 (dd, *J* = 21.7, 17.4 Hz, 1 H); the only assigned signals of *Z*-isomer in the mixture: 8.43–8.35 (m), 8.04–7.83 (m), 7.39–7.28 (m), 6.65–6.51 (m).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 148.39, 144.76 (d, *J* = 3.6 Hz), 141.01 (d, *J* = 17.8 Hz), 132.33 (d, *J* = 2.7 Hz), 131.95 (d, *J* = 106.8 Hz), 131.37 (d, *J* = 10.2 Hz), 128.86 (d, *J* = 12.4 Hz), 128.49, 124.60 (d, *J* = 100.4 Hz), 124.18.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 23.84 (*E*), 19.74 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{32}N_2O_6P_2Na^+$: 721.1628; found: 721.1629.

(2-Methoxystyryl)diphenylphosphine Oxide (18a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **18a** as a white solid; yield: 206 mg (81%); mixture of *E*/*Z* isomers (ratio of *E*/*Z* = 96:4).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.85–7.70 (m, 5 H), 7.50–7.38 (m, 7 H), 7.32–7.24 (m, 1 H), 6.98–6.82 (m, 3 H), 3.77 (s, 3 H); the only assigned signals of *Z*-isomer in the mixture: 8.09–7.87 (m), 7.17–7.00 (m), 6.71–6.54 (m), 3.71 (s).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 158.12, 143.18 (d, *J* = 4.8 Hz), 133.18 (d, *J* = 105.3 Hz), 131.76 (d, *J* = 2.7 Hz), 131.49 (d, *J* = 9.9 Hz), 131.30, 128.83, 128.56 (d, *J* = 12.2 Hz), 124.09 (d, *J* = 17.9 Hz), 120.61, 119.52 (d, *J* = 104.6 Hz), 111.19, 55.45.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 25.42 (*E*), 20.00 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{42}H_{38}O_4P_2Na^+$: 691.2138; found: 691.2140.

(3-Methoxystyryl)diphenylphosphine Oxide (19a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **19a** as a white solid; yield: 216 mg (85%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 92:8).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.79–7.71 (m, 4 H), 7.59–7.45 (m, 7 H), 7.29 (t, *J* = 7.9 Hz, 1 H), 7.11 (dt, *J* = 7.7, 1.3 Hz, 1 H), 7.04 (dd, *J* = 2.6, 1.6 Hz, 1 H), 6.91 (ddd, *J* = 8.2, 2.6, 0.9 Hz, 1 H), 6.82 (dd, *J* = 22.2, 17.4 Hz, 1 H), 3.81 (s, 3 H); the only assigned signals of *Z*-isomer in the mixture: 7.37 (ddd, *J* = 7.5, 3.0, 1.1 Hz).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 159.93, 147.57 (d, *J* = 3.8 Hz), 136.48 (d, *J* = 18.0 Hz), 132.76 (d, *J* = 105.9 Hz), 131.97 (d, *J* = 2.7 Hz), 131.44 (d, *J* = 10.0 Hz), 129.89, 128.67 (d, *J* = 12.2 Hz), 120.44, 119.44 (d, *J* = 104.2 Hz), 115.93, 112.82, 55.36.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.81 (*E*), 20.64 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{42}H_{38}O_4P_2Na^+$: 691.2138; found: 691.2129.

(4-Methoxystyryl)diphenylphosphine Oxide (20a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **20a** as a white solid; yield: 180 mg (71%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 95:5).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.84–7.73 (m, 4 H), 7.65–7.53 (m, 2 H), 7.54–7.35 (m, 7 H), 6.92 (d, *J* = 8.8 Hz, 2 H), 6.69 (dd, *J* = 22.3, 17.3 Hz, 1 H), 3.85 (s, 3 H); the only assigned signals of *Z*-isomer in the mixture: 7.45 (d, *J* = 2.6 Hz), 7.42–7.39 (m), 3.76 (s).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 161.23, 147.29, 133.08 (d, *J* = 103.5 Hz), 131.85, 131.44 (d, *J* = 10.1 Hz), 129.42, 128.61 (d, *J* = 12.2 Hz), 127.95 (d, *J* = 18.7 Hz), 115.91 (d, *J* = 110.7 Hz), 114.24, 55.41.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 25.20 (*E*), 20.76 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{42}H_{38}O_4P_2Na^+$: 691.2138; found: 691.2131.

(*E*)-(4-Methylstyryl)diphenylphosphine Oxide (21a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **21a** as a white solid; yield: 72 mg (30%); mp 193–195 °C (Lit.[29] mp 191–192 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.75 (dd, *J* = 12.2, 7.5 Hz, 4 H), 7.57–7.39 (m, 9 H), 7.18 (d, *J* = 7.7 Hz, 2 H), 6.77 (dd, *J* = 22.4, 17.3 Hz, 1 H), 2.36 (s, 3 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 147.58 (d, *J* = 3.8 Hz), 140.50, 133.09 (d, *J* = 105.7 Hz), 132.44 (d, *J* = 18.0 Hz), 131.84 (d, *J* = 2.8 Hz), 131.43 (d, *J* = 10.0 Hz), 129.58, 128.61 (d, *J* = 12.0 Hz), 127.78, 117.82 (d, *J* = 105.4 Hz), 21.45.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.85.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{42}H_{38}O_2P_2Na^+$: 659.2239; found: 659.2230.

[2-(Furan-2-yl)vinyl]diphenylphosphine Oxide (22a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **22a** as a white solid; yield: 145 mg (65%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 95:5).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.82–7.66 (m, 4 H), 7.59–7.35 (m, 7 H), 7.27 (dd, *J* = 19.5, 17.1 Hz, 1 H), 6.71 (dd, *J* = 22.9, 17.1 Hz, 1 H), 6.52 (d, *J* = 3.3 Hz, 1 H), 6.44 (dd, *J* = 3.4, 1.8 Hz, 1 H); the only assigned signals of *Z*-isomer in the mixture: 7.19–7.03 (m), 6.38–6.24 (m), 6.05 (dd, *J* = 19.7, 14.4 Hz).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 151.45 (d, *J* = 20.1 Hz), 144.40, 134.00 (d, *J* = 4.5 Hz), 133.00 (d, *J* = 106.3 Hz), 131.87 (d, *J* = 2.7 Hz), 131.34 (d, *J* = 10.0 Hz), 128.62 (d, *J* = 12.2 Hz), 116.47 (d, *J* = 106.3 Hz), 113.82, 112.22.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.37 (*E*), 20.54 (*Z*).

