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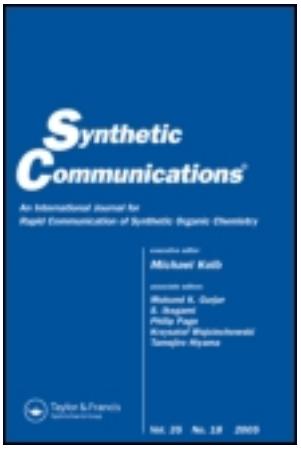

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Simple and Advantageneous Stereoselective Synthesis of (Z)-Allyl Phosphonates Starting from Baylis-Hillman Adducts

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SIMPLE AND ADVANTAGENEOUS STEREOSELECTIVE SYNTHESIS OF (*Z*)-ALLYL PHOSPHONATES STARTING FROM BAYLIS–HILLMAN ADDUCTS

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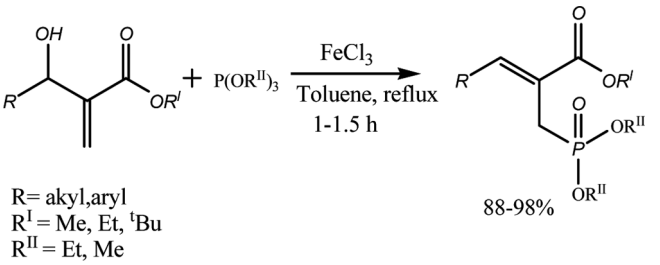
GRAPHICAL ABSTRACT



Abstract *Baylis–Hillman adducts 3-hydroxyl-2-methylene alkanoates have been converted in one pot into the corresponding (Z)-allyl phosphonates by treatment with $FeCl_3$ and trialkyl phosphites in toluene under reflux. The products are formed in excellent yields (88–98%) within 1–1.5 h. The process is highly convenient and efficient, cost-effective, and remarkably stereoselective.*

Keywords Arbuzov reaction; Baylis–Hillman adduct; $FeCl_3$; trialkyl phosphite; (*Z*)-allyl phosphonates

INTRODUCTION

Baylis–Hillman adducts are important precursors for the stereoselective synthesis of various multifunctional molecules.[1] They have been widely employed for the preparation of several natural products, their analogs, and other bioactive compounds.[1,2] However, their utility for the preparation of allyl phosphonates is limited.[3] Allyl phosphonates are important bioactive compounds. They exhibit interesting antimicrobial and antimalarial properties.[4] They are also useful precursors for the synthesis of various valuable organic compounds.[5]

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In an earlier method,[3a] allyl phosphonates were prepared by thermal Arbuzov rearrangement of allyl phosphites derived from Baylis–Hillman adducts by treatment with diethyl phosphorochloride in the presence of Et_3N. The intermediates, allyl phophites, were separated. Subsequently, these compounds underwent rearrangement by heating for 1–4 h at 70–100 °C. The allyl phosphonates containing ester moiety (yields: 61–81%) were formed with stereoselectivity of 95:5 for (*Z*)/(*E*) isomers. In another method,[3b] Baylis–Hillman adducts were not directly converted into allyl phosphonates but they were initially converted into activated Baylis–Hillman acetates, which on treatment with trialkyl phosphites at 80 °C afforded the corresponding allyl phosphonates. The products containg ester group (yields: 87–95%) possessed 93–68% (*Z*) and 7–32% (*E*) selectivity. Herein, we report an efficient advantageous method for the preparation of (*Z*)-allyl phosphonates starting directly from Baylis–Hillman adducts.

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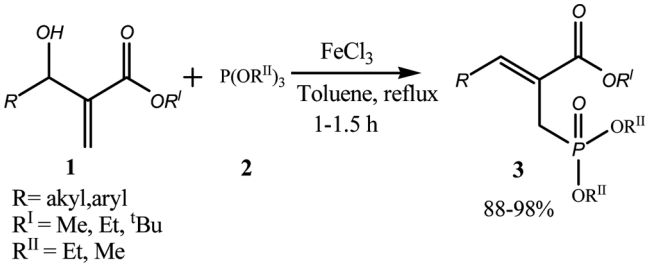
RESULTS AND DISCUSSION

In continuation of our work[6] on the applications of Baylis–Hillman reaction, we have observed that the adduct, 3-hydroxy-2-methylene-alkanoates (**1**), when treated with $FeCl_3$ and trialkyl phosphites in toluene under reflux, were directly converted into the corresponding (*Z*)-allyl phosphonates (Scheme 1).

