Synthesis of [1-(Dimethylamino)alkyl]phosphonates from (1-Hydroxyalkyl)phosphonates: Transformation of Allylic Hydroxyphosphonates into Allylic Aminophosphonates

Babak Kaboudin,* Mohammad Reza Faghihi

Department of Chemistry, Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan 45137-66731, Iran
Fax +98(241)4214949; E-mail: kaboudin@iasbs.ac.ir

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Abstract: A noncatalyzed reaction of (1-hydroxyalkyl)phosphonates with *N*,*N*-dimethylformamide diethyl acetal for the synthesis of novel [1-(dimethylamino)alkyl]phosphonates is described. Treatment of allylic (1-hydroxyalkyl)phosphonates with *N*,*N*-dimethylformamide diethyl acetal without any catalyst and under reflux in xylene gives novel allylic [1-(dimethylamino)alkyl]phosphonates. By using this method, a series of [1-(dimethylamino)alkyl]phosphonates was synthesized in good yields.

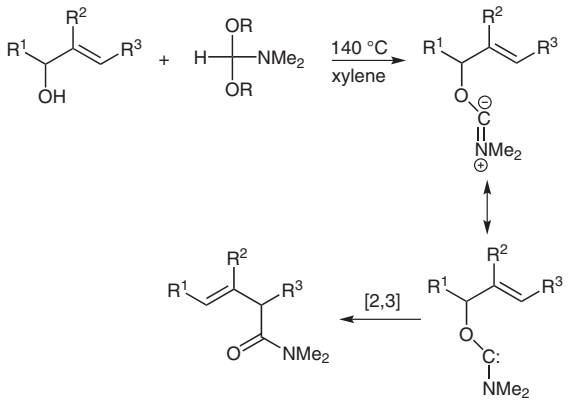
Key words: 1-aminophosphonates, 1-hydroxyphosphonates, *N*,*N*-dimethylformamide diethyl acetal, allylic alcohols, allylic amines

Organophosphorus compounds have found a wide range of applications in the areas of industrial, agricultural, and medicinal chemistry owing to their biological and physical properties as well as their utility as synthetic intermediates. α-Functionalized phosphonic acids are valuable intermediates for the preparation of medicinal compounds and synthetic intermediates.[1–4] Among α-functionalized phosphonic acids, 1-aminophosphonic acids make up an important class of compounds that exhibit a variety of interesting and useful properties. 1-Aminophosphonic acids are important substitutes for the corresponding α-amino acids in biological systems.[5] On the other hand, methylamino acids containing peptide natural products have found clinical use, due, in part, to the physical properties and chemical stability conferred by the methylamino acids present in their structures.[6] A number of potent antibiotics,[7] enzyme inhibitors,[8] and pharmacological agents[9] are, indeed, 1-aminophosphonic acids or peptide analogues.

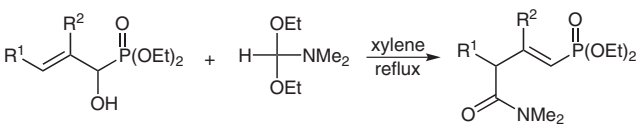
These important compounds have been synthesized by various routes: (a) the addition of a P–H function to imines and enamines,[10] (b) the addition of a P–H function to nitriles,[11] (c) Arbuzov and Michaelis–Beacker reactions,[12] (d) the condensation of X–NH_2 with acyl phosphorus species,[13] (e) Curtius and Hoffmann rearrangement of substituted phosphonoacetic esters, and (f) alkylation of nucleophilic precursors such as Schiff bases.[14] Despite this wide range of synthetic methods for the synthesis of 1-aminophosphonates, little attempt has been made to convert readily accessible 1-hydroxyphosphonates into 1-aminophosphonates. Replacement of the hydroxy group in (1-hydroxyalkyl)phosphonates by an azide group, followed by reduction, has given the amino function by way of the Mitsunobu reaction.[15] Yuan and Li have reported the conversion of (1-hydroxyalkyl)phosphonate into (1-hydrazinoalkyl)phosphonates by nucleophilic substitution of hydrazine by mesylated (1-hydroxyalkyl)phosphonates.[16] Recently, we have reported a novel method for the synthesis of 1-aminophosphonates by the reaction of 1-hydroxyphosphonates with amines by means of microwave irradiation.[17]

