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ISOMERIZATION OF DIETHYL 1-ALKYNYLPHOSPHONATES TO 1,3-DIENYLPHOSPHONATES FOLLOWED BY DIELS-ALDER REACTION WITH DEAD, MALEIC ANHYDRIDE AND MALEIMIDE†

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† Dedicated to Prof. Dr. Albert Eschenmoser on occasion of his 85th birthday.

Abstract – Isomerization of diethyl 1-alkynylphosphonates, **1**, with $Pd[(PPh)_3]_4$ in refluxing 1,4-dioxane provides 1,3-dienylphosphonates, **2**, in satisfactory to excellent isolated yield (45-83%). The reaction is tolerant of chlorides and cyclic substituents. Cycloaddition reaction of **2** with DEAD provided the corresponding diethyl 3-(diethoxyphosphoryl)-6-alkyl-3,6-dihydropyridazine-1,2-dicarboxylates, **3**, in 85% isolated yield. The cycloaddition products can be obtained in a one-pot reaction directly from the isomerized 1-alkynylphosphonates with no loss in yields. Similarly, 1,3-dioxo-1,3,3a,4,7,7a-hexahydroisobenzofuran-4-ylphosphonate, and 1,3-dioxo-2,3,3a,4,7,7a-hexahydro-1*H*-isoindol-4-ylphosphonate **4** were obtained by reacting 1,3-dienylphosphonates with maleic anhydride and maleimide respectively.

INTRODUCTION

1,3-Dienylphosphonates are interesting compounds that undergo a variety of reactions including

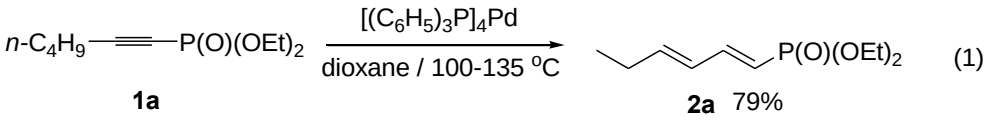
1,3-additions,[1] cycloaddition with CH_2N_2,[2] [2 + 2] cycloadditions,[3] and enolate alkylations.[4] We have previously prepared 1,3-dienylphosphonates by alkyne insertion into zirconacyclopropenes.[5] They have also been prepared by reaction of unsaturated cyanophosphonates with *N*-tosylsulfonylimines,[6] by nickel-catalyzed addition of P(O)-H bonds to propargyl alcohols,[7] by Knoevenagel reaction,[3] and by procedures similar to the preparation of vinylphosphonates.[8]

1-Alkynylphosphonates are a readily available group of compounds.[9] Isomerization of alkynes to 1,3-dienes by metal catalysis is a known process.[10,11] Isomerization of 1-alkynylphosphonates to 1,3-dienylphosphonates is essentially unknown. In this paper we discuss our results on the isomerization of 1-alkynylphosphonates to 1,3-dienylphosphonates under a variety of conditions. We also explored a one-pot isomerization/Diels-Alder reaction of 1-alkynylphosphonates with DEAD to give diethyl 3-(diethoxyphosphoryl)-6-alkyl-3,6-dihydropyridazine-1,2-dicarboxylates.[12]

RESULTS AND DISCUSSION

Isomerization

When **1a** was heated in refluxing dioxane in the presence of a $Pd[(PPh_3)]_4$, **2a** was isolated in very good yield (eq. 1).



Equation 1. Isomerization of **1a** to **2a**

Various palladium and other metal catalysts in different solvents were investigated but in all cases either no reaction occurred or a complex reaction mixture was obtained as shown in Table 1. Even under similar conditions, except for using different palladium catalysts, $Pd[(PPh)_3]_4$ was most successful (entries 2, 5). In addition, attempts to activate catalysts containing carbonyl ligands such as ($Ru_3(CO)_{12}$, $Mo(CO)_6$) by activation with $(CH_3)_3NO$ (TMANO) were also unsuccessful.

Table 1. Yields of **2a** using different catalysts and solvents

Run	Catalyst	Solvent[a]/ Temp.	Yield %
1	$Pd[(PPh)_3]_4$	dioxane/reflux	83
2	$Pd[(PPh)_3]_4$	toluene/reflux	79
3	$Pd_2(dba)_3$	MeCN/reflux	[f]0
4	$Pd_2(dba)_3$	dioxane/reflux	[f]0
5	[b]$Pd_2(dba)_3$	toluene/reflux	30
6	$Pd(acac)_2$	MeCN/reflux	[f]0
7	$Pd(acac)_2$	dioxane/reflux	[f]0
8	palladium 5% carbon	MeCN/reflux	[f]0
9	palladium 5% carbon	dioxane/reflux	[f]0
10	palladium 5% $Ca(CO_3)_2$	MeCN/reflux	[f]0
11	palladium 5% $Ca(CO_3)_2$	dioxane/reflux	[f]0
12	[g]$Pd(OAc)_2$ / $4PPh_3$ /allyl acetate	xylene /reflux	80
13	[c]APC	MeCN/reflux	[f]0
14	[c]APC	dioxane/reflux	[f]0
15	$PdCl_2$	MeCN/reflux	[f]0
16	$PdCl_2$	dioxane/reflux	[f]0
17	$Ru_3(CO)_{12}$	MeCN/reflux	[f]0
18	$Ru_3(CO)_{12}$	dioxane/reflux	[f]0
19	$Ru_3(CO)_{12}$ + TMANO[d]	MeCN/reflux	[e]0
20	$Ru_3(CO)_{12}$ + TMANO[d]	dioxane/reflux	[e]0
21	Nickel(II) $(acac)_2$	MeCN/reflux	[f]0
22	Nickel(II) $(acac)_2$	dioxane/reflux	[f]0
23	$Mo(CO)_6$ + TMANO[d]	MeCN/reflux	[e]0
24	$Mo(CO)_6$ + TMANO[e]	dioxane/reflux	[e]0
25	rhodium 5% on alumina	MeCN/reflux	[f]0
26	rhodium 5% on alumina	dioxane/reflux	[f]0

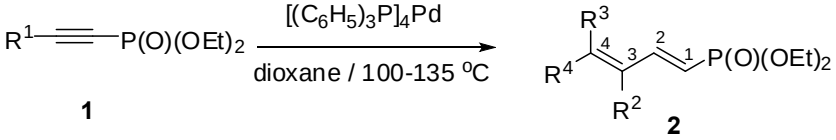
[a]Conditions:1-hexynylphosphonate (1mmol.), catalyst (0.1 mmol.) solvent (1 mL) at reflux for 1.5-3.5 h. [b]Alkynylphosphonate (1 mmol.), acetic acid (1 mL), $(i\text{-Pr})_3P$ (0.2 mmol.), $Pd_2(dba)_3CHCl_3$ (0.05 mmol.), toluene (5 mL) 110 °C for 3 h according to reference 12. [c]allylpalladium(II) chloride dimer $[C_3H_5PdCl]_2$). [d] [e]TMANO (trimethylamine *N*-oxide) (0.1 eq). [e]Starting alkyne consumed to give complex reaction mixture with no trace of **2a**. [f]Starting alkyne recovered intact. [g]According to: H. Yasui, H. Yorimitsu, and K. Oshima, *Synlett*, 2006, 1783.