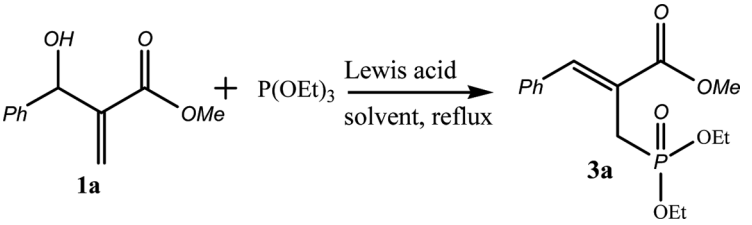
Initially, the reaction of the adduct, **1a** (R = Ph, R^I = Me), with triethyl phosphite [$P(OEt)_3$] was monitored using various metal chlorides and solvents (Scheme 2), Table 1). Considering the reaction time and yield, $FeCl_3$ was found to be the most effective in toluene. The activity of $InCl_3$ was next to that of $FeCl_3$. A similar sequence was also observed in the preparation of allyl chlorides from Baylis–Hillman adducts using different metal chlorides.[6a] The reaction with other metal halides required longer reaction times, and the yields were also less. The activity of $FeCl_3$ in tetrahydrofuran (THF) was also diminished. The products were formed within 1–1.5 h in good yields (88–98%).

The reaction of **1a** (R = Ph, R^I = Me) was also carried out with different phosphites (Table 2). $P(OEt)_3$ was identified as the best phosphorylating agent, though $P(OMe)_3$ was also highly effective. However, the other phosphites were not useful to prepare the allyl phosphonates from the Baylis–Hillman adducts.

Finally, a series of allyl phosphonates was prepared from different Baylis–Hillman adducts containing ester moiety and $P(OEt)_3$ using $FeCl_3$ in toluene under



Scheme 1. Synthesis of (*Z*)-allyl phosphonates from Baylis–Hillman adducts.



Scheme 2. Synthesis of (*Z*)-allyl phosphonates from Baylis–Hillman adducts using triethyl phosphite.

reflux (Table 3). $FeCl_3$ is easily available and less expensive, and thus the process is cost-effective. The adducts were derived from aromatic, heteroaromatic, and aliphatic aldehydes, and the ester groups were −COOMe, -COOEt, and -COO^{t}Bu. The products were formed within 1–1.5 h, and the yields were excellent (88–98%). The presence of electron-donating or electron-withdrawing groups in the aromatic ring of the adducts did not affect the conversion. Various functional groups such as halogen, nitro, ether, and nitrile remained unchanged.

The present method is highly stereoselective, only the (*Z*)-allyl phosphonates were obtained exclusively from the adducts derived from aromatic, aliphatic, and heteroaromatic aldehydes. The structures of the products were established by comparison of their spectral data (IR, ^{1}H NMR, ^{13}C NMR, and HRMS) with those reported for the known or related compounds.[3]

The treatment of the Baylis–Hillman adducts (**1**) with $FeCl_3$ is known to produce the corresponding (*Z*)-allyl chlorides.[6a] The mechanism of the conversion involves the activation of the hydroxyl group of adducts by the Lewis acid $FeCl_3$ to produce the intermediate **4**. Chloride ion then attacks this intermediate to afford the allyl chloride via a general transition state 5. The configuration of allyl chloride

Table 1. Synthesis of (*Z*)-allyl phosphonates from Baylis–Hillman adduct, **1a**, using different Lewis acids (Scheme 2)[a]

Entry	Lewis acid	Solvent	Time (h)	Yield (%)[b]
1	$CeCl3 \cdot 7H_2O$	Toluene	6	36
2	$CeCl3 \cdot 7H_2O$	THF	10	51
3	$ZrCl_4$	Toluene	10	42
4	$ZrCl_4$	Toluene	20	54
5	VCl_3	Toluene	10	48
6	VCl_3	Toluene	20	57
7	$ZnCl_2$	Toluene	10	35
8	$ZnCl_2$	Toluene	20	62
9	$InCl_3$	Toluene	10	79
10	$InCl_3$	Toluene	20	85
11	$FeCl_3$	Toluene	1	95
12	$FeCl_3$	THF	6	77
13	$FeCl_3$	Toluene	4	95

[a]Reaction conditions: Baylis–Hillman adduct, **1a** (1 mmol), triethyl phosphite (1.2 mmol), Lewis acid (0.35 mmol), and toluene (10 ml) under reflux.
[b]Yields of isolated pure compound after column chromatography.