N,*N*-Dimethylformamide dialkyl acetals have been used widely as alkylating agents of various compounds.[18] These reagents have also been reported to be efficient in some organic transformations. Recently, an efficient method for the synthesis of arylpropargyl aldehydes from arylacetylenes and amide acetals was reported by Kim et al.[19]

A wide variety of allylic alcohols were transformed into β,γ-unsaturated amides when heated to approximately 160 °C with *N*,*N*-dimethylacetamide dialkyl acetals. The proposed mechanism for this transformation appears in Scheme 1.[20] We were interested in examining the treatment of allylic (1-hydroxyalkyl)phosphonates with *N*,*N*-dimethylformamide diethyl acetal (Scheme 2).



Scheme 1



Scheme 2

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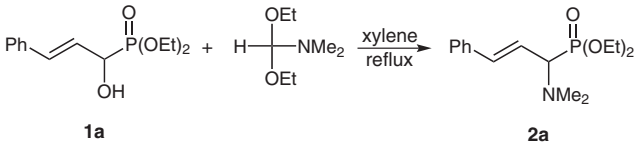
As part of our efforts in exploring novel reactions for the synthesis of organophosphorus compounds,[17,21–23] the method we report herein is for the preparation of [1-(dimethylamino)alkyl]phosphonates by the reactions of (1-hydroxyalkyl)phosphonates with *N*,*N*-dimethylformamide diethyl acetal in the absence of any catalyst under reflux in xylene.

Treatment of diethyl (1-hydroxy-3-phenylallyl)phosphonate (**1a**), chosen as a model compound and prepared by our previously reported method,[24] was studied in the presence of *N*,*N*-dimethylformamide diethyl acetal in xylene, and the progress of the reaction was monitored by TLC (Scheme 3).



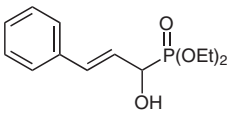
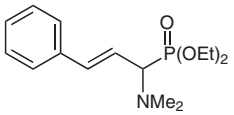
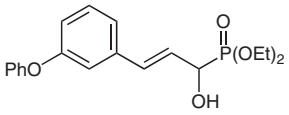
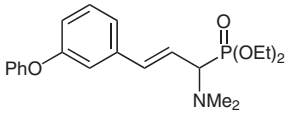
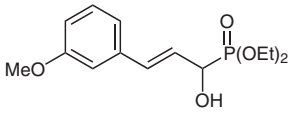
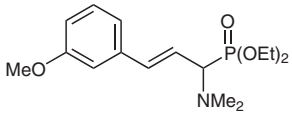
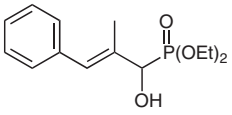
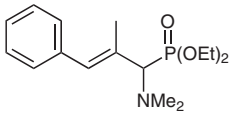
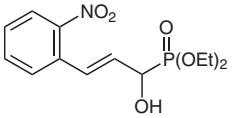
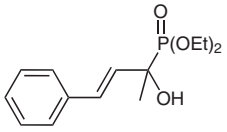
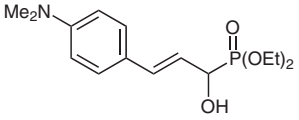
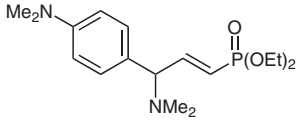
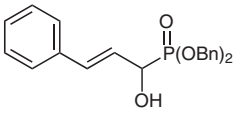
1a **2a**

Scheme 3

Treatment of **1a** with *N*,*N*-dimethylformamide diethyl acetal in xylene gave **2a** in 56% yield after 18 hours under reflux (Scheme 3). The structure of **2a** was confirmed by NMR data and elemental analysis. In the ^{31}P NMR spectrum, a singlet peak appeared at δ = 23.94. The ^{1}H NMR spectrum had two sets of doublet of doublet peaks at δ = 3.44 ($^{2}J_{HP}$ = 21.5 and $^{3}J_{HH}$ = 9.5 Hz) and 6.56 ($^{4}J_{HP}$ = 2.8 and $^{3}J_{HH}$ = 15.8 Hz), along with a singlet peak at δ = 2.40. The ^{13}C NMR spectrum exhibited a doublet peak at δ = 66.0 (J_{CP} = 158.4 Hz) and one singlet peak at δ = 43.0, which corresponds to the resonances for the methyl groups (NMe_2). The absence of a carbonyl group in the ^{13}C NMR spectrum also confirmed the structure of compound **2a**.