LCMS: *m*/*z* [2 M+ Na]$^+$ calcd for $C_{36}H_{30}O_4P_2Na^+$: 611.1512; found: 611.1502.

(*E*)-(2-Cyclohexylvinyl)diphenylphosphine Oxide (23a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **23a** as a white solid; yield: 64 mg (27%); mp 159–161 °C (Lit.[30] mp 157–158 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.72–7.64 (m, 4 H), 7.55–7.41 (m, 6 H), 6.71 (ddd, *J* = 20.1, 17.1, 6.3 Hz, 1 H), 6.16 (ddd, *J* = 24.8, 17.2, 1.5 Hz, 1 H), 2.26–2.15 (m, 1 H), 1.86–1.59 (m, 5 H), 1.29–0.96 (m, 5 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 157.98, 133.04 (d, *J* = 104.8 Hz), 131.74 (d, *J* = 2.8 Hz), 131.36 (d, *J* = 9.8 Hz), 128.53 (d, *J* = 12.0 Hz), 118.67 (d, *J* = 103.4 Hz), 42.36 (d, *J* = 15.8 Hz), 31.65, 25.93, 25.75.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.78.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{46}O_2P_2Na^+$: 643.2865; found: 643.2869.

(*E*)-[2-(Pyridin-2-yl)vinyl]diphenylphosphine Oxide (24a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **24a** as a white solid; yield: 174 mg (75%); mp 138–140 °C.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.59 (dd, *J* = 5.1, 1.8 Hz, 1 H), 7.81–7.64 (m, 5 H), 7.62–7.51 (m, 2 H), 7.51–7.38 (m, 6 H), 7.35 (d, *J* = 7.7 Hz, 1 H), 7.23 (ddd, *J* = 8.1, 4.2, 1.1 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 152.69 (d, *J* = 17.8 Hz), 149.78, 145.64, 137.34, 132.73 (d, *J* = 106.2 Hz), 131.95 (d, *J* = 2.8 Hz), 131.35 (d, *J* = 10.1 Hz), 128.66 (d, *J* = 12.2 Hz), 124.72, 124.32.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 23.95.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{38}H_{32}N_2O_2P_2Na^+$: 633.1831; found: 633.1841.

(*E*)-(4-Trifluoromethylstyryl)diphenylphosphine Oxide (25a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **21a** as a yellow solid; yield: 235 mg (83%); mp 123–125 °C.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.79–7.70 (m, 4 H), 7.61 (s, 4 H), 7.57–7.51 (m, 3 H), 7.50–7.44 (m, 4 H), 6.96 (dd, *J* = 22.0, 17.4 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 145.77 (d, *J* = 3.6 Hz), 138.38 (d, *J* = 17.8 Hz), 132.38 (d, *J* = 106.4 Hz), 132.15 (d, *J* = 2.7 Hz), 131.59 (d, *J* = 32.8 Hz), 131.36 (d, *J* = 10.0 Hz), 128.77 (d, *J* = 12.2 Hz), 127.98, 125.83 (q, *J* = 3.8 Hz), 123.83 (d, *J* = 272.4 Hz), 122.45 (d, *J* = 102.1 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.02.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{42}H_{32}F_6O_2P_2Na^+$: 767.1674; found: 767.1664.

[2-(Naphthalen-1-yl)vinyl]diphenylphosphine Oxide (26a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **26a** as a yellow solid; yield: 49 mg (18%); mixture of *E*/*Z* isomers (ratio of *E*/*Z* = 99:1).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.35 (dd, *J* = 19.7, 17.1 Hz, 1 H), 8.18–8.08 (m, 1 H), 7.95–7.71 (m, 7 H), 7.61–7.43 (m, 9 H), 6.97 (dd, *J* = 23.4, 17.1 Hz, 1 H); the only assigned signals of *Z*-isomer in the mixture: 9.04 (d, *J* = 8.6 Hz), 8.01 (d, *J* = 8.1 Hz), 7.62 (dd, *J* = 12.0, 8.3 Hz), 7.15 (dd, *J* = 8.5, 6.7 Hz), 6.72 (dd, *J* = 19.3, 13.4 Hz).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 145.08 (d, *J* = 4.1 Hz), 133.65, 132.84 (d, *J* = 17.7 Hz), 132.82 (d, *J* = 105.9 Hz), 132.02 (d, *J* = 2.7 Hz), 131.49 (d, *J* = 10.0 Hz), 131.14, 130.70 (d, *J* = 9.8 Hz), 130.38, 128.72 (d, *J* = 16.0 Hz), 128.65, 126.90, 126.25, 125.40, 124.82 (d, *J* = 1.8 Hz), 123.42, 122.39 (d, *J* = 103.0 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.90 (*E*), 20.01 (*Z*).

LCMS: *m*/*z* [M + Na]$^+$ calcd for $C_{24}H_{19}OPNa^+$: 377.1066; found: 377.1054.

(2-Formylstyryl)diphenylphosphine Oxide (27a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **27a** as a white solid; yield: 121 mg (48%); mixture of *E*/*Z* isomers (ratio of *E*/*Z* = 6:94).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 9.93 (s, 1 H), 8.05 (dd, *J* = 39.1, 13.6 Hz, 1 H), 7.76 (d, *J* = 7.6 Hz, 1 H), 7.66–7.58 (m, 4 H), 7.55–7.47 (m, 2 H), 7.39 (td, *J* = 7.6, 1.4 Hz, 1 H), 7.36–7.29 (m, 3 H), 7.29–7.22 (m, 4 H), 6.61 (dd, *J* = 19.9, 13.6 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 192.45, 149.13, 136.78 (d, *J* = 8.4 Hz), 133.55 (d, *J* = 105.3 Hz), 133.40, 132.94, 132.13 (d, *J* = 2.0 Hz), 131.35 (d, *J* = 2.9 Hz), 130.79 (d, *J* = 9.6 Hz), 128.96, 128.28 (d, *J* = 12.2 Hz), 125.00 (d, *J* = 98.2 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 25.09 (*E*), 18.74 (*Z*).

LCMS: *m*/*z* [2 M+ Na]$^+$ calcd for $C_{42}H_{34}O_4P_2Na^+$: 687.1816; found: 687.1825.