The optimized conditions were then applied to a series of 1-alkynylphosphonates **1** (Table 2). The reaction proceeds in satisfactory yields (45-85%) and is tolerant of halogenated (**1d**), cyclic **1h-i**, short and long chain alkynylphosphontes. All the reactions were carried out in dioxane at (100 - 135 °C) except

2d which was carried out in toluene. The reaction time was variable from 1.5 h (**2d**) to 5 h (**2a**) (see experimental).

The stereochemistry of the products **2a-i** was determined by NMR coupling constants. The $^3J_{PC}$ of the C3 carbon (26.4-29.2 Hz) and $^3J_{PH}$ of the hydrogen on C2 (21.2-35.4) are indicatives that C3 is *trans* to phosphorous and that the hydrogen on C2 is *cis*. Moreover, the hydrogens on (26.4-29.2 Hz) and $^3J_{PH}$ of the hydrogen on C2 (21.2-35.4) are indicatives that C3 is *trans* to phosphorous and that the hydrogen on C2 is *cis*. Moreover, the hydrogens on C3 and C4 are *trans*, and consequently C3-C4 double bond has *E* stereochemistry. Thus, the 1,3-dienylphosphonates **2** have *E*, *E* stereochemistry.[5]

Table 2. Isomerization of 1-alkynylphosphonates to 1,3-butadienylphosphonates , **2**, with $Pd[(PPh_3)]_4$ in dioxane

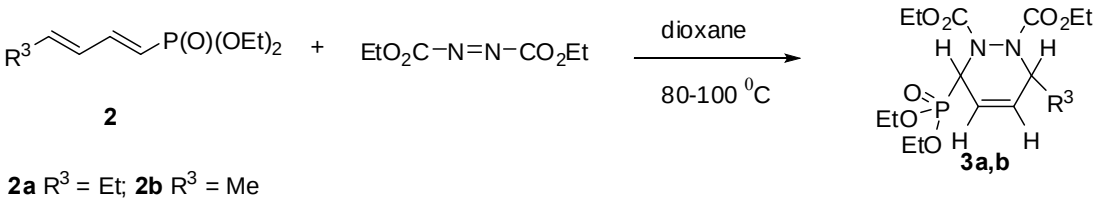


Entry	R^1	R^2	R^4	R^3	Isolated yield[a] %
2a	*n*-butyl	H	H	ethyl	83
2b	*n*-propyl	H	H	methy	83
2c	dodecyl	H	H	decyl	85
2d	4-Cl-*n*-butyl	H	H	2-Cl-ethyl	79
2e	*n*-pentyl	H	H	n-propyl	81
2f	tetradecyl	H	H	dodecyl	72
2g	hexadecyl	H	H	tetradecyl	70
2h	cyclohexyl	tetramethylene		H	45
2i	(cyclohexyl)methyl	H	cyclohexylidene		68

[a]Conditions: 1-alkynylphosphonate (1mmol), catalyst (0.1 mmol), solvent (1 mL) at reflux for 1.5-3.5 h (see experimental).

Diels-Alder reaction of 2 with DEAD

The 1,3-dienylphosphonates **2** were further utilized by investigating their reactivity with diethyl azodicarboxylate (DEAD). Cycloaddition products **3a** and **3b** were obtained by reacting **2b** and **2a** with DEAD respectively. Starting either from pure or *in situ* prepared 1,3-dienylphosphonates **2a**-**b**, the cyclic products **3** were successfully obtained in 85% yield (Scheme 1).



2

2a R^3 = Et; **2b** R^3 = Me

Scheme 1. Cyclization of **2** and DEAD to give **3a,b**

The structure and the stereochemistry of the cycloaddition products were confirmed by 2D-COSY, ^{1}H, and ^{13}C NMR. The cyclohexene-like nature of the six-membered ring system tetrahydropyridazines is generally regarded to have a half chair configuration based on the relationship between vicinal coupling constants and dihedral angles.[13] According to 2D-COSY NMR no coupling between the hydrogen on C4 at ~ 4 ppm and the neighboring vinylic hydrogen at 5.84 ppm was observed (this numbering is just to be consistent with 1,3-dienylphosphonates numbering). Thus, based on the Karplus relation, the ~ 0 Hz coupling constant corresponds to a dihedral angle of ~ 90 º between the hydrogens on C4 and C3. On the other hand, the doublet of doublet in the region 5.07 ppm corresponds to the allylic hydrogen on C1 split by phosphorus and hydrogen of C2 at 5.99 ppm with a coupling constant $^3J_{HH}$ of 4.2 Hz that corresponds to a dihedral angle of ~ 45 º between the hydrogen on C1 and the adjacent vinylic hydrogen on C2.[13,14] Thus, the methyl group is in a quasi equatorial configuration, whilst the phosphorus group is in a quasi axial configuration as shown in Figure 1.

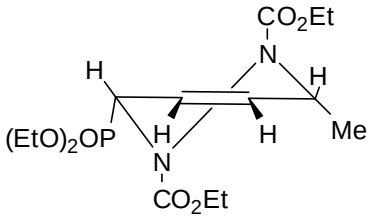


Figure 1. Conformation of compound **3a**

Regarding the ethyl carboxylate groups on the nitrogen atoms, we suggest that they are *trans* axial due to steric factors and energetic stability. This proposed stereochemistry of the cycloaddition compounds is consistent with the literature.[15] A Newman's projection conformation for compound **3a** is presented in Figure 2.