To study the scope and limitations of the reaction, various (3-aryl-1-hydroxyallyl)phosphonates **1** were treated with *N*,*N*-dimethylformamide diethyl acetal in refluxing xylene (Table 1). The reactions of diethyl (3-aryl-1-hy-

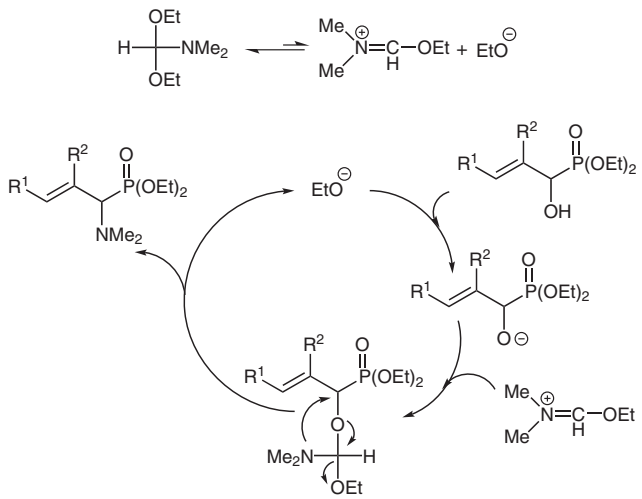
Table 1 Conversion of Allylic (1-Hydroxyalkyl)phosphonates **1** into Novel Allylic [1-(Dimethylamino)alkyl]phosphonates

Entry	Alcohol	**1**	Product		Time (h)	Yield[a] (%)	^{31}P NMR (δ) of product
1		**1a**		**2a**	18	65	23.94
2		**1b**		**2b**	24	60	23.87
3		**1c**		**2c**	24	63	24.71
4		**1d**		**2d**	24	54	24.42
5		**1e**	–	–[b]	24	–	–
6		**1f**	–	–[b]	24	–	–
7		**1g**		**3**	18	71	18.87
8		**1h**	–	–[b]	24	–	–

[a] Yield of isolated, pure product after column chromatography.
[b] Unknown mixture.

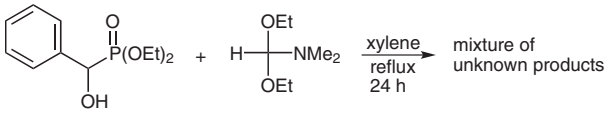
droxyallyl)phosphonates **1a–d** with *N*,*N*-dimethylformamide diethyl acetal in refluxing xylene afforded the corresponding [3-aryl-1-(dimethylamino)allyl]phosphonates **2a–d** in good yields (entries 1–4). Treatment of [1-hydroxy-3-(*o*-nitrophenyl)allyl]phosphonate **1e** and (1-hydroxy-1-methyl-3-phenylallyl)phosphonate **1f**, a tertiary allylic hydroxyphosphonate, with *N*,*N*-dimethylformamide diethyl acetal in refluxing xylene gave mixtures of unknown products (entries 5 and 6). The reaction also gave a mixture of unknown products when the dibenzyl derivative of a (3-aryl-1-hydroxyallyl)phosphonate **1h** was used (entry 8). An interesting result was obtained from the reaction of diethyl {3-[4-(dimethylamino)phenyl]-1-hydroxyallyl}phosphonate (**1g**) with *N*,*N*-dimethylformamide diethyl acetal in refluxing xylene (entry 7): {3-(dimethylamino)-3-[4-(dimethylamino)phenyl]prop-1-enyl}phosphonate **3** was obtained as the major product.

It has been suggested that, in the reaction of a diethyl (1-hydroxyallyl)phosphonate **1**, a trace amount of ethoxide ion can deprotonate the (1-hydroxyalkyl)phosphonate, the product of which is subsequently quenched by iminium salt in the reaction mixture (Scheme 4). The product **2** is obtained by intramolecular nucleophilic substitution of the amine residue (Scheme 4).



Scheme 4

Treatment of diethyl [(hydroxy)(phenyl)methyl]phosphonate as a nonallylic 1-hydroxyphosphonate with *N*,*N*-dimethylformamide diethyl acetal in refluxing xylene gave a mixture of unknown products (Scheme 5).