(4-Formylstyryl)diphenylphosphine Oxide (28a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **28a** as a white solid; yield: 179 mg (71%); mixture of *E*/*Z* isomers (ratio of *E*/*Z* = 95:5).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 10.03 (s, 1 H), 7.91 (d, *J* = 8.3 Hz, 2 H), 7.82–7.74 (m, 4 H), 7.72–7.67 (m, 2 H), 7.62–7.54 (m, 3 H), 7.51 (dddd, *J* = 8.3, 5.8, 3.0, 1.5 Hz, 4 H), 7.03 (dd, *J* = 21.9, 17.4 Hz, 1 H), 6.54; the only assigned signals of *Z*-isomer in the mixture: 7.85 (d, *J* = 8.1 Hz), 7.43–7.34 (m), 6.54 (dd, *J* = 19.0, 14.1 Hz)

^{13}C NMR (126 MHz, $CDCl_3$): δ = 191.49, 145.83 (d, *J* = 3.6 Hz), 140.63 (d, *J* = 17.6 Hz), 137.04, 132.43 (d, *J* = 106.5 Hz), 132.15 (d, *J* = 2.8 Hz), 131.37 (d, *J* = 10.0 Hz), 130.19, 128.77 (d, *J* = 12.2 Hz), 128.29, 123.37 (d, *J* = 101.5 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 23.70 (*E*), 19.62 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{42}H_{34}O_4P_2Na^+$: 687.1816; found: 687.1820.

(1*E*,3*E*)-(4-Phenyl-1,3-butadienyl)diphenylphosphine Oxide (29a)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **29a** as a white solid; yield: 73 mg (29%); mp 173–174 °C (Lit.[31] mp 174 °C).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.81–7.68 (m, 4 H), 7.61–7.43 (m, 8 H), 7.40–7.29 (m, 3 H), 7.28–7.18 (m, 1 H), 6.96 (ddd, *J* = 15.6, 10.5, 1.6 Hz, 1 H), 6.83 (d, *J* = 15.5 Hz, 1 H), 6.42 (dd, *J* = 22.3, 16.6 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 147.49 (d, *J* = 3.4 Hz), 139.48, 135.97, 133.06 (d, *J* = 105.8 Hz), 131.83 (d, *J* = 2.8 Hz), 131.38 (d, *J* = 10.0 Hz), 128.89 (d, *J* = 21.4 Hz), 128.81, 128.61 (d, *J* = 12.2 Hz), 127.39 (d, *J* = 21.3 Hz), 127.16, 122.45 (d, *J* = 105.3 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 24.18.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{44}H_{37}OPNa^+$: 683.2240; found: 683.2220.

(2-Bromostyryl)(2-methoxyphenyl)phenylphosphine Oxide (30b)

According to the general procedure, the reaction of **2b** (221 mg, 0.76 mmol) afforded product **30b** as a white solid; yield: 192 mg (61%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 98:2).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.85 (dd, *J* = 20.3, 17.4 Hz, 1 H), 7.63 (dd, *J* = 12.8, 7.5 Hz, 2 H), 7.57–7.26 (m, 7 H), 7.19 (t, *J* = 7.6 Hz, 1 H), 7.10–7.00 (m, 2 H), 6.94 (dd, *J* = 22.9, 17.4 Hz, 1 H), 6.81 (t, *J* = 7.1 Hz, 1 H), 3.59 (s, 3 H); the only assigned signals of *Z*-isomer in the mixture: 7.78 (dt, *J* = 7.0, 2.3 Hz).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 160.15 (d, *J* = 4.1 Hz), 145.27 (d, *J* = 4.7 Hz), 135.74 (d, *J* = 1.9 Hz), 135.59 (d, *J* = 1.8 Hz), 135.41, 134.25, 134.04 (d, *J* = 109.4 Hz), 133.89, 133.34, 131.47 (d, *J* = 2.8 Hz), 130.80 (d, *J* = 15.2 Hz), 130.78, 128.28 (d, *J* = 12.4 Hz), 127.90, 127.62, 124.70, 123.20 (d, *J* = 104.4 Hz), 121.23 (d, *J* = 11.4 Hz), 119.84 (d, *J* = 105.4 Hz), 111.10 (d, *J* = 6.8 Hz), 55.46.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 22.26 (*E*), 17.94 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{42}H_{36}Br_2O_4P_2Na^+$: 847.0348; found: 847.0340.

(*E*)-(2-Methoxystyryl)(2-methoxyphenyl)phenylphosphine Oxide (31b)

According to the general procedure, the reaction of **2b** (221 mg, 0.76 mmol) afforded product **31b** as a white solid; yield: 202 mg (73%).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.08 (ddd, *J* = 13.1, 7.6, 1.8 Hz, 1 H), 8.00 (dd, *J* = 21.3, 17.7 Hz, 1 H), 7.69 (dd, *J* = 12.8, 7.5 Hz, 2 H), 7.52 (d, *J* = 7.5 Hz, 1 H), 7.49–7.32 (m, 4 H), 7.30–7.22 (m, 1 H), 7.21–7.04 (m, 2 H), 6.97–6.77 (m, 3 H), 3.77 (d, *J* = 2.7 Hz, 3 H), 3.64 (d, *J* = 2.3 Hz, 3 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 160.13 (d, *J* = 4.1 Hz), 157.94, 142.18 (d, *J* = 3.9 Hz), 135.08 (d, *J* = 108.3 Hz), 133.99 (d, *J* = 5.9 Hz), 133.90 (d, *J* = 2.1 Hz), 131.13 (d, *J* = 2.8 Hz), 130.95, 130.67 (d, *J* = 10.5 Hz), 128.46, 128.14 (d, *J* = 12.6 Hz), 124.56 (d, *J* = 18.3 Hz), 121.09 (d, *J* = 11.3 Hz), 120.80 (d, *J* = 104.3 Hz), 120.53, 119.72 (d, *J* = 105.8 Hz), 111.17, 111.10 (d, *J* = 6.7 Hz), 55.35.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 22.27 (*E*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{44}H_{42}O_6P_2Na^+$: 751.2348; found: 751.2327.