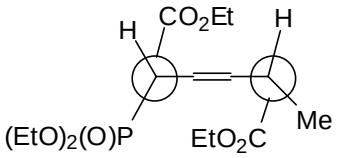
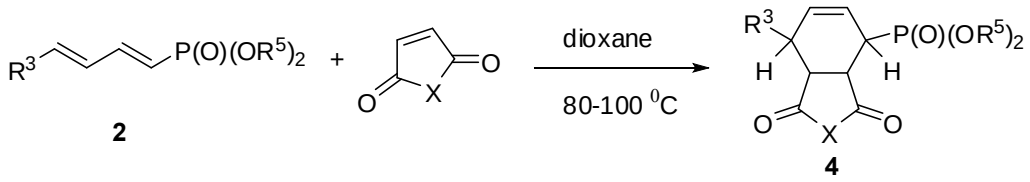


Figure 2. Partial Newman projection of **3a.**

In a similar manner, various other Diels Alder products were obtained in good yields (Table 3) as a result of reacting 1,3-dienylphosphonates **2** with maleic anhydride and maleimide as shown in scheme 2.



Scheme 2. Diels-Alder reaction between **2** and dienophiles

Table 3. Yiels of Diels-Alder adducts of Maleic anhydride and Maleimide

Entry	R^3	R^5	X	Isolated yield Mass (mgr), %
4a	Et	Et	O	262 , 83
4b	Me	Et	O	242 , 80
4c	dodecyl	Et	O	306 , 67
4d	decyl	Et	O	300 , 70
4e	Me	Et	NH	244 , 81
4f	dodecyl	Et	NH	282 , 62
4g	Et	Ph	O	301 , 73

CONCLUSIONS

Various 1,3-butadienylphosphontates have been obtained by isomerization of 1-alkynylphosphonates in good isolated yields. This reaction was studied under many different catalysts and conditions, but it proceeded only when $[(C_6H_5)_3P]_4Pd$ is used in dioxane at reflux. Interestingly, the products 1,3-butadienylphosphontates reacted efficiently either pure or in a one-pot reaction with DEAD to produce diethyl 3-(diethoxyphosphoryl)-6-alkyl-3,6-dihydropyridazine-1,2-dicarboxylates. Reactions of some of the 1,3-dienes was also satisfactory, in terms of reaction times and yields, with two other dienophiles: maleic anhydride and maleimide.

EXPERIMENTAL

Typical procedure for the synthesis of diethyl (1*E*,3*E*)-hexa-1,3-dienylphosphonate (2a). To (0.116 g, 0.1 mmol) of $[(C_6H_5)_3P]_4Pd$ dissolved in dioxane (1 mL) in a screw caped vial were added (1mmol) of **1** under nitrogen atmosphere. After reflux for the required amount of time, the solvent was evaporated and the product was isolated by silica gel column chromatography using (30% EtOAc: 70% petroleum ether) and was analyzed by GCMS, elemental analysis, and NMR spectroscopy.

Diethyl (1*E*,3*E*)-hexa-1,3-dienylphosphonate (2a). ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 1.01 (3H, $C\underline{H}_3CH_2CH$, t, J_{HH} = 7.5 Hz), 1.29 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 7.2 Hz), 2.15 (2H, $CH_3C\underline{H}_2CH$, m), 4.04 (4H, $OC\underline{H}_2CH_3$, qn), 5.51 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 19.5 Hz, J_{HH} = 16.8 Hz), 6.00-6.12 (2H, CH_2-C<u>H</u>=C<u>H</u>-CH, m), 7.04 (1H, CH-C<u>H</u>=CH-P, ddd, $^{3}J_{PH}$ = 21.4 Hz, J_{HH} = 17.4 Hz). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 21.06. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 13.0, 16.6 (d, $^{3}J_{PC}$ = 6.6 Hz), 26.0, 61.8 (d, $^{3}J_{PC}$ = 5.1 Hz), 114.5 (d, $^{1}J_{PC}$ = 191.7 Hz), 128.6 (d, $^{3}J_{PC}$ = 26.7 Hz), 145.5, 149.6 (d, $^{2}J_{PC}$ = 6.3 Hz). MS (EI): *m/z* (%) 109.0 (76.9), 111.0 (70.0), 137.0 (76.9), 161.1 (56.5), 189.1 (59.3), 190.2 (49.1), 191.1 (39.8), 218.2 (100). Anal. Calcd for $C_{10}H_{19}O_3P$: C, 54.54; H, 8.64; P, 14.22. Found: C, 54.51; H, 8.55; P, 14.18.

Diethyl (1*E*,3*E*)-penta-1,3-dienylphosphonate (**2b).** Synthesis identical to procedure **2a** except refluxed for 3.5 h. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 1.26 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 7.2 Hz), 1.80 (3H, $C\underline{H}_3$-CH=CH, d, J_{HH} = 6.0 Hz), 4.03 (4H, $OC\underline{H}_2CH_3$, qn), 5.51 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 16.8 Hz, J_{HH} = 16.2 Hz), 6.00-6.12 (2H, CH_3-C<u>H</u>=C<u>H</u>, m), 7.04 (1H, CH-C<u>H</u>=CH-P, ddd, $^{3}J_{PH}$ = 21.2 Hz, J_{HH} = 17.2 Hz); ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 21.20. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 16.6 (d, $^{3}J_{PC}$ = 6.6 Hz), 18.7, 61.8 (d, $^{3}J_{PC}$ = 5.2 Hz), 114.4 (d, $^{1}J_{PC}$ = 191.5 Hz), 131.0 (d, $^{3}J_{PC}$ = 26.4 Hz), 138.8, 149.4 (d, $^{2}J_{PC}$ = 6.0 Hz). MS (EI): *m/z* (%) 110.9 (32.4), 130.7 (38.5), 132.7 (58.3), 148.0 (55.6), 158.8 (21.3), 175.8 (39.8), 189.0 (14.8), 204.0 (100). Anal. Calcd for $C_9H_{17}O_3P$: C, 52.94; H, 8.33; P, 15.20. Found: C, 52.88; H, 8.28; P, 15.16.