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Table 2. Synthesis of (*Z*)-allyl phosphonates from Baylis–Hillman adduct, **1a** (R=Ph), using different phosphite reagents under reflux (Scheme 1)[a]

Entry	Phosphite reagent	Yield (%)[b]
1	$P(OEt)_3$	95
2	$HP(O)(OEt)_2$	Trace
3	$P(OMe)_3$	90
4	$HP(O)(OMe)_2$	Trace
5	$P(OPh)_3$	30
6	$HP(O)(OPh)_2$	Trace

[a]Reaction conditions: Baylis–Hillman adduct, **1a** (1 mmol), trialkyl/triphenyl phosphite (1.2 mmol), $FeCl_3$ (0.35 mmol), and toluene (10 ml); the reaction mixture was stirred for 1 h under reflux.
[b]Yields of isolated pure compound after column chromatography.

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can possibly be rationalized by considering the transition-state models A and B (Fig. 1). Model A is more favored than B, and (*Z*)-products are formed predominantly. The reaction was initially conducted at room temperature but under the reflux condition the reaction times are decreased and the yields and selectivity are increased. The intermediate (*Z*)-allyl chlorides could not be isolated as these active compounds spontaneously undergo the Arbuzov reaction with trialkyl phosphites and form the (*Z*)-allyl phosphonates (Scheme 3). However, when the (*Z*)-allyl chlorides prepared

Table 3. $FeCl_3$-catalyzed synthesis of (*Z*)-allyl phosphonates from Baylis–Hillman adducts with triethylphosphite (Scheme 1)[a]

Entry	R[b]	Product[c]	Time (h)	Yield[d] (%)
1	C_6H_5	**3a**	1	95
2	4-MeC_6H_4	**3b**	1	97
3	4-$(CH_3)_2CHC_6H_4$	**3c**	1	98
4	4-ClC_6H_4	**3d**	1	93
5	4-BrC_6H_4	**3e**	1	94
6	4-FC_6H_4	**3f**	1	97
7	4-CNC_6H_4	**3g**	1	93
8	4-MeO C_6H_4	**3h**	1.25	94
9	4-$NO_2C_6H_4$	**3i**	0.5	96
10	2-$NO_2C_6H_4$	**3j**	1	92
11	2-Napthyl	**3k**	1.25	92
12	2-Furyl	**3l**	1	90
13	$(CH_3)_2CHCH_2$	**3m**	1.5	89
14	$CH_3(CH_2)_3CH_2$	**3n**	1.5	88
15	C_6H_5, (R^I = Et)	**3o**	1	94
16	C_6H_5, (R^I = ^{t}Bu)	**3p**	1	91
17	C_6H_5, (R^{II} = Me)	**3q**	1.5	90

[a]Reaction conditions: Baylis–Hillman adduct, **1** (1 mmol), triethyl phosphate (1.2 mmol), $FeCl_3$ (0.35 mmol), and toluene (10 ml); the reaction mixture was stirred under reflux.
[b]R^1 = Me and R^{II} = Et in each entity otherwise stated.
[c]The products were characterized from their IR, ^{1}H NMR, ^{13}C NMR, and HRMS spectra.
[d]Yields of isolated pure compound after column chromatography.