Scheme 5

In summary, we have presented a novel procedure for the conversion of allylic (1-hydroxyalkyl)phosphonates into allylic [1-(dimethylamino)alkyl]phosphonates by using *N*,*N*-dimethylformamide diethyl acetal without any catalyst under reflux in xylene. By using this method, a series of [1-(dimethylamino)alkyl]phosphonates was synthesized in good yields. The main advantages of this protocol are that it is a simple procedure, involving easy workup, leading to good yields, and proceeds under catalyst-free reaction conditions.

All the chemicals that were used were commercially available and distilled or recrystallized before use. NMR spectra were recorded on a 250 Bruker Avance instrument. The chemical shift data are reported relative to the solvent resonances (δ = 7.26 ppm, $CHCl_3$, ^1H NMR; δ = 77.0 ppm, $CDCl_3$, ^{13}C NMR). Column chromatography was carried out on silica gel 100 (Merck No. 10184). Merck silica gel 60 F254 plates (No. 5744) were used for preparative TLC.

Allylic (1-Hydroxyalkyl)phosphonates 1; General Procedure

Allylic (1-hydroxyalkyl)phosphonates **1** were obtained according to the method described in our previously published article.[24]

Diethyl (1-Hydroxy-3-phenylallyl)phosphonate (1a)

White solid;[24] mp 105 °C (*n*-hexane–EtOAc).

^1H NMR (250 MHz, $CDCl_3$): δ = 1.22–1.38 (m, 6 H), 4.03–4.30 (m, 4 H), 4.68 (dd, *J* = 6.0 Hz, J_{HP} = 12.7 Hz, 1 H), 5.22 (br, 1 H, OH), 6.27–6.38 (m, 1 H), 6.75–6.81 (m, 1 H), 7.25–7.39 (m, 5 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.5 (d, J_{PC} = 5.7 Hz), 63.2 (d, J_{PC} = 6.9 Hz), 63.4 (d, J_{PC} = 6.9 Hz), 69.4 (d, J_{PC} = 161.0 Hz), 123.7 (d, J_{PC} = 4.4 Hz), 126.6, 127.9, 128.6, 132.2 (d, J_{PC} = 13.2 Hz), 136.4.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 22.32.

Diethyl [1-Hydroxy-3-(*m*-phenoxyphenyl)allyl]phosphonate (1b)

Colorless oil.

^1H NMR (250 MHz, $CDCl_3$): δ = 1.22–1.40 (m, 6 H), 4.09–4.24 (m, 4 H), 4.30 (br, 1 H), 4.66 (dd, *J* = 6.3, 13.0 Hz, 1 H), 6.30 (dt, *J* = 5.25, 10.5 Hz, 1 H), 6.74 (dd, *J* = 3.75, 16.0 Hz, 1 H), 6.80–7.40 (m, 9 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.4 (d, J_{PC} = 5.7 Hz), 63.1 (d, J_{PC} = 6.9 Hz), 63.2 (d, J_{PC} = 6.9 Hz), 69.2 (d, J_{PC} = 161.0 Hz), 116.8, 118.2, 118.8 121.6, 123.3, 124.7 (d, J_{PC} = 4.4 Hz), 129.8, 131.4, 131.5 (d, J_{PC} = 13.2 Hz), 138.3 (d, J_{PC} = 2.5 Hz), 157.0, 157.5.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 21.99.

Anal. Calcd for $C_{19}H_{23}O_5P$: C, 62.96; H, 6.35. Found: C, 62.80; H, 6.30.

Diethyl [1-Hydroxy-3-(*m*-methoxyphenyl)allyl]phosphonate (1c)

Colorless oil.