Diethyl (1*E*,3*E*)-tetradeca-1,3-dienylphosphonate (**2c).** Synthesis identical to procedure **2b**. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.85 (3H, $C\underline{H}_3$-CH_2-CH_2, t, J_{HH} = 7.2 Hz), 1.29 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 6.9 Hz), 1.20-1.40 (16H, CH_3-($C\underline{H}_2$)$_8$-CH_2, overlap), 2.10 (2H, CH_2-C<u>H</u>$_2$-CH, q, J_{HH} = 6.9 Hz), 4.04 (4H, $OC\underline{H}_2CH_3$, qn), 5.52 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 19.5 Hz, J_{HH} = 17.1 Hz), 6.00-6.10 (2H, CH_2-C<u>H</u>=C<u>H</u>, m), 7.04 (1H, CH-C<u>H</u>=CH-P, ddd, $^{3}J_{PH}$ = 27.9 Hz, J_{HH} = 9.6 Hz, J_{HH} = 4.2 Hz). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 21.03. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 14.3, 16.3 (d, $^{3}J_{PC}$ = 6.3 Hz), 22.9, 28.9, 29.4, 29.5, 29.6, 29.8, 29.9, 32.1, 33.0, 61.5 (d, $^{3}J_{PC}$ = 5.4 Hz), 114.1 (d, $^{1}J_{PC}$ = 192.0 Hz), 129.3 (d, $^{3}J_{PC}$ = 26.7 Hz), 144.0, 149.4 (d, $^{2}J_{PC}$ = 6.3 Hz). MS (EI): *m/z* (%) 124.9 (27.8), 137.8 (45.6), 151.9 (99.5), 160.9 (62.9), 189.0 (70.4), 204.1 (59.3), 217.0 (100), 231.1 (25.0), 259.2 (24.7), 273.2 (21.3), 287.2 (13.7), 301.3 (11.1), 330.3 (50.9). Anal. Calcd for $C_{18}H_{35}O_3P$: C, 65.45; H, 10.61, 9.39. Found: C, 65.40; H, 10.55; P, 9.33.

Diethyl (1*E*,3*E*)-6-chlorohexa-1,3-dienylphosphonate (**2d).** Synthesis identical to procedure **2a** except refluxed in toluene for 1.5 h. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 1.29 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 7.2 Hz), 2.62 (2H, $ClCH_2$-C<u>H</u>$_2$-CH, q, J_{HH} = 6.9 Hz), 3.56 (2H, $ClC\underline{H}_2$, t, J_{HH} = 6.9 Hz), 4.06 (4H, $OC\underline{H}_2CH_3$, qn), 5.63 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 19.2 Hz, J_{HH} = 17.1 Hz), 6.05-6.23 (2H, CH_2-C<u>H</u>=C<u>H</u>, m), 7.05 (1H,

CH-C<u>H</u>=CH-P, ddd, J_{HH} = 10.5 Hz, J_{HH} = 3.9 Hz $^{3}J_{PH}$ = 27.3 Hz). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 20.17. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 16.3 (d, $^{3}J_{PC}$ = 6.6 Hz), 35.6, 43.1, 61.7 (d, $^{3}J_{PC}$ = 5.4 Hz), 116.4 (d, $^{1}J_{PC}$ = 191.5 Hz), 132.0 (d, $^{3}J_{PC}$ = 27.0 Hz), 138.0, 148.2 (d, $^{2}J_{PC}$ = 6.0 Hz). MS (EI): MS (EI): *m/z* (%) 128.8 (16.7), 132.8 (57.4), 146.8 (25.9), 160.9 (100), 189.0 (85.2), 217.0 (94.4), 252.1 (21.3), 254.2 (16.9). Anal. Calcd for $C_{10}H_{18}ClO_3P$: C, 47.52; H, 7.13; Cl, 14.06; P, 12.28. Found: C, 47.47; H, 7.09; Cl, 14.01 P, 12.25.

Diethyl (1*E*,3*E*)-hepta-1,3-dienylphosphonate (**2e).** Synthesis identical to procedure **2a** except refluxed for 3 h. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.91 (3H, C<u>H</u>$_3$-CH_2-CH_2, t, J_{HH} = 7.5 Hz), 1.32 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 6.9 Hz), 1.45 (2H, CH_3-C<u>H</u>$_2$-CH_2, m), 2.12 (2H, CH_2-C<u>H</u>$_2$-CH, q, J_{HH} = 7.2 Hz), 4.07 (4H, OC<u>H</u>$_2CH_3$, qn), 5.51 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 19.5 Hz, J_{HH} = 17.1 Hz), 6.00-6.18 (2H, CH_2-C<u>H</u>=C<u>H</u>, m), 7.04 (1H, CH-C<u>H</u>=CH-P, ddd, $^{3}J_{PH}$ = 28.0 Hz, J_{HH} = 9.6 Hz, J_{HH} = 4.2 Hz). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 21.05. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 13.7, 16.3 (d, $^{3}J_{PC}$ = 6.6 Hz), 21.9, 34.8, 61.6 (d, $^{3}J_{PC}$ = 5.2 Hz), 114.3 (d, $^{1}J_{PC}$ = 191.8 Hz), 129.5 (d, $^{3}J_{PC}$ = 26.7 Hz), 143.8, 149.4 (d, $^{2}J_{PC}$ = 6.0 Hz). MS (EI): *m/z* (%) 110.9 (40.4.9), 132.8 (57.8), 160.9 (78.0), 175.0 (43.1), 189.0 (54.1), 203.0 (41.8), 204.1 (27.9), 232.1 (100). Anal. Calcd for $C_{11}H_{21}O_3P$: C, 56.90; H, 9.05; P, 13.36. Found: C, 56.85; H, 8.99; P, 13.29.