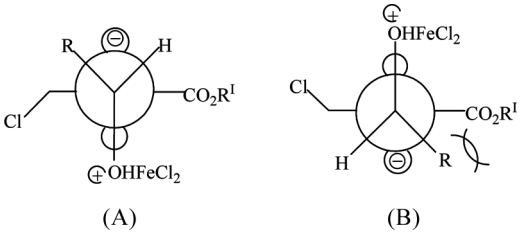
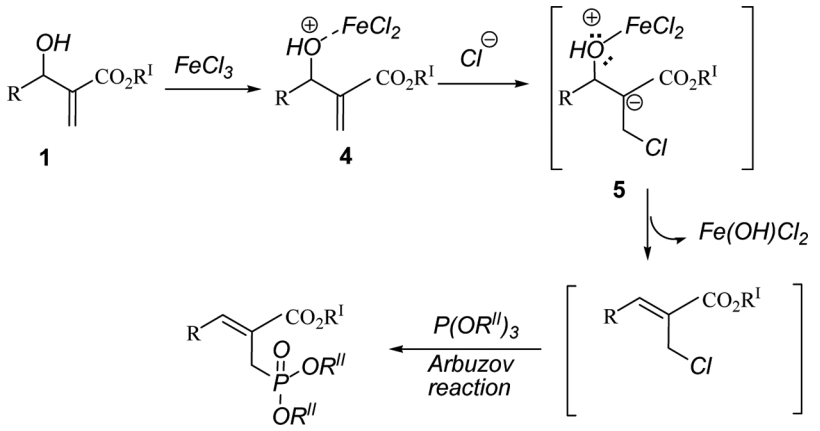


Figure 1.



Scheme 3. Transition-state analysis for the rationalization of the observed stereoselectivity in the reaction leading to the *Z*-allyl chloride and *Z*-allyl phosphonates.

by the reaction of the Baylis–Hillman adducts with $FeCl_3$[6a] were separately treated with trialkyl phosphites under the present reaction conditions, the (*Z*)-allyl phosphonates were obtained. In absence of $FeCl_3$, the reaction did not proceed, and in the presence of catalytic amount of $FeCl_3$, only a minor amount of the product was obtained. Even with the less of one third equivalent of $FeCl_3$ compared to the amount of the adduct, the yields of the products were reasonably less. It has been clearly shown in the mechanism that for the conversion of each mole of an adduct one-third equivalent of $FeCl_3$ is required (Scheme 3). Thus, for an efficient preparation of (*Z*)-allyl phosphonates, 0.35 equivalent of $FeCl_3$ compared to the amount of the adducts has been used.

CONCLUSION

In conclusion, we have developed a simple and efficient method for the synthesis of (*Z*)-allyl phosphonates from the Baylis–Hillman adducts by treatment with $FeCl_3$ and trialkyl phosphates. The direct conversion of the adducts, convenient experimental procedure, application of less expensive reagents, impressive yields, and excellent stereoselectivity are the advantages of the present method.

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EXPERIMENTAL

Anhydrous $FeCl_3$ (0.35 mmol) and trialkyl phosphite **2** (1.2 mmol) were added to a stirring solution of 3-hydroxy-2-methylene alkanoate **1** (1 mmol) in toluene (10 ml). The mixture was heated under reflux for 1–1.5 h. The reaction was monitored by thin-layer chromatography (TLC). After completion, the solvent was removed under vaccum, and water (10 ml) was added. The mixture was extracted with EtOAc (3×10 ml). The extract was washed with water (3×10 ml), dried over anhydrous Na_2SO_4, and concentrated. The residue was subjected to column chromatography (silica gel, hexane/EtOAc, 4:1) to obtained pure (*Z*)-allyl phosphonates, **3**.

The spectral (IR, ^1H and ^{13}C NMR, and MS) and analytical data of all compounds are given.

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Compound 3a: (*Z*)-Methyl-2-((diethoxyphosphoryl)-methyl)-3-phenylacrylate

IR υ_{max} (neat): 1717, 1633, 1442, 1268 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 7.81 (1H, d, $J = 6.0$ Hz), 7.60 (2H, d, $J = 8.0$ Hz), 7.46 (1H, d, $J = 6.0$ Hz), 7.46–7.31 (3H, m), 4.14–4.01 (4H, q, $J = 7.0$ Hz), 3.85 (3H, s), 3.23 (2H, d, $J = 22.0$ Hz), 1.22 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 168.3, 141.4 (d, $J = 11.0$ Hz), 134.7, 129.5, 129.0, 128.6, 123.6 (d, $J = 11.5$ Hz), 62.2 (d, $J = 6.5$ Hz), 52.1, 26.0 (d, $J = 140.0$ Hz), 16.2 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.05; ESIMS: m/z 313 $[M + H]^+$, 335 $[M + Na]^+$; HRMS (ESI): m/z 335.1025 $[M + Na]^+$ (calculated for $C_{15}H_{21}O_5PNa$: 335.1024).