[2-(Pyridin-2-yl)vinyl](2-methoxyphenyl)phenylphosphine Oxide (32b)

According to the general procedure, the reaction of **2b** (221 mg, 0.76 mmol) afforded product **32b** as a white solid; yield: 237 mg (93%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 93:7).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.60–8.54 (m, 1 H), 8.06–7.98 (m, 1 H), 7.77–7.56 (m, 5 H), 7.49–7.25 (m, 5 H), 7.19–7.00 (m, 2 H), 6.88–6.76 (m, 1 H), 3.59 (s, 3 H); the only assigned signals of *Z*-isomer in the mixture: 8.33 (t, *J* = 5.5 Hz), 7.92 (dt, *J* = 12.7, 5.3 Hz), 7.02–6.90 (m), 6.75–6.65 (m).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 160.19 (d, *J* = 4.1 Hz), 153.15 (d, *J* = 18.7 Hz), 149.88, 145.63 (d, *J* = 3.6 Hz), 136.93, 134.29 (d, *J* = 105.2 Hz), 134.13 (d, *J* = 2.1 Hz), 133.83, 131.31 (d, *J* = 2.8 Hz), 130.61 (d, *J* = 10.7 Hz), 128.17 (d, *J* = 12.6 Hz), 124.51, 124.20 (d, *J* = 103.1 Hz), 123.98, 121.04 (d, *J* = 11.3 Hz), 120.01 (d, *J* = 105.7 Hz), 111.11 (d, *J* = 6.8 Hz), 55.42.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 22.03 (*E*), 18.37 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{40}H_{36}N_2O_4P_2Na^+$: 693.2042; found: 693.2023.

(*E*)-(2-Methoxyphenyl)styrylphenylphosphine Oxide (33b)

According to the general procedure, the reaction of **2b** (221 mg, 0.76 mmol) afforded product **33b** as a white solid; yield: 158 mg (62%).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.98 (ddd, *J* = 13.1, 7.5, 1.8 Hz, 1 H), 7.73–7.51 (m, 3 H), 7.49–7.37 (m, 3 H), 7.35–7.13 (m, 6 H), 7.05–6.89 (m, 2 H), 6.78 (dd, *J* = 8.3, 5.5 Hz, 1 H), 3.56 (s, 3 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 160.12 (d, *J* = 4.1 Hz), 146.98 (d, *J* = 3.0 Hz), 135.59 (d, *J* = 18.3 Hz), 134.66 (d, *J* = 109.3 Hz), 134.11 (d, *J* = 2.1 Hz), 134.02 (d, *J* = 5.7 Hz), 131.35 (d, *J* = 2.8 Hz), 130.63 (d, *J* = 10.6 Hz), 129.80, 128.80, 128.26 (d, *J* = 12.4 Hz), 127.72, 121.23 (d, *J* = 11.3 Hz), 120.33 (d, *J* = 105.0 Hz), 119.20 (d, *J* = 105.8 Hz), 111.14 (d, *J* = 6.7 Hz), 55.47.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 22.16.

LCMS: *m*/*z* [2 M+ Na]$^+$ calcd for $C_{42}H_{38}O_4P_2Na^+$: 691.2148; found: 691.2146.

(2-Bromostyryl)(*tert*-butyl)phenylphosphine Oxide (34d)

According to the general procedure, the reaction of **2d** (183 mg, 0.76 mmol) afforded product **34d** as a white solid; yield: 190 mg (69%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 94:6).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.92 (t, *J* = 17.3 Hz, 1 H), 7.87–7.78 (m, 2 H), 7.65–7.44 (m, 5 H), 7.32 (td, *J* = 7.6, 1.3 Hz, 1 H), 7.19 (td, *J* = 7.6, 1.7 Hz, 1 H), 6.89 (dd, *J* = 24.2, 17.3 Hz, 1 H), 1.18 (d, *J* = 15.2 Hz, 9 H); the only assigned signals of *Z*-isomer in the mixture: 6.53–6.42 (m).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 147.48 (d, *J* = 3.4 Hz), 135.84 (d, *J* = 16.3 Hz), 133.42, 131.95 (d, *J* = 8.1 Hz), 131.66 (d, *J* = 2.7 Hz), 130.78, 130.41 (d, *J* = 93 Hz), 128.27 (d, *J* = 11.0 Hz), 127.98 (d, *J* = 1.5 Hz), 127.61, 124.53, 119.51 (d, *J* = 91.2 Hz), 33.08 (d, *J* = 73.6 Hz), 24.28.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 38.96 (*E*), 37.44 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{36}H_{40}Br_2O_4P_2Na^+$: 747.0762; found: 747.0774.

(2-Methoxystyryl)(*tert*-butyl)phenylphosphine Oxide (35d)

According to the general procedure, the reaction of **2d** (183 mg, 0.76 mmol) afforded product **35d** as a white solid; yield: 179 mg (75%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 96:4).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.10–7.59 (m, 3 H), 7.62–7.37 (m, 4 H), 7.39–7.23 (m, 1 H), 7.11–6.84 (m, 3 H), 3.86 (s, 2 H), 1.17 (d, *J* = 15.0 Hz, 9 H); the only assigned signals of *Z*-isomer in the mixture: (d, *J* = 8.4 Hz), 3.76 (s).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 158.08, 144.39 (d, *J* = 2.9 Hz), 131.93 (d, *J* = 8.1 Hz), 131.38 (d, *J* = 2.7 Hz), 131.27 (d, *J* = 93.3 Hz), 131.03, 128.86, 128.12 (d, *J* = 10.9 Hz), 124.49 (d, *J* = 16.0 Hz), 120.56, 115.61 (d, *J* = 94.2 Hz), 111.23, 55.47, 32.97 (d, *J* = 73.2 Hz), 24.32.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 39.74 (*E*), 37.89 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{38}H_{46}O_4P_2Na^+$: 651.2764; found: 651.2759.

[2-(Pyridin-2-yl)vinyl](*tert*-butyl)phenylphosphine Oxide (36d)

According to the general procedure, the reaction of **2d** (183 mg, 0.76 mmol) afforded product **36d** as a white solid; yield: 204 mg (94%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 95:5).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.62 (dd, *J* = 4.8, 1.8 Hz, 1 H), 7.85–7.77 (m, 2 H), 7.73–7.56 (m, 3 H), 7.51–7.38 (m, 3 H), 7.29 (d, *J* = 7.7 Hz, 1 H), 7.22 (ddd, *J* = 7.6, 4.7, 1.1 Hz, 1 H), 1.15 (d, *J* = 15.1 Hz, 9 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 152.65 (d, *J* = 16.0 Hz), 149.69, 146.79, 137.33, 131.82 (d, *J* = 8.2 Hz), 130.94 (d, *J* = 94.1 Hz), 128.18 (d, *J* = 11.1 Hz), 124.57 (d, *J* = 101.2 Hz), 33.01 (d, *J* = 73.6 Hz), 24.23.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 39.20.