Diethyl (1*E*,3*E*)-hexadeca-1,3-dienylphosphonate (**2f).** Synthesis identical to procedure **2a** except refluxed for 2 h. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.83 (3H, C<u>H</u>$_3$-CH_2-CH_2, t, J_{HH} = 7.2 Hz), 1.28 ($OCH_2C\underline{H}_3$, 6 H, t, J_{HH} = 7.2 Hz), 1.15-1.42 (20H, CH_3-(C<u>H</u>$_2$)$_{10}$-CH_2, overlap), 2.09 (2H, CH_2-C<u>H</u>$_2$-CH, q, J_{HH} = 6.9 Hz), 4.03 (4H, OC<u>H</u>$_2CH_3$, qn, J_{HH} = 3.9 Hz), 5.52 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 19.5 Hz, J_{HH} = 16.5 Hz), 6.07-6.14 (2H, CH_2-C<u>H</u>=C<u>H</u>, m), 7.04 (1H, CH-C<u>H</u>=CH-P, ddd, $^{3}J_{PH}$ = 35.4 Hz, J_{HH} = 9.6 Hz, J_{HH} = 4.2 Hz). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 21.11. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 14.3, 16.6 (d, $^{3}J_{PC}$ = 6.3 Hz), 22.6, 28.1, 28.6, 29.1, 29.2, 29.3, 29.4, 29.5, 29.6, 29.7, 31.8, 61.5 (d, $^{3}J_{PC}$ = 5.4 Hz), 114.1 (d, $^{1}J_{PC}$ = 192.0 Hz), 129.2 (d, $^{3}J_{PC}$ = 26.7 Hz), 144.1, 149.3 (d, $^{2}J_{PC}$ = 6.3 Hz). MS (EI): *m/z* (%) 110.9 (21.1), 135.0 (32.1), 138.0 (38.5), 151.9 (100), 160.9 (42.2), 189.0 (40.4), 204.2 (36.7), 217.1 (62.4), 259.3 (18.3), 273.3 (16.5), 287.3 (11.9), 315.3 (9.2), 329.5 (9.2),358.5 (39.4). Anal. Calcd for $C_{20}H_{39}O_3P$: C, 67.04; H, 10.89; P, 8.66. Found: C, 66.99.51; H, 10.87; P, 8.63.

Diethyl (1*E*,3*E*)-octadeca-1,3-dienylphosphonate (**2g).** Synthesis identical to procedure **2a**. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.87 (3H, C<u>H</u>$_3$-CH_2-CH_2, t, J_{HH} = 7.2 Hz), 1.29 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 7.2 Hz), 1.05-1.46 (24H, CH_3-(C<u>H</u>$_2$)$_{12}$-CH_2, m, overlap), 2.11 (2H, CH_2-C<u>H</u>$_2$-CH, q, J_{HH} = 6.6 Hz), 4.03 (4H, OC<u>H</u>$_2CH_3$, qn), 5.34 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 19.5 Hz, J_{HH} = 17.1 Hz), 6.07-6.14 (2H, CH_2-C<u>H</u>=C<u>H</u>, m), 7.04

(1H, CH-C<u>H</u>=CH-P, ddd, $^{3}J_{PH}$ = 27.9 Hz, J_{HH} = 9.6 Hz, J_{HH} = 3.9 Hz). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 21.08. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 14.4, 16.6 (d, $^{3}J_{PC}$ = 6.3 Hz), 22.9, 28.9, 29.4, 29.6, 29.7, 29.8, 29.9, 32.1, 33.0, 61.8 (d, $^{3}J_{PC}$ = 5.7 Hz), 114.4 (d, $^{1}J_{PC}$ = 191.7 Hz), 129.5 (d, $^{3}J_{PC}$ = 26.7 Hz), 144.4, 149.7 (d, $^{2}J_{PC}$ = 6.0 Hz). MS (EI): *m/z* (%) 111.0 (23.6), 125.0 (30.9), 138.0 (36.4), 152.0 (100), 153.1 (31.8), 189.1 (33.6), 204.2 (40.0), 217.2 (60.0), 231.2 (17.3), 259.3 (14.5), 273.3 (14.5), 301.4 (6.4), 341.6 (6.2), 357.7 (6.4) 386.8 (38.2). Anal. Calcd for $C_{22}H_{43}O_3P$: C, 68.39; H, 11.14; P, 8.03. Found: C, 68.31; H, 11.10; P, 7.99.

(*E*)-Diethyl cyclohex-2-enylidenemethylphosphonate (**2h).** Synthesis identical to procedure **2a**. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 1.32 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 6.9 Hz), 1.60-1.72 (4H, CH_2-$C\underline{H}_2$-$C\underline{H}_2$-CH_2, overlap), 2.12 (2H, CH_2-$C\underline{H}_2$-C, broad t), 2.19 (2H, CH_2-$C\underline{H}_2$-CH, m), 4.07 (4H, $OC\underline{H}_2CH_3$, qn), 5.34 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 19.0 Hz, J_{HH} = 18.0 Hz), 6.02 (1H, CH_2-C<u>H</u>-C, dd, J_{HH} = 7.4 Hz, J_{HH} = 7.9 Hz), 6.96 (1H, C-C<u>H</u>=CH, ddd, $^{3}J_{PH}$ = 22.5 Hz, J_{HH} = 17.4 Hz). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 20.03. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 16.4 (d, $^{3}J_{PC}$ = 6.6 Hz), 22.0, 23.8, 26.3, 30.1, 61.6 (d, $^{3}J_{PC}$ = 5.1 Hz), 109.3 (d, $^{1}J_{PC}$ = 191.7 Hz), 131.6 (d, $^{3}J_{PC}$ = 29.2 Hz), 138.3, 152.4 (d, $^{2}J_{PC}$ = 6.6 Hz); MS (EI): *m/z* (%) 106.0 (44.4), 135.1 (25.9), 151.0 (9.3), 169.0 (21.8), 187.0 (50.1), 188.1 (94.4), 215.2 (23.1), 216.2 (47.2), 244.2 (100). Anal. Calcd for $C_{12}H_{21}O_3P$: C, 59.02; H, 8.61; P, 12.70. Found: C, 58.97; H, 8.59; P, 12.66.

(*E*)-Diethyl 3-cyclohexylideneprop-1-enylphosphonate (**2i).** Synthesis identical to procedure **2a**. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 1.27 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 6.9 Hz), 1.53-1.58 (6H, CH_2-$(C\underline{H}_2)_3$-CH_2, overlap), 2.18 (2H, CH_2-$C\underline{H}_2$-C, broad t), 2.37 (2H, C-$C\underline{H}_2$-CH_2, broad t), 4.07 (4H, $OC\underline{H}_2CH_3$, qn), 5.54 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 20.4 Hz, J_{HH} = 16.8 Hz), 5.90 (1H,C-C<u>H</u>=CH, d, J_{HH} = 11.4 Hz), 6.96 (1H, CH-C<u>H</u>-CH, ddd, $^{3}J_{PH}$ = 26.4 Hz, J_{HH} = 11.4 Hz, J_{HH} = 4.5 Hz). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 21.66. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 16.2 (d, $^{3}J_{PC}$ = 6.4 Hz), 26.3, 27.5, 29.1, 29.9, 37.5, 61.5 (d, $^{3}J_{PC}$ = 5.1 Hz), 113.8 (d, $^{1}J_{PC}$ = 191.2 Hz), 121.8 (d, $^{3}J_{PC}$ = 27.8 Hz), 145.1, 153.6 (d, $^{2}J_{PC}$ = 6.2 Hz). MS (EI): *m/z* (%) 120.0 (100), 121.1 (19.1), 122.0 (5.9), 183.0 (4.5), 201.0 (10.0), 229.1 (9.1), 257.3 (31.8), 258.2 (30.0). Anal. Calcd For $C_{13}H_{23}O_3P$: C, 60.47; H, 8.91; P, 12.02. Found: C, 60.42; H, 8.87; P, 11.99.