Compound 3b: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)-3-ptolylacrylate

IR υ_{max} (neat): 1714, 1631, 1438, 1269 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 7.72 (1H, d, $J = 6.0$ Hz), 7.49 (2H, d, $J = 8.0$ Hz), 7.19 (2H, d, $J = 8.0$ Hz), 4.15–4.02 (4H, m), 3.82 (3H, s), 3.19 (2H, d, $J = 22.0$ Hz), 2.40 (3H, s), 1.27 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 168.4, 142.0 (d, $J = 11.0$ Hz), 139.1, 132.0, 129.9, 129.0, 123.1 (d, $J = 11.5$ Hz), 62.0 (d, $J = 6.5$ Hz), 52.1, 22.0, 26.1 (d, $J = 140.0$ Hz), 16.2 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.10; ESIMS: m/z 327 $[M + H]^+$, 349 $[M + Na]^+$; HRMS (ESI): m/z 327.1369 $[M + H]^+$ (calculated for $C_{16}H_{24}O_5P$: m/z 327.1361).

Compound 3c: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)-3-(4-isopropylphenyl)acrylate

IR υ_{max} (neat): 1716, 1631, 1438, 1270 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 7.72 (1H, d, $J = 6.0$ Hz), 7.52 (2H, d, $J = 8.0$ Hz), 7.23 (2H, d, $J = 8.0$ Hz), 4.11–4.02 (4H, m), 3.82 (3H, s), 3.20 (2H, d, $J = 22.0$ Hz), 2.91 (1H, m), 1.31–1.20 (12H, m); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 168.3, 150.5, 141.7 (d, $J = 11.0$ Hz), 132.2, 129.9, 126.5, 122.4 (d, $J = 11.5$ Hz), 62.0 (d, $J = 6.5$ Hz), 52.0, 33.9, 26.0 (d, $J = 140.0$ Hz), 24.0, 16.3 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.15; ESIMS: m/z 355 $[M + H]^+$, 374 $[M + Na]^+$; HRMS (ESI): m/z 355.1665 $[M + H]^+$ (calculated for $C_{15}H_{28}O_5P$: m/z 355.1674).

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Compound 3d: (*Z*)-Methyl-3-(4-chlorophenyl)-2-((diethoxyphosphoryl) methyl)acrylate

IR υ_{max} (neat): 1719, 1634, 1439, 1269 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 77.71 (1H, d, $J = 6.0$ Hz), 7.57 (2H, d, $J = 8.0$ Hz), 7.36 (2H, d, $J = 8.0$ Hz), 4.15–4.01 (4H, m), 3.82 (3H, s), 3.13 (2H, d, $J = 22.0$ Hz), 1.28 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 168.2, 140.2 (d, $J = 11.0$ Hz), 135.1, 133.5, 131.1, 129.5, 124.8 (d, $J = 11.5$ Hz), 62.2 (d, $J = 6.5$ Hz), 52.5, 26.2 (d, $J = 140.0$ Hz), 16.6 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 26.08; ESIMS: m/z 347 $[M + H]^+$, 369 $[M + Na]^+$; HRMS (ESI): m/z 347.0831 $[M + H]^+$ (calculated for $C_{16}H_{21}ClO_5P$ m/z 347.0815).

Compound 3e: (*Z*)-Methyl-3-(4-bromophenyl)-2-((diethoxyphosphoryl)methyl)acrylate

IR υ_{max} (neat): 1717, 1633, 1438, 1272 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 7.69 (1H, d, $J = 6.0$ Hz), 7.02 (2H, d, $J = 8.0$ Hz), 7.49 (1H, d, $J = 8.0$ Hz), 4.12–4.02 (4H, m), 3.83 (3H, s), 3.12 (2H, d, $J = 22.0$ Hz), 1.26 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ 167.5, 140.2 (d, $J = 11.0$ Hz), 133.7, 131.2, 131.0, 124.1 (d, $J = 11.5$ Hz), 123.1, 62.2 (d, $J = 6.5$ Hz), 52.1, 26.0 (d, $J = 140.0$ Hz), 16.2 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 26.07; ESIMS: m/z 391 $[M + H]^+$, 413 $[M + Na]^+$; HRMS (ESI): m/z 391.0297 $[M + H]^+$ (calculated for $C_{16}H_{21}BrO_5P$ m/z 391.0309).