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{34}H_{40}N_2O_2P_2Na^+$: 593.2457; found: 593.2446.

(*tert*-Butyl)styrylphenylphosphine Oxide (37d)

According to the general procedure, the reaction of **2d** (183 mg, 0.76 mmol) afforded product **37d** as a white solid; yield: 134 mg (62%); mixture of *E*/*Z*-isomers (ratio of *E*/*Z* = 96:4).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.86–7.78 (m, 2 H), 7.67 (t, *J* = 17.5 Hz, 1 H), 7.58–7.30 (m, 9 H), 6.91 (dd, *J* = 25.4, 17.3 Hz, 1 H), 1.18 (d, *J* = 15.1 Hz, 9 H); the only assigned signals of *Z*-isomer in the mixture: 8.14–8.09 (m), 7.11–7.06 (m), 6.31 (dd, *J* = 20.1, 14.3 Hz).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 149.04 (d, *J* = 2.3 Hz), 135.43 (d, *J* = 16.1 Hz), 131.82 (d, *J* = 8.1 Hz), 131.57 (d, *J* = 2.7 Hz), 130.91 (d, *J* = 94.1 Hz), 129.95, 128.84, 128.25 (d, *J* = 11.0 Hz), 127.68, 114.83 (d, *J* = 93.9 Hz), 33.06 (d, *J* = 73.6 Hz), 24.26.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 39.62 (*E*), 37.58 (*Z*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{36}H_{42}O_2P_2Na^+$: 591.2552; found: 591.2553.

(*E*)-[2-(Thien-2-yl)vinyl](*tert*-butyl)phenylphosphine Oxide (38d)

According to the general procedure, the reaction of **2d** (183 mg, 0.76 mmol) afforded product **38d** as a white solid; yield: 168 mg (76%).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.84–7.62 (m, 3 H), 7.57–7.41 (m, 3 H), 7.33 (d, *J* = 5.1 Hz, 1 H), 7.19 (dd, *J* = 3.6, 1.0 Hz, 1 H), 7.02 (dd, *J* = 5.1, 3.6 Hz, 1 H), 6.63 (dd, *J* = 24.3, 17.0 Hz, 1 H), 1.16 (d, *J* = 15.1 Hz, 9 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 141.23 (d, *J* = 2.6 Hz), 141.08, 131.77 (d, *J* = 8.1 Hz), 131.53 (d, *J* = 2.7 Hz), 130.98 (d, *J* = 94.3 Hz), 129.93, 128.23 (d, *J* = 11.0 Hz), 128.06, 127.59, 113.64 (d, *J* = 94.5 Hz), 33.07 (d, *J* = 74.0 Hz), 24.24.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 39.16 (*E*).

LCMS: *m*/*z* [2 M + Na]$^+$ calcd for $C_{32}H_{38}O_2P_2S_2Na^+$: 603.1681; found: 603.1686.

Knoevenagel Condensation between 2-(Diphenylphosphino)benzaldehyde and Phosphinoylacetic Acids 2; General Procedure

The aldol reactions were carried out in a 15 mL vial. In a typical reaction, the vial was charged at r.t. with the reactants in the following order: the respective phosphinoylacetic acid **2** (0.76 mmol), aldehyde

(0.95 mmol), toluene (6 mL), catalysts (Table 4), and molecular sieves (100 mg). The flask was purged with argon atmosphere, capped with a stopper, and sealed. Then, the reaction mixture was stirred at 110 °C for the 24 h. The mixture was filtered and concentrated under reduced pressure. The product conversion with respect to the phosphinoylacetic acids and *E*/*Z* ratio were determined by ^{31}P NMR analysis in $CDCl_3$ on the crude mixture. The crude residue was purified by column chromatography on silica gel (eluent: EtOAc/*i*-PrOH with a gradient mixture ratio from 90:10 to 70:30).

(*E*)-[2-(Diphenylphosphine)styryl]diphenylphosphine Oxide (L1)

According to the general procedure, the reaction of **2a** (198 mg, 0.76 mmol) afforded product **L1** as a white solid; yield: 338 mg (91%).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.73 (ddd, *J* = 20.1, 17.2, 4.9 Hz, 1 H), 7.66–7.58 (m, 1 H), 7.52–7.43 (m, 6 H), 7.41–7.28 (m, 11 H), 7.23 (t, *J* = 7.6 Hz, 1 H), 7.16 (td, *J* = 8.0, 1.5 Hz, 4 H), 6.81 (ddd, *J* = 7.8, 4.3, 1.3 Hz, 1 H), 6.64 (td, *J* = 17.1, 1.1 Hz, 1 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 146.15 (dd, *J* = 24.7, 6.0 Hz), 140.10 (d, *J* = 18.4 Hz), 139.93 (d, *J* = 18.4 Hz), 137.33 (d, *J* = 16.4 Hz), 135.69 (d, *J* = 10.3 Hz), 134.15 (d, *J* = 20.0 Hz), 133.05, 131.95 (d, *J* = 100.8 Hz), 131.75 (d, *J* = 2.7 Hz), 131.58 (d, *J* = 10.0 Hz), 129.63, 129.13, 129.01, 128.67 (d, *J* = 7.2 Hz), 128.50 (d, *J* = 12.2 Hz), 126.81 (d, *J* = 3.3 Hz), 122.88 (dd, *J* = 103.5, 3.4 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 26.41, –13.82.

LCMS: *m*/*z* [M + H]$^+$ calcd for $C_{32}H_{27}O_2P_2^+$: 505.1481; found: 505.1486.