^1H NMR (250 MHz, $CDCl_3$): δ = 1.20–1.38 (m, 6 H), 3.76 (s, 3 H), 4.04–4.21 (m, 4 H), 4.54 (br, 1 H, OH), 4.65 (dd, *J* = 6.3, 13.5 Hz, 1 H), 6.28 (dt, *J* = 5.25, 15.75 Hz, 1 H), 6.72 (dd, *J* = 4.75, 15.5 Hz, 1 H), 6.75 (d, *J* = 6.75 Hz, 1 H), 6.89 (s, 1 H), 6.95 (d, *J* = 7.75 Hz, 1 H), 6.75 (t, *J* = 7.75 Hz, 1 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.4 (d, J_{PC} = 5.7 Hz), 55.1, 63.1 (d, J_{PC} = 7.5 Hz), 63.2 (d, J_{PC} = 7.5 Hz), 69.1 (d, J_{PC} = 162.3 Hz), 111.9 (d, J_{PC} = 1.9 Hz), 113.3, 119.2, 124.5 (d, J_{PC} = 4.4 Hz), 129.5, 131.9 (d, J_{PC} = 13.2 Hz), 137.9 (d, J_{PC} = 2.5 Hz), 159.7.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 22.29.

Anal. Calcd for $C_{14}H_{21}O_5P$: C, 55.98; H, 7.05. Found: C, 56.12; H, 7.18.

Diethyl (1-Hydroxy-2-methyl-3-phenylallyl)phosphonate (1d)
Colorless oil.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.29 (t, J_{HP} = 7.5 Hz, 3 H), 1.30 (t, J_{HP} = 7.5 Hz, 3 H), 2.00 (d, J_{HP} = 2.3 Hz, 3 H), 4.11–4.23 (m, 4 H), 4.54 (dd, J = 5.3 Hz, J_{HP} = 12.3 Hz, 1 H), 4.85 (dd, J = 5.7 Hz, J_{HP} = 9.8 Hz, 1 H, OH), 6.67 (d, J_{HP} = 4.5 Hz, 1 H), 7.19–7.34 (m, 5 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 15.4 (d, J_{PC} = 2.1 Hz), 16.4 (d, J_{PC} = 5.7 Hz), 62.9 (d, J_{PC} = 7.3 Hz), 63.2 (d, J_{PC} = 7.3 Hz), 73.7 (d, J_{PC} = 157.8 Hz), 126.6, 127.8, 128.1, 128.9 (d, J_{PC} = 2.5 Hz), 133.9 (d, J_{PC} = 4.0 Hz), 137.3 (d, J_{PC} = 3.0 Hz).

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 22.82.

Anal. Calcd for $C_{14}H_{21}O_4P$: C, 59.13; H, 7.45. Found: C, 59.41; H, 7.35.

Diethyl [1-Hydroxy-3-(*o*-nitrophenyl)allyl]phosphonate (1e)
Yellow solid; mp 99 °C (*n*-hexane–EtOAc).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.30 (t, J_{HP} = 7.5 Hz, 3 H), 1.31 (t, J_{HP} = 7.5 Hz, 3 H), 4.10–4.30 (m, 4 H), 4.65–4.82 (m, 1 H), 5.20 (t, J = 5.8 Hz, 1 H, OH), 6.31 (dt, J = 5.3, 15.7 Hz, 1 H), 7.15–7.30 (m, 1 H), 7.35–7.63 (m, 3 H), 7.87 (d, J = 7.8 Hz, 1 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.4 (d, J_{PC} = 5.7 Hz), 63.2 (d, J_{PC} = 7.5 Hz), 63.6 (d, J_{PC} = 7.5 Hz), 69.1 (d, J_{PC} = 161.0 Hz), 124.4, 127.1 (d, J_{PC} = 13.2 Hz), 128.2, 128.3, 128.9 (d, J_{PC} = 2.5 Hz), 129.9 (d, J_{PC} = 4.4 Hz), 132.1 (d, J_{PC} = 3.1 Hz), 147.7.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 21.53.

Anal. Calcd for $C_{13}H_{18}NO_6P$: C, 49.51; H, 8.76; N, 4.44. Found: C, 49.32; H, 8.55; N, 4.40.

Diethyl (1-Hydroxy-1-methyl-3-phenylallyl)phosphonate (1f)
Colorless oil.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.24–1.35 (m, 6 H), 1.60 (d, J_{HP} = 15.5 Hz, 3 H), 4.00–4.30 (m, 4 H), 4.21 (br, 1 H, OH), 6.34 (dd, J = 4.25, 16.0 Hz, 1 H), 6.78 (dd, J = 5.0, 16.0 Hz, 1 H), 7.19–7.38 (m, 5 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.4 (d, J_{PC} = 5.0 Hz), 23.9, 63.1 (d, J_{PC} = 7.5 Hz), 63.4 (d, J_{PC} = 7.5 Hz), 72.5 (d, J_{PC} = 161.6 Hz), 126.6 (d, J_{PC} = 1.6 Hz), 124.5, 128.5, 129.5, 129.7 (d, J_{PC} = 10.4 Hz), 136.7 (d, J_{PC} = 3.1 Hz).