Compound 3f: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)-3-(4-fluorophenyl)acrylate

IR υ_{max} (neat): 1717, 1601, 1501, 1439, 1268 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 77.72 (1H, d, $J = 6.0$ Hz), 7.62–7.60 (2H, m), 7.09 (2H, t, $J = 8.0$ Hz), 4.12–4.01 (4H, m), 3.81 (3H, s), 3.12 (2H, d, $J = 22.0$ Hz), 1.25 (6, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 168.2, 163.1 (d, $J = 280.0$ Hz), 140.2 (d, $J = 11.0$ Hz), 131.1 (d, $J = 10.0$ Hz), 130.8, 123.3 (d, $J = 11.5$ Hz), 115.5 (d, $J = 18.0$ Hz), 61.7 (d, $J = 6.5$ Hz), 52.0, 26.0 (d, $J = 140.0$ Hz), 16.1 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 26.06; ESIMS: m/z 331 $[M + H]^+$, 353 $[M + Na]^+$; HRMS (ESI): m/z 353.0938 $[M + Na]^+$ (calculated for $C_{16}H_{20}FO_5PNa$ m/z 353.0930).

Compound 3g: (*Z*)-Methyl-3-(4-cyanophenyl)-2-((diethoxyphosphoryl)methyl)acrylate

IR υ_{max} (neat): 1717, 1635, 1437, 1267 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 7.80–7.68 (5H, m), 4.18–4.02 (14H, m), 3.86 (3H, s), 3.10 (2H, d, $J = 22.0$ Hz), 7.81 (1H, d, $J = 6.0$ Hz), 1.29 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 167.5, 139.2 (d, $J = 11.0$ Hz), 132.2, 130.0, 127.0 (d, $J = 11.5$ Hz), 118.2, 112.4, 62.2 (d, $J = 6.5$ Hz), 52.2, 26.1 (d, $J = 140.0$ Hz), 16.1 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 26.09; ESIMS: m/z 338 $[M + H]^+$, 360 $[M + Na]^+$; HRMS (ESI): m/z 360.0976 $[M + Na]^+$ (calculated for $C_{16}H_{20}NO_5PNa$ m/z 360.0976).

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Compound 3h: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)-3-(4-methoxyphenyl)acrylate

IR υ_{max} (neat): 1713, 1605, 1512, 1439, 1257 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 7.72 (1H, d, $J = 6.0$ Hz), 7.59 (2H, d, $J = 8.0$ Hz), 6.92 (2H, d, $J = 8.0$ Hz), 4.12–4.04 (4H, m), 3.82 (6H, s), 3.21 (2H, d, $J = 22.0$ Hz), 1.28 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 167.8, 151.0, 128.0 (d, $J = 11.0$ Hz), 127.3, 127.0, 119.0 (d, $J = 11.5$ Hz), 116.5, 62.2, 62.0 (d, $J = 6.5$ Hz), 52.2, 26.0 (d, $J = 140.0$ Hz), 16.0 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.17; ESIMS: m/z 334 $[M + H]^+$, 356 $[M + Na]^+$; HRMS (ESI): m/z 343.1323 $[M + H]^+$ (calculated for $C_{16}H_{24}O_6P$ m/z 343.1310).

Compound 3i: (*Z*)-Methyl-2-((diethoxyphosphoryl methyl)-3-(4-nitrophenyl)acrylate

IR υ_{max} (neat): 1721, 1637, 1520, 1346, 1238 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 8.19 (1H, d, $J = 8.0$ Hz), 7.40 (2H, d, $J = 8.0$ Hz), 6.99 (1H, d, $J = 6.0$ Hz), 4.20–4.02 (4H, m), 3.64 (3H, s), 2.99 (2H, d, $J = 22.0$ Hz), 1.34 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 167.3, 138.8, 137.0 (d, $J = 10.0$ Hz), 129.0, 128.0 (d, $J = 11.5$ Hz), 123.9, 123.0, 62.5 (d, $J = 6.5$ Hz), 52.0, 32.0 (d, $J = 140.0$ Hz), 22.0, 16.7 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 26.03; ESIMS: m/z 358 $[M + H]^+$, 380 $[M + Na]^+$; HRMS (ESI): m/z 380.0882 $[M + Na]^+$ (calculated for $C_{15}H_{20}NO_7PNa$ m/z 380.0875).