Synthesis of diethyl 3-(diethoxyphosphoryl)-6-ethylpyridazine-1,2(3*H*,6*H*)-dicarboxylate (3a). Method A: To 0.218 g (1mmol) of **2a** dissolved in dioxane (1 mL), was added 0.174 g (1 mmol) of diethyl azodicarboxylate (DEAD). After reflux of the reaction mixture for 12 h, the solvent was evaporated and the product was isolated by silica gel column chromatography using a gradient eluent starting from (50% EtOAc: 50% petroleum ether) to pure EtOAc, and was analyzed by GCMS, elemental analysis, and NMR

spectroscopy.

Method B: After synthesis of **2a** as presented above, 0.174 g (1 mmol) of diethyl azodicarboxylate was *in situ* added to the reaction mixture. The mixture was refluxed for 12 h, then the solvent was evaporated and the product was isolated by silica gel column chromatography using a gradient eluent starting from (50% EtOAc: 50% petroleum ether) to pure EtOAc, and was analyzed by GCMS, elemental analysis, and NMR spectroscopy.

Diethyl 3-(diethoxyphosphoryl)-6-ethylpyridazine-1,2(3*H*,6*H*)-dicarboxylate (3a). ^{1}H NMR (300 MHz, CD_3OD, Me_4Si): δ 0.91 (3H, C<u>H</u>$_3$-CH$_2$-CH, t, J_{HH} = 7.5 Hz), 1.13-1.41 (12H, OCH$_2$C<u>H</u>$_3$, COOCH$_2$C<u>H</u>$_3$, overlap), 1.93 (2H, CH$_3$-C<u>H</u>$_2$-CH, m), 3.95-4.60 (9H, CH$_3$-CH$_2$-C<u>H</u>, OC<u>H</u>$_2$CH$_3$, COOC<u>H</u>$_2$CH$_3$, overlap), 5.07 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 25.2 Hz, J_{HH} = 4.2 Hz), 5.84 (1H, CH$_2$-CH-C<u>H</u>=CH, m), 5.99 (1H, CH=C<u>H</u>-CH-P, m). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 19.04. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 8.49, 14.3, 16.2 (d, $^{3}J_{PC}$ = 6.4 Hz), 25.7, 51.9 (d, $^{1}J_{PC}$ = 119.5 Hz), 56.6, 62.4 (d, $^{3}J_{PC}$ = 6.2 Hz), 63.2, 128.8 (d, $^{3}J_{PC}$ = 12.1 Hz), 131.9 (d, $^{2}J_{PC}$ = 12.1 Hz). MS (EI): *m/z* (%) 66.9 (9.2), 80.8 (83.5), 94.0 (11.3), 108.9 (38.5), 111.0 (17.4), 136.9 (80.7), 153.0 (33.9), 155.0 (9.2), 183.0 (100), 184.2 (11.9), 211.1 (11.9), 255.2 (47.7), 256.3 (5.5), 392.5 (1.8). Anal. Calcd For $C_{16}H_{29}N_2O_7P$: C, 48.98; H, 7.40; N, 7.14 P, 7.91. Found: C, 48.88; H, 7.36; N, 7.11 P, 7.87; Isolated yield: 333 mgr, 85%.

Diethyl 3-(diethoxyphosphoryl)-6-methylpyridazine-1,2(3*H*,6*H*)-dicarboxylate (**3b).** Synthesis identical to procedure **3a**. ^{1}H NMR (300 MHz, CD_3OD, Me_4Si): δ 1.13-1.41 (12H, OCH$_2$C<u>H</u>$_3$, COOCH$_2$C<u>H</u>$_3$, overlap), 1.59 (3H, C<u>H</u>$_3$-CH, d, J_{HH} = 6.9 Hz), 3.95-4.40 (9H, CH$_3$-C<u>H</u>, OC<u>H</u>$_2$CH$_3$, COOC<u>H</u>$_2$CH$_3$, overlap), 5.33 (1H, C<u>H</u>-P, dd, $^{2}J_{PH}$ = 20.4 Hz, J_{HH} = 4.2 Hz), 5.75 (1H, CH$_2$-CH-C<u>H</u>=CH, m), 5.95 (1H, CH=C<u>H</u>-CH-P, m). ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 19.06. ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 14.4, 16.3 (d, $^{3}J_{PC}$ = 6.4 Hz), 20.4, 51.0, 52.3 (d, $^{1}J_{PC}$ = 119.5 Hz), 62.5 (d, $^{3}J_{PC}$ = 6.2 Hz), 63.2, 128.4 (d, $^{3}J_{PC}$ = 12.0 Hz), 132.0 (d, $^{2}J_{PC}$ = 10.0 Hz). MS (EI): *m/z* (%) 53.0 (10.9), 81.0 (51.5), 95.0 (21.8), 123.0 (59.4), 153.0 (16.3), 169.0 (100), 197.0 (5.9), 207.0 (15.8), 241.0 (26.7), 378.0 (1.1). Anal. Calcd For $C_{15}H_{27}N_2O_7P$: C, 47.62; H, 7.14; N, 7.41 P, 8.20. Found: C, 47.57; H, 7.12; N, 7.37 P, 8.17. Isolated yield: 321 mgr, 85%.