(*E*)-[2-(Diphenylphosphine)styryl](2-methoxyphenyl)phenylphosphine Oxide (L2)

According to the general procedure, the reaction of **2b** (221 mg, 0.76 mmol) afforded product **L2** as a white solid; yield: 366 mg (93%).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.07 (ddd, *J* = 21.2, 17.3, 4.4 Hz, 1 H), 7.80 (ddd, *J* = 13.3, 7.6, 1.8 Hz, 1 H), 7.53 (ddd, *J* = 7.9, 4.2, 1.3 Hz, 1 H), 7.41 (td, *J* = 7.9, 1.8 Hz, 1 H), 7.39–7.29 (m, 3 H), 7.29–7.15 (m, 8 H), 7.20 (s, 1 H), 7.16–7.06 (m, 5 H), 6.99 (td, *J* = 7.5, 1.9 Hz, 1 H), 6.83–6.64 (m, 3 H), 3.45 (s, 3 H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 160.33 (d, *J* = 3.8 Hz), 145.43 (dd, *J* = 24.0, 4.6 Hz), 140.82 (dd, *J* = 22.5, 18.7 Hz), 137.38 (d, *J* = 17.1 Hz), 136.16 (d, *J* = 3.2 Hz), 136.07 (d, *J* = 3.0 Hz), 134.34 (d, *J* = 6.3 Hz), 134.23, 134.09 (d, *J* = 4.5 Hz), 133.99 (d, *J* = 2.1 Hz), 133.95, 133.37, 131.14 (d, *J* = 2.8 Hz), 130.95 (d, *J* = 10.8 Hz), 129.27, 129.01, 128.80 (d, *J* = 5.4 Hz), 128.59 (d, *J* = 4.8 Hz), 128.54 (d, *J* = 4.6 Hz), 128.09 (d, *J* = 12.5 Hz), 127.06 (d, *J* = 3.6 Hz), 122.67 (dd, *J* = 105.0, 4.1 Hz), 121.03 (d, *J* = 11.4 Hz), 119.99 (d, *J* = 104.9 Hz), 111.04 (d, *J* = 6.6 Hz), 55.29..

^{31}P NMR (202 MHz, $CDCl_3$): δ = 23.39, –14.47.

LCMS: *m*/*z* [M + H]$^+$ calcd for $C_{33}H_{28}O_2P_2^+$: 535.1587; found: 535.1578.

[2-(Diphenylphosphine)styryl]methylphenylphosphine Oxide (L3)

According to the general procedure, the reaction of **2c** (151 mg, 0.76 mmol) afforded product **L3** as a white solid; yield: 256 mg (79%); mixture of *E*/*Z* isomers (ratio of *E*/*Z* = 95:5).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.83 (ddd, *J* = 20.0, 17.3, 5.0 Hz, 1 H), 7.66–7.53 (m, 3 H), 7.53–7.41 (m, 3 H), 7.33 (dddd, *J* = 9.5, 7.5, 3.8, 2.3 Hz, 9 H), 7.21 (dq, *J* = 5.3, 1.5 Hz, 4 H), 6.40 (td, *J* = 17.1, 1.2 Hz, 1 H), 1.63 (d, *J* = 13.2 Hz, 3 H); the only assigned signals of *Z*-isomer in the mixture: 7.00 (dd, *J* = 14.0, 7.6 Hz), 6.05 (dd, *J* = 18.4, 13.7 Hz).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 143.54 (dd, *J* = 25.2, 5.6 Hz), 139.73 (dd, *J* = 20.8, 18.1 Hz), 137.15 (d, *J* = 15.6 Hz), 135.72 (d, *J* = 9.5 Hz), 135.45 (d, *J* = 9.6 Hz), 134.25 (d, *J* = 6.8 Hz), 134.10 (d, *J* = 6.6 Hz), 133.53, 133.08, 132.72, 132.35 (d, *J* = 2.8 Hz), 132.08 (d, *J* = 10.2 Hz), 131.55 (d, *J* = 2.8 Hz), 130.37 (d, *J* = 9.9 Hz), 129.59, 129.13 (d, *J* = 4.4 Hz), 129.08, 128.73 (d, *J* = 2.7 Hz), 128.73 (d, *J* = 12.1 Hz), 128.56 (d, *J* = 11.9 Hz), 126.58 (d, *J* = 3.9 Hz), 123.96 (dd, *J* = 100.5, 3.3 Hz), 16.17 (d, *J* = 74.8 Hz).

^{31}P NMR (202 MHz, $CDCl_3$): δ = 28.92, –13.65 (*E*); 24.76, –14.55 (*Z*).

LCMS: *m*/*z* [M + H]$^+$ calcd for $C_{27}H_{25}O_2P_2^+$: 443.1325; found: 443.1339.

[2-(Diphenylphosphine)styryl](*tert*-butyl)phenylphosphine Oxide (L4)

According to the general procedure, the reaction of **2d** (183 mg, 0.76 mmol) afforded product **L4** as a white solid; yield: 310 mg (87%); mixture of *E*/*Z* isomers (ratio of *E*/*Z* = 92:8).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.06 (td, *J* = 17.4, 3.8 Hz, 1 H), 7.64–7.56 (m, 2 H), 7.53 (ddd, *J* = 8.0, 4.2, 1.3 Hz, 1 H), 7.48–7.39 (m, 1 H), 7.39–7.28 (m, 3 H), 7.29–7.23 (m, 6 H), 7.18 (dddd, *J* = 7.9, 5.7, 3.9, 2.5 Hz, 5 H), 6.83 (ddd, *J* = 7.7, 4.2, 1.3 Hz, 1 H), 6.64 (dd, *J* = 22.9, 17.2 Hz, 1 H), 0.93 (d, *J* = 15.0 Hz, 9 H); the only assigned signals of *Z*-isomer in the mixture: 7.01–6.91 (m), 6.26 (dd, *J* = 20.0, 14.1 Hz), 1.00 (d, *J* = 14.7 Hz).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 147.02 (dd, *J* = 20.8, 2.9 Hz), 141.10 (dd, *J* = 22.6, 16.1 Hz), 136.92 (d, *J* = 17.2 Hz), 136.10 (d, *J* = 10.9 Hz), 136.00 (d, *J* = 10.8 Hz),134.16 (d, *J* = 17.3 Hz), 134.01 (d, *J* = 17.0 Hz), 133.52, 24.21–23.85 (m), 25.65–24.93 (m), 132.03 (d, *J* = 8.1 Hz), 131.30 (d, *J* = 2.7 Hz), 130.44 (d, *J* = 93.0 Hz), 129.21, 129.00, 128.87 (d, *J* = 5.7 Hz), 128.64 (d, *J* = 4.7 Hz), 128.59 (d, *J* = 4.5 Hz), 128.06 (d, *J* = 10.9 Hz), 127.66 (d, *J* = 4.3 Hz), 120.07 (dd, *J* = 91.3, 5.7 Hz), 32.84 (d, *J* = 73.5 Hz), 24.12.