Compound 3j: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)-3-(2-nitrophenyl)acrylate

IR υ_{max} (neat): 1719, 1641, 1526, 1384 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 8.20 (1H, d, $J = 8.0$ Hz), 8.04 (1H, d, $J = 6.0$ Hz), 7.78–7.69 (2H, m), 7.55 (1H, t, $J = 8.0$ Hz), 4.09–3.96 (4H, m), 3.88 (3H, s), 2.91 (2H, d, $J = 22.0$ Hz), 1.22 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 167.7, 147.5, 139.1 (d, $J = 10.0$ Hz), 138.7, 134.8, 131.0, 129.9, 125.4 (d, $J = 11.0$ Hz), 125.2, 62.0 (d, $J = 6.5$ Hz), 52.4, 25.4 (d, $J = 140.0$ Hz), 16.0 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 26.25; ESIMS: m/z 358 $[M + H]^+$, 380 $[M + Na]^+$; HRMS (ESI): m/z 380.0882 $[M + Na]^+$ (calculated for $C_{15}H_{20}NO_7PNa$ m/z 380.0875).

Compound 3k: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)-3-(2-naphthyl)acrylate

IR υ_{max} (neat): 1719, 1630, 1445, 1256 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 8.19 (1H, d, $J = 6.0$ Hz), 7.90–7.72 (4H, m), 7.54–7.38 (3H, m), 4.17–4.03 (4H, m), 3.86 (3H, s), 3.28 (2H, d, $J = 140.0$ Hz), 1.30 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 168.2, 141.8 (d, $J = 11.0$ Hz), 133.8, 129.0, 128.4, 128.1, 127.3, 126.2, 126.0, 123 (d, $J = 11.5$ Hz), 62.2 (d, $J = 6.5$ Hz), 51.8, 26.3 (d, $J = 140.0$ Hz), 22.0, 16.1 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.2; ESIMS: m/z 363 $[M + H]^+$, 385 $[M + Na]^+$; HRMS (ESI): m/z 385.1183 $[M + Na]^+$ (calculated for $C_{19}H_{23}O_5PNa$ m/z 385.1180).

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Compound 3l: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)-3-(furan-2-yl)acrylate

IR υ_{max} (neat): 1718, 1646, 1440, 1260 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ ppm 7.58 (1H, m), 7.48 (1H, d, $J = 6.0$ Hz), 6.74 (1H, m), 6.50 (1H, m), 4.10–3.99 (4H, m), 3.81 (3H, s), 3.42 (2H, t, $J = 22.0$ Hz), 1.21 (6H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 167.8, 144.7, 127.9 (d, $J = 10.0$ Hz), 127.0, 119.1 (d, $J = 11.0$ Hz), 116.5, 112.0, 61.1 (d, $J = 6.0$ Hz), 51.8, 25.8 (d, $J = 140.0$ Hz), 16.0 (d, $J = 6.5$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.35; ESIMS: m/z 303 $[M + H]^+$, 325 $[M + Na]^+$; HRMS (ESI): m/z 325.0814 $[M + Na]^+$ (calculated for $C_{13}H_{19}O_6$ PNa m/z 325.0816).

Compound 3m: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)-5-methylhex-2-enoate

IR υ_{max} (neat): 1718, 1646, 1440, 1260 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ ppm 6.91 (1H, dd, $J = 7.0$, 5.0 Hz), 4.12–4.01 (4H, m), 3.79 (3H, s), 2.94 (2H, d, $J = 22.0$ Hz), 2.20–2.14 (2H, m), 1.77 (1H, m), 1.30 (6H, d, $J = 8.0$ Hz), 0.95 (6H, t, $J = 8.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 167.2, 145.2 (d, $J = 11.0$ Hz), 123.5 (d, $J = 11.5$ Hz), 61.5 (d, $J = 6.5$ Hz), 52.0, 38.0, 27.9, 24.5 (d, $J = 140.0$ Hz), 22.1, 15.7 (d, $J = 6.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.64; ESIMS: m/z 293 $[M + H]^+$, 315 $[M + Na]^+$; HRMS (ESI): m/z 293.1511 $[M + H]^+$ (calculated for $C_{13}H_{26}O_5P$ m/z 293.1517).