Diethyl 7-ethyl-1,3-dioxo-1,3,3a,4,7,7a-hexahydroisobenzofuran-4-ylphosphonate (4a). Identical to **3a** except the addition of maleic anhydride and refluxing for 6 hrs. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.92 (3H, C<u>H</u>$_3$CH$_2$CH, t, J_{HH} = 7.1 Hz), 1.26 (6H, OCH$_2$C<u>H</u>$_3$, t, J_{HH} = 7.5 Hz), 1.28 (2H, CH$_3$C<u>H</u>$_2$CH, m), 2.24 (1H, CH$_2$CHC<u>H</u>CO, dd, J_{HH} = 7.5 Hz, J_{HH} = 4.5 Hz), 2.51 (1H, CH$_3$CH$_2$C<u>H</u>, m), 3.39 (1H, COC<u>H</u>CHP, m), 3.47 (1H, C<u>H</u>P, m), 4.10 (4H, OC<u>H</u>$_2$CH$_3$, m), 5.66 (1H, CH$_2$CH-C<u>H</u>=CH, dd, J_{HH} = 6.4 Hz, J_{HH} = 4.5

Hz), 5.81 (m, CH=CH-CHP, 1H). ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 15.2, 16.2 (d, $^3J_{PC}$ = 4.9 Hz), 21.5, 32.1, 33.0 (d, $^2J_{PC}$ = 7.9 Hz), 42.2, 43.1 (d, $^1J_{PC}$ = 160.0 Hz), 60.9 (d, $^2J_{PC}$ = 8.1 Hz), 129.0, 136.2 (d, $^2J_{PC}$ = 8.0 Hz), 176.7, 177.4. ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 31.55. MS (EI): *m/z* (%) 79.0 (36.0), 91.0 (100), 105.0 (85.0), 125.0 (94.0), 152.0 (59.0), 173.0 (31.0), 187.0 (22.0), 201.0 (28.0), 229.0 (69.0), 316.0 (11.0). Anal. Calcd for $C_{14}H_{21}O_6P$: C, 53.16; H, 6.69; P, 9.79. Found: C, 53.11; H, 6.68; P, 9.78.

Diethyl 7-methyl-1,3-dioxo-1,3,3a,4,7,7a-hexahydroisobenzofuran-4-ylphosphonate (4b). Identical to **4a**. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 1.16 (3H, CH_3CH, d, J_{HH} = 7.3 Hz), 1.28 (6H, OCH_2CH_3, t, J_{HH} = 7.3 Hz), 2.25 (1H, CH_3CHCHCO, dd, J_{HH} = 7.6 Hz, J_{HH} = 4.9 Hz), 2.52 (1H, CH_3CH, m), 3.43 (1H, COCHCHP, m), 3.50 (1H, CHP, m), 4.07 (4H, OCH_2CH_3, m), 5.64 (1H, CH_3CH-CH=CH, dd, J_{HH} = 6.8 Hz, J_{HH} = 4.6 Hz), 5.83 (CH=CH-CHP, H^2 m). ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 15.1, 16.2 (d, $^3J_{PC}$ = 5.6 Hz), 31.8, 32.6 (d, $^2J_{PC}$ = 8.6 Hz), 40.1, 40.7 (d, $^1J_{PC}$ = 145.9 Hz), 62.2 (d, $^2J_{PC}$ = 8.6 Hz), 128.2, 133.1 (d, $^2J_{PC}$ = 7.1 Hz), 172.3, 173.4. ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 29.20. MS (EI): *m/z* (%) 51.0 (14.9), 77.0 (63.3), 91.0 (100), 109.0 (97.0), 119.0 (33.7), 138.0 (92.1), 155.0 (19.8), 173.0 (11.9), 302.0 (10.9). Anal. Calcd for $C_{13}H_{19}O_6P$: C, 51.66; H, 6.34; P, 10.25. Found: C, 51.61; H, 6.33; P, 10.24.

Diethyl 7-dodecyl-1,3-dioxo-1,3,3a,4,7,7a-hexahydroisobenzofuran-4-ylphosphonate (4c). Identical to **4a**. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.90 (3H, CH_3CH_2, t, J_{HH} = 7.4 Hz), 1.24 (6H, OCH_2CH_3, t, J_{HH} = 7.7 Hz), 1.26-1.36 (20H, $CH_3(CH_2)_{10}CH_2$, overlap), 1.31 (2H, CH_2CH_2CH, m) 2.26 (1H, CH_2CHCHCO, dd, J_{HH} = 8.1 Hz, J_{HH} = 4.7 Hz), 2.50 (1H, CH_2CH, m), 3.36 (1H, COCHCHP, m), 3.44 (1H, CHP, m), 4.08 (4H, OCH_2CH_3, m), 5.63 (1H, CH_2CH-CH=CH, dd, J_{HH} = 6.4 Hz, J_{HH} = 5.0 Hz), 5.82 (1H, CH=CH-CHP, m). ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 15.0, 16.1 (d, $^3J_{PC}$ = 5.1 Hz), 21.3, 21.4, 25.4, 26.4, 27.2, 29.3, 30.4, 30.8, 33.0, 36.4 (d, $^2J_{PC}$ = 8.0 Hz), 36.6, 44.4, 45.1 (d, $^1J_{PC}$ = 159.9 Hz), 61.6 (d, $^2J_{PC}$ = 8.7 Hz), 128.7, 136.8 (d, $^2J_{PC}$ = 8.4 Hz), 171.5, 171.8. ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 30.83. MS (EI): *m/z* (%) 163.0 (75.2), 178.1 (59.6), 191.1 (100), 205.1 (35.8), 219.1 (45.0), 233.2 (42.2), 247.2 (31.2), 261.2 (27.5), 275.3 (23.9), 303.4 (20.2), 331.5 (23.9), 360.7 (43.1), 411.4 (2.1), 456.2 (0.1). Anal. Calcd for $C_{24}H_{41}O_6P$: C, 63.14; H, 9.05; P, 6.78. Found: C, 63.05; H, 9.04; P, 6.77.