^{31}P NMR (202 MHz, $CDCl_3$): δ = 38.82, –13.53 (*E*); 36.47, –14.26 (*Z*).

LCMS: *m*/*z* [M + H]$^+$ calcd for $C_{30}H_{31}O_2P_2^+$: 485.1721; found: 485.1739.

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Supporting Information

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References

(1) (a) Quin, L. D. *A Guide to Organophosphorus Chemistry*; Wiley Interscience: New York, **2000**. (b) *Aminophosphonic and Aminophosphinic Acids: Chemistry and Biological Activity*; Kukhar, V. P.; Hudson, H. R., Ed.; Wiley: Chichester, **2000**. (c) *The Chemistry*

of Organophosphorus Compounds, Vol. 4; Hartley, F. R., Ed.; Wiley: Chichester, **1996**. (d) Horsman, G. P.; Zechel, D. L. *Chem. Rev.* **2017**, *117*, 5704. (e) Kudzin, Z. H.; Kudzin, M. H.; Drabowicz, J.; Stevens, C. V. *Curr. Org. Chem.* **2011**, *15*, 2015. (f) Mucha, A.; Kafarski, P.; Berlicki, L. *J. Med. Chem.* **2011**, *54*, 5955.

(2) (a) *Organophosphorus Chemistry, Vol. 48*; Allen, D. W.; Loakes, D.; Tebby, J. C., Ed.; The Royal Society of Chemistry: Cambridge, **2019**. (b) *Phosphorus Ligands in Asymmetric Catalysis: Synthesis and Applications*; Börner, A., Ed.; Wiley-VCH: Weinheim, **2008**. (c) Grabulosa, A. *P-Stereogenic Ligands in Enantioselective Catalysis*; Royal Society of Chemistry: Cambridge, **2010**. (d) Julienne, D.; Toulgoat, F.; Delacroix, O.; Gaumont, A.-C. *Curr. Org. Chem.* **2010**, *14*, 1195. (e) Xi, C.; Yu, B.; Yan, X.; Tang, N. *Polyhedron* **2013**, *52*, 1323. (f) Tseng, Y.-Y.; Kamikawa, K.; Wu, Q.; Takahashi, T.; Ogasawara, M. *Adv. Synth. Catal.* **2015**, *357*, 2255.

(3) (a) Li, H.; Luo, J.; Li, B.; Yi, X.; He, Z. *Org. Lett.* **2017**, *19*, 5637. (b) Dubrovina, N. V.; Boerner, A. *Angew. Chem. Int. Ed.* **2004**, *43*, 5883. (c) Ackermann, L. *Synthesis* **2006**, 1557. (d) Nemoto, T.; Masuda, T.; Matsumoto, T.; Hamada, Y. *J. Org. Chem.* **2005**, *70*, 7172. (e) Galland, A.; Dobrota, C.; Toffano, M.; Fiaud, J.-C. *Tetrahedron: Asymmetry* **2006**, *17*, 2354. (f) Loup, J.; Müller, V.; Ghorai, D.; Ackermann, L. *Angew. Chem. Int. Ed.* **2019**, *58*, 1749. (g) Mitsushige, Y.; Yasuda, H.; Carrow, B. P.; Ito, S.; Kobayashi, M.; Tayano, T.; Watanabe, Y.; Okuno, Y.; Hayashi, S.; Kuroda, J.; Okumura, Y.; Nozaki, K. *ACS Macro Lett.* **2018**, *7*, 305. (h) Chen, M.; Chen, C. *Angew. Chem. Int. Ed.* **2018**, *57*, 3094.

(4) (a) Rahman, M. S.; Steed, J. W.; Hii, K. K. *Synthesis* **2000**, 1320. (b) Maj, A. M.; Pietrusiewicz, K. M.; Suisse, I.; Agbossou, F.; Mortreux, A. *J. Organomet. Chem.* **2001**, *626*, 157. (c) Rahman, M. S.; Oliana, M.; Hii, K. K. *Tetrahedron: Asymmetry* **2004**, *15*, 1835. (d) Pietrusiewicz, K. M.; Zablocka, M. *Tetrahedron Lett.* **1988**, *29*, 937. (e) Oliana, M.; King, F.; Horton, P. N.; Hursthouse, M. B.; Hii, K. K. *J. Org. Chem.* **2006**, *71*, 2472. (f) Gonzalez-Nogal, A. M.; Cuadrado, P.; Sarmentero, M. A. *Tetrahedron* **2010**, *66*, 9610.

(5) (a) Baumgartner, T.; Réau, R. *Chem. Rev.* **2006**, *106*, 4681. (b) Queffelec, C.; Petit, M.; Janvier, P.; Knight, D. A.; Bujoli, B. *Chem. Rev.* **2012**, *112*, 3777.

(6) (a) Wilkie, C. A.; Morgan, A. B.; Nelson, G. L. *Fire and Polymers V: Materials and Concepts for Fire Retardancy*; American Chemical Society: Washington DC, **2009**, 205–248. (b) Green, J. In *Fire Retardancy of Polymeric Materials*; Grand, A. F.; Wilkie, C. A., Ed.; Marcel Dekker: New York, **2000**, 147–170. (c) Zhang, Y.; Yu, B.; Wang, B.; Liew, K. M.; Song, L.; Wang, C.; Hu, Y. *Ind. Eng. Chem. Res.* **2017**, *56*, 1245. (d) You, G.; Cheng, Z.; Tang, Y.; He, H. *Ind. Eng. Chem. Res.* **2015**, *54*, 7309.

(7) *Science of Synthesis: Organophosphorus Compounds, Vol. 42*; Mathey, F., Ed.; Thieme: Stuttgart, **2009**.

(8) (a) Han, L.-B.; Tanaka, M. *J. Am. Chem. Soc.* **1996**, *118*, 1571. (b) Han, L.-B.; Hua, R.; Tanaka, M. *Angew. Chem. Int. Ed.* **1998**, *37*, 94.