Compound 3n: (*Z*)-Methyl-2-((diethoxyphosphoryl)methyl)oct-2-enoate

IR υ_{max} (neat): 1719, 1646, 1440, 1282 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ ppm 6.69 (1H, dd, $J = 7.0$, 5.0 Hz), 4.11–4.01 (4H, m), 3.53 (3H, s), 2.91 (2H, d, $J = 22.0$ Hz), 2.30–2.22 (2H, m), 1.51–1.40 (2H, m), 1.38–1.22 (10H, m), 0.90 (3H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 167.3, 146.5 (d, $J = 11.0$ Hz), 122.5 (d, $J = 11.5$ Hz), 62.0 (d, $J = 6.5$ Hz), 52.0, 31.2, 29.2, 28.0, 25.2 (d, $J = 140.0$ Hz), 22.5, 16.1 (d, $J = 6.0$ Hz), 14.0); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.72; ESIMS: m/z 307 $[M + H]^+$, 329 $[M + Na]^+$; HRMS (ESI): m/z 307.1667 $[M + H]^+$ (calculated for $C_{14}H_{28}O_5P$ m/z 307.1674).

Compound 3o: (*Z*)-Ethyl-2-((diethoxyphosphoryl)methyl)-3-phenylacrylate

IR υ_{max} (neat): 1717, 1633, 1442, 1268 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ ppm 7.75 (1H, d, $J = 6.0$ Hz), 7.58 (2H, d, $J = 8.0$ Hz), 7.40–7.29 (3H, m), 4.29 (2H, q, $J = 7.0$ Hz), 4.12–4.09 (4H, m), 3.20 (2H, d, $J = 22.0$ Hz), 1.38 (3H, t, $J = 7.0$ Hz), 1.32 (3H, t, $J = 7.0$ Hz), 1.25 (3H, t, $J = 7.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 167.5, 141.1 (d, $J = 11.0$ Hz), 134.5, 129.5, 129.0, 128.5, 124.1 (d, $J = 11.5$ Hz), 62.0 (d, $J = 6.5$ Hz), 61.2, 26.1 (d, $J = 140.0$ Hz), 16.1 (d, $J = 6.0$ Hz), 14.1; ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.04; ESIMS: m/z 327 $[M + H]^+$, 349 $[M + Na]^+$; HRMS (ESI): m/z 327.1356 $[M + H]^+$ (calculated for $C_{16}H_{24}O_5P$ m/z 327.1361).

Compound 3p: (*Z*)-*tert*-Butyl-2-((diethoxyphosphoryl)methyl)-3-phenylacrylate

IR υ_{max} (neat): 1717, 1630, 1439, 1271 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 7.64 (1H, d, $J = 6.0$ Hz), 7.56 (2H, d, $J = 8.0$ Hz), 7.40–7.29 (3H, m), 4.12–4.01 (4H, m), 3.13 (2H, d, $J = 22.0$ Hz), 1.58 (9H, s), 1.30 (6H, t, $J = 8.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 166.9, 140.6 (d, $J = 11.0$ Hz), 135.2, 129.1, 129.0, 128.9, 125.5, 81.0, 62.0 (d, $J = 6.5$ Hz), 28.1, 26.0 (d, $J = 140.0$ Hz), 16.4; ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.03; ESIMS: m/z 355 $[M + H]^+$, 377 $[M + Na]^+$; HRMS (ESI): m/z 377.1496 $[M + H]^+$ (calculated for $C_{18}H_{27}O_5PNa$ m/z 377.1493).

Compound 3q: (*Z*)-Methyl-2-((dimethoxyphosphoryl)methyl)-3-phenylacrylate

IR υ_{max} (neat): 1719, 1646, 1440, 1282 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ ppm 7.76 (1H, d, $J = 6.0$ Hz), 7.51 (2H, d, $J = 8.0$ Hz), 7.41–7.28 (3H, m), 3.82 (3H, S), 3.68 (6H, d, $J = 10.0$ Hz), 3.15 (2H, d, $J = 22.0$ Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ ppm 168.1, 142.0 (d, $J = 6.0$ Hz), 134.9, 129.5, 129.1,129.0, 123.4 (d, $J = 6.5$ Hz), 52.5 (d, $J = 6.5$ Hz), 52.1, 26.2 (d, $J = 140.0$ Hz); ^{31}P NMR (161.9 MHz, $CDCl_3$) δ ppm 27.12; ESIMS: m/z 285 $[M + H]^+$, 307 $[M + Na]^+$; HRMS (ESI): m/z 307.0713 $[M + Na]^+$ (calculated for $C_{13}H_{17}O_5PNa$ m/z 307.0711).

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