Diethyl 7-decyl-1,3-dioxo-1,3,3a,4,7,7a-hexahydroisobenzofuran-4-ylphosphonate (4d). Identical to **4a**. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.94 (3H, CH_3CH_2, t, J_{HH} = 8.4 Hz), 1.23-1.34 (16H, $CH_3(CH_2)_8CH_2$, overlap), 1.27 (6H, OCH_2CH_3, t, J_{HH} = 8.2 Hz), 1.30 (2H, CH_2CH_2CH, m) 2.26 (1H, CH_2CHCHCO, dd, J_{HH} = 8.2 Hz, J_{HH} = 5.0 Hz), 2.52 (1H, CH_2CH, m), 3.33 (1H, COCHCHP, m), 3.44 (1H, CHP, m), 4.08 (4H, OCH_2CH_3, m), 5.63 (1H, CH_2CH-CH=CH, dd, J_{HH} = 6.3 Hz, J_{HH} = 5.1 Hz), 5.78 (1H, CH=CH-CHP, m). ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 15.7, 16.9 (d, $^3J_{PC}$ = 5.2 Hz), 22.5, 27.8, 29.1,

29.2, 29.3, 29.4, 30.8, 31.6, 38.1 (d, $^{2}J_{PC}$ = 8.8 Hz), 39.9, 43.6, 46.1 (d, $^{1}J_{PC}$ = 161.0 Hz), 64.2 (d, $^{2}J_{PC}$ = 10.0 Hz), 131.2, 139.0 (d, $^{2}J_{PC}$ = 8.7 Hz), 170.6, 171.9. ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 30.73. MS (EI): *m/z* (%) 55.0 (16.3), 91.0 (84.8), 105.0 (43.3), 108.0 (25.2), 111.0 (34.4), 125.0 (90.4), 138.0 (33.9), 152.0 (100), 173.0 (34.3), 199.0 (17.0), 207.0 (19.5), 229.0 (54.6), 301.0 (27.8), 428.2 (4.8). Anal. Calcd for $C_{22}H_{37}O_6P$: C, 61.67; H, 8.30; P, 7.23. Found: C, 61.61; H, 8.70; P, 7.22.

Diethyl 7-methyl-1,3-dioxo-2,3,3a,4,7,7a-hexahydro-1*H*-isoindol-4-ylphosphonate (4e). Identical to **4a** except using maliemide (1*H*-pyrrole-2,5-dione). ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 1.14 (3H, $C\underline{H}_3CH$, d, J_{HH} = 8.1 Hz), 1.26 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 7.9 Hz), 2.27 (1H, $CH_3CHC\underline{H}CO$, dd, J_{HH} = 7.9 Hz, J_{HH} = 4.7 Hz), 2.54 (1H, $CH_3C\underline{H}$, m), 3.41 (1H, $COC\underline{H}CHP$, m), 3.49 (1H, $C\underline{H}P$, m), 4.09 (4H, $OC\underline{H}_2CH_3$, m), 5.65 (1H, $CH_3CH\text{-}C\underline{H}$=CH, dd, J_{HH} = 6.9 Hz, J_{HH} = 4.7 Hz), 5.82 (1H, CH=C$\underline{H}$-CHP, m), 8.95 (1H, N$\underline{H}$ s, broad). ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 15.3, 16.8 (d, $^{3}J_{PC}$ = 4.9 Hz),, 32.0, 35.1 (d, $^{2}J_{PC}$ = 9.2 Hz), 44.3, 46.3 (d, $^{1}J_{PC}$ = 150.1 Hz), 66.1 (d, $^{2}J_{PC}$ = 9.5 Hz), 130.1, 133.4 (d, $^{2}J_{PC}$ = 8.9 Hz), 177.7, 178.6. ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 31.45. MS (EI): *m/z* (%) 18.0 (65.9), 28.1 (70.2), 29.1 (25.9), 65.0 (36.4), 77.0 (29.7), 83.0 (30.0), 91.0 (96.5), 92.0 (34.0), 93.0 (38.3), 97.0 (45.0), 111.0 (100), 125.4 (65.4), 138.0 (57.0), 152.0 (66.1), 164.0 (13.5), 256.0 (10.3), 301.1 (35.5). Anal. Calcd for $C_{13}H_{20}NO_5P$: C, 51.83; H, 6.69; N, 4.65; P, 10.28. Found: C, 51.76; H, 6.68; N, 4.64; P, 10.27.

Diethyl 7-dodecyl-1,3-dioxo-2,3,3a,4,7,7a-hexahydro-1*H*-isoindol-4-ylphosphonate (4f). ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.91 (3H, $C\underline{H}_3CH_2CH_2$, t, J_{HH} = 7.5 Hz), 1.22 (2H, $C\underline{H}_2C\underline{H}_2CH$, m), 1.25-1.35 (20H, $CH_3(C\underline{H}_2)_{10}CH_2$, overlap), 1.23 (6H, $OCH_2C\underline{H}_3$, t, J_{HH} = 7.9 Hz), 2.25 (1H, $CH_2CHC\underline{H}CO$, dd, J_{HH} = 7.9 Hz, J_{HH} = 4.6 Hz), 2.51 (1H, $CH_2C\underline{H}$, m), 3.35 (1H, $COC\underline{H}CHP$, m), 3.45 (1H, $C\underline{H}P$, m), 4.11 (4H, $OC\underline{H}_2CH_3$, m), 5.67 (1H, $CH_2CH\text{-}C\underline{H}$=CH, dd, J_{HH} = 6.3 Hz, J_{HH} = 4.2 Hz), 5.81 (1H, CH=C$\underline{H}$-CHP, m), 9.13 (1H, N$\underline{H}$ s, broad). ^{3}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 14.9, 16.0 (d, $^{3}J_{PC}$ = 4.6 Hz), 21.4, 23.9, 24.2, 26.5, 27.3, 28.9, 30.1, 32.5, 33.3, 36.8 (d, $^{2}J_{PC}$ = 7.8 Hz), 36.9, 44.9, 45.8 (d, $^{1}J_{PC}$ = 166.9 Hz), 63.1 (d, $^{2}J_{PC}$ = 9.9 Hz), 128.1, 135.9 (d, $^{2}J_{PC}$ = 8.9 Hz), 177.6, 178.5. ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 31.47. MS (EI): *m/z* (%) 163.0 (56.9), 178.1 (55.0), 191.1 (100), 205.1 (34.9), 219.1 (43.1), 233.2 (40.4), 247.2 (33.0), 261.2 (27.5), 275.3 (22.9), 289.3 (20.2), 303.4 (18.3), 317.4 (20.2), 331.5 (18.3), 345.5 (10.1), 360.7 (28.4.1), 410.5 (2.9), 455.2 (0.2). Anal. Calcd for $C_{24}H_{42}NO_5P$: C, 63.27; H, 9.29; N, 3.07; P, 6.80. Found: C, 63.21; H, 9.28; N, 3.07; P, 6.79.

Diphenyl 7-ethyl-1,3-dioxo-1,3,3a,4,7,7a-hexahydroisobenzofuran-4-ylphosphonate (4g). Identical to **4a**. ^{1}H NMR (300 MHz, $CDCl_3$, Me_4Si): δ 0