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 24.66.

Anal. Calcd for $C_{14}H_{21}O_4P$: C, 59.13; H, 7.45. Found: C, 59.00; H, 7.28.

Diethyl {3-[*p*-(Dimethylamino)phenyl]-1-hydroxyallyl}phosphonate (1g)
Yellow solid; mp 99 °C (*n*-hexane–EtOAc).

^{1}H NMR (250 MHz, DMSO-d_6): δ = 1.17–1.23 (m, 6 H), 2.88 (s, 6 H), 3.95–4.09 (m, 4 H), 4.46 (dd, J = 6.7 Hz, J_{HP} = 13.5 Hz, 1 H), 5.76 (br, 1 H, OH), 5.95 (dt, J = 5.5, 15.7 Hz, 1 H), 6.54 (dd, J = 4.5, 16.0 Hz, 1 H), 6.66 (d, J = 8.5 Hz, 2 H), 7.24 (d, J = 8.5 Hz, 2 H).

^{13}C NMR (63 MHz, DMSO-d_6): δ = 16.4 (d, J_{PC} = 3.8 Hz), 38.8, 62.5 (d, J_{PC} = 6.9 Hz), 62.8 (d, J_{PC} = 6.9 Hz), 68.8 (d, J_{PC} = 165.4 Hz), 112.7, 120.6 (d, J_{PC} = 3.8 Hz), 124.5 (d, J_{PC} = 2.5 Hz), 127.8, 132.1 (d, J_{PC} = 13.2 Hz), 150.5.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 22.98.

Anal. Calcd for $C_{15}H_{24}NO_4P$: C, 57.48; H, 7.72; N, 4.47. Found: C, 57.35; H, 7.55; N, 4.63.

Dibenzyl (1-Hydroxy-3-phenylallyl)phosphonate (1h)
White solid; mp 138 °C (*n*-hexane–EtOAc).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 3.00 (br, 1 H, OH), 4.70 (dd, J = 6.5 Hz, J_{HP} = 12.5 Hz, 1 H), 5.05–5.30 (m, 4 H), 6.30 (dt, J = 6.0, 16.0 Hz, 1 H), 6.65 (dd, J = 4.8, 15.8 Hz, 1 H), 7.20–7.35 (m, 15 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 68.5 (d, J_{PC} = 3.1 Hz), 68.6 (d, J_{PC} = 3.1 Hz), 71. 4 (d, J_{PC} = 161.7 Hz, 1 H), 123.3 (d, J_{PC} = 4.8 Hz), 126.7, 128.1, 128.6 (d, J_{PC} = 4.4 Hz), 128.6, 128.6, 132.3, 134.9, 136.3.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 22.67.

Anal. Calcd for $C_{23}H_{23}O_4P$: C, 70.02; H, 5.88. Found: C, 69.85; H, 5.60.

[1-(Dimethylamino)allyl]phosphonates 2; General Procedure
N,*N*-Dimethylformamide diethyl acetal (4 mmol) was added to a mixture of compound **1** (2 mmol) in xylene (10 mL) and the soln was stirred for 18–24 h at reflux. Evaporation of the solvent and chromatography (silica gel, EtOAc–*n*-hexane, 5:5) gave the pure products as colorless oils. All products gave satisfactory spectral data in accord with the assigned structures.

Diethyl [1-(Dimethylamino)-3-phenylallyl]phosphonate (2a)
Colorless oil.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.17–1.30 (m, 6 H), 2.40 (s, 6 H), 3.44 (dd, J = 9.5 Hz, J_{HP} = 21.5 Hz, 1 H), 4.00–4.18 (m, 4 H), 6.21–6.34 (m, 1 H), 6.56 (dd, J = 2.8 Hz, J_{HP} = 15.8 Hz, 1 H), 7.18–7.36 (m, 5 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.4, 16.5, 43.0, 62.2, 62.5, 66.0 (d, J_{PC} = 158.4 Hz), 119.8, 126.5, 127.9, 128.6, 136.2, 136.5.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 23.94.