(9) (a) Han, L.-B.; Choi, N.; Tanaka, M. *J. Am. Chem. Soc.* **1996**, *118*, 7000. (b) Chen, T.; Zhao, C.-Q.; Han, L.-B. *J. Am. Chem. Soc.* **2018**, *140*, 3139. (c) Sajna, K. V.; Srinivas, V.; Kumara Swamy, K. C. *Adv. Synth. Catal.* **2010**, *352*, 3069.

(10) (a) Liu, L.; Wu, Y.; Wang, Z.; Zhu, J.; Zhao, Y. *J. Org. Chem.* **2014**, *79*, 6816. (b) Niu, M.; Fu, H.; Jiang, Y.; Zhao, Y. *Chem. Commun.* **2007**, 272. (c) Trostyanskaya, I. G.; Beletskaya, I. P. *Tetrahedron* **2014**, *70*, 2556.

(11) (a) Han, L.-B.; Zhang, C.; Yazawa, H.; Shimada, S. *J. Am. Chem. Soc.* **2004**, *126*, 5080. (b) Wu, Y.; Liu, L.; Yang, K.; Gao, Y.; Zhao, Y. *J. Org. Chem.* **2014**, *79*, 8118. (c) Khemchyan, L. L.; Ivanova, J. V.; Zalesskiy, S. S.; Ananikov, V. P.; Beletskaya, I. P.; Starikova, Z. A. *Adv. Synth. Catal.* **2014**, *356*, 771.

(12) (a) Zhao, C. Q.; Han, L. B.; Goto, M.; Tanaka, M. *Angew. Chem. Int. Ed.* **2001**, *40*, 1929. (b) Han, L.-B.; Zhao, C.-Q.; Tanaka, M. *J. Org. Chem.* **2001**, *66*, 5929. (c) Kondoh, A.; Yorimitsu, H.; Oshima, K. *Bull. Chem. Soc. Jpn.* **2008**, *81*, 502. (d) Huang, Y.; Hao, W.; Ding, G.; Cai, M.-Z. *J. Organomet. Chem.* **2012**, *715*, 141.

(13) Lai, C.; Xi, C.; Chen, C.; Ma, M.; Hong, X. *Chem. Commun.* **2003**, 2736.

(14) (a) Takaki, K.; Takeda, M.; Koshoji, G.; Shishido, T.; Takehira, K. *Tetrahedron Lett.* **2001**, *42*, 6357. (b) Takaki, K.; Koshoji, G.; Komeyama, K.; Takeda, M.; Shishido, T.; Kitani, A.; Takehira, K. *J. Org. Chem.* **2003**, *68*, 6554.

(15) (a) Li, X.; Yang, F.; Wu, Y.; Wu, Y. *Org. Lett.* **2014**, *16*, 992. (b) Tang, L.; Wen, L.; Sun, T.; Zhang, D.; Yang, Z.; Feng, C.; Wang, Z. *Asian J. Org. Chem.* **2017**, *6*, 1683. (c) Liu, L.; Zhou, D.; Dong, J.; Zhou, Y.; Yin, S.-F.; Han, L.-B. *J. Org. Chem.* **2018**, *83*, 4190.

(16) (a) Yuan, J.-W.; Yang, L.-R.; Mao, P.; Qu, L.-B. *RSC Adv.* **2016**, *6*, 87058. (b) Xue, J.-F.; Zhou, S.-F.; Liu, Y.-Y.; Pan, X.; Zou, J.-P.; Asekun, O. T. *Org. Biomol. Chem.* **2015**, *13*, 4896.

(17) (a) Xu, Y.; Xia, J.; Guo, H. *Synthesis* **1986**, 691. (b) Liu, L.; Wang, Y.; Zeng, Z.; Xu, P.; Gao, Y.; Yin, Y.; Zhao, Y. *Adv. Synth. Catal.* **2013**, *355*, 659. (c) Koranteng, E.; Liu, Y.-Y.; Liu, S.-Y.; Wu, Q.-X.; Lu, L.-Q.; Xiao, W.-J. *Chin. J. Catal.* **2019**, *40*, 1841.

(18) Krawczyk, H.; Albrecht, Ł. *Synthesis* **2005**, 2887.

(19) Knoevenagel, E. *Ber. Dtsch. Chem. Ges.* **1894**, *27*, 2345.

(20) (a) Laue, T.; Plagens, A. *Named Organic Reactions*; Wiley: New York, **2005**. (b) Tietze, L. F. *Chem. Rev.* **1996**, *96*, 115.

(21) Tsvetkov, E. N.; Bondarenko, N. A.; Malakhova, I. G.; Kabachnik, M. I. *Synthesis* **1986**, 198.

(22) Richard, J. J.; Banks, C. V. *J. Org. Chem.* **1963**, *28*, 123.

(23) Kielbasinski, P.; Zurawinski, R.; Pietrusiewicz, K. M.; Zablocka, M.; Mikolajczyk, M. *Pol. J. Chem.* **1998**, *72*, 564.

(24) Malevannaya, R. A.; Tsvetkov, E. N.; Kabachnik, M. I. *J. Gen. Chem. USSR* **1971**, *41*, 1432.

(25) Brown, A. D. Jr.; Kosolapoff, G. M. *J. Chem. Soc.* **1968**, *2*, 839.

(26) Sowa, S.; Stankevič, M.; Flis, A.; Pietrusiewicz, K. M. *Synthesis* **2018**, *50*, 2106.

(27) Frynas, S.; Lastawiecka, E.; Koziol, A. E.; Flis, A.; Pietrusiewicz, K. M. *J. Org. Chem.* **2019**, *84*, 1818.

(28) Kabachnik, M. I.; Jung-Yü, C.; Tsvtekov, E. N. *Doklady Chem.* **1960**, *135*, 1309.

(29) Shen, J.; Yu, R-X.; Luo, Y.; Zhu, L-X.; Zhang, Y.; Wang, X.; Xiao, B.; Cheng, J-B.; Yang, B.; Li, G-Z. *Eur. J. Org. Chem.* **2019**, 2065.

(30) Horner, L.; Binder, H. *Phosphorus, Sulfur Rel. Elem.* **1971**, *1*, 17.

(31) Gatignol, J.; Alayrac, C.; Lohier, J.-F.; Ballester, J.; Taillefer, M.; Gaumont, A.-C. *Adv. Synth. Catal.* **2013**, *355*, 2822.