Anal. Calcd for $C_{15}H_{24}NO_3P$: C, 60.58; H, 8.14; N, 4.71. Found: C, 60.35; H, 8.15; N, 4.45.

Diethyl [1-(Dimethylamino)-3-(3-phenoxyphenyl)allyl]phosphonate (2b)
Colorless oil.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.26–1.37 (m, 6 H), 2.47 (s, 6 H), 3.50 (dd, J = 9.3 Hz, J_{HP} = 21.3 Hz, 1 H), 4.06–4.25 (m, 4 H), 6.25–6.38 (m, 1 H), 6.60 (dd, J_{HP} = 3.0 Hz, J = 15.8 Hz, 1 H), 6.90–7.38 (m, 9 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.5, 16.6, 43.1, 62.3, 62.5, 66.1 (d, J_{PC} = 157.3 Hz), 117.0, 118.3, 118.9, 120.9, 121.5, 123.4, 129.8, 138.2, 157.0, 157.8.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 23.87.

Anal. Calcd for $C_{21}H_{28}NO_4P$: C, 64.75; H, 7.25; N, 3.60. Found: C, 64.35; H, 7.15; N, 3.40.

Diethyl [1-(Dimethylamino)-3-(3-methoxyphenyl)allyl]phosphonate (2c)
Colorless oil.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.19–1.34 (m, 6 H), 2.47 (s, 6 H), 3.50 (dd, J = 9.3 Hz, J_{HP} = 21.3 Hz, 1 H), 3.82 (s, 3 H), 4.08–4.39 (m, 4 H), 6.22–6.39 (m, 1 H), 6.82 (dd, J_{HP} = 3.8 Hz, J = 16.0 Hz, 1 H), 6.89–7.38 (m, 4 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.5, 16.6, 41.9, 55.4, 62.3, 62.5, 66.1 (d, J_{PC} = 158.4 Hz), 114.4, 117.7, 122.1, 123.4, 129.9, 130.2, 138.2, 155.8.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 24.71.

Anal. Calcd for $C_{16}H_{26}NO_4P$: C, 58.69; H, 8.01; N, 4.28. Found: C, 58.55; H, 8.15; N, 4.35.

Diethyl [1-(Dimethylamino)-2-methyl-3-phenylallyl]phosphonate (2d)
Colorless oil.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.26–1.35 (m, 6 H), 1.99 (d, J_{HP} = 2.0 Hz, 3 H), 2.78 (s, 6 H), 3.59 (d, J_{HP} = 15.5 Hz, 1 H), 4.07–4.22 (m, 4 H), 6.66 (d, J_{HP} = 4.5 Hz, 1 H), 7.19–7.33 (m, 5 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 13.2, 16.5, 16.6, 44.8, 62.4 (d, J_{PC} = 6.9 Hz), 62.7 (d, J_{PC} = 6.9 Hz), 65.9 (d, J_{PC} = 176.1 Hz), 126.7, 128.1, 129.0, 130.1, 137.2.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 24.42.

Anal. Calcd for $C_{16}H_{26}NO_3P$: C, 61.70; H, 8.42; N, 4.50. Found: C, 61.58; H, 8.35; N, 4.30.

Diethyl {3-(Dimethylamino)-3-[4-(dimethylamino)phenyl]prop-1-enyl}phosphonate (3)
Colorless oil.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.23–1.31 (m, 6 H), 2.18 (s, 6 H), 2.93 (s, 6 H), 3.47–4.26 (m, 5 H), 5.81 (dd, J = 17.3 Hz, J_{HP} = 26.5 Hz, 1 H), 6.67 (d, J = 8.8 Hz, 2 H), 6.85 (ddd, J = 8.0, 17.3 Hz, J_{HP} = 21.8 Hz, 1 H), 7.11 (d, J = 8.8 Hz, 2 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 16.5, 16.6, 43.6, 60.6, 61.6, 73.9 (d, J_{PC} = 22.0 Hz), 112.9, 117.3 (d, J_{PC} = 182.4 Hz), 128.00, 128.7, 150.25, 154.20.

^{31}P NMR (101 MHz, $CDCl_3$–H_3PO_4): δ = 18.87.

Anal. Calcd for $C_{17}H_{29}N_2O_3P$: C, 59.97; H, 8.59; N, 8.23. Found: C, 59.80; H, 8.63; N, 8.13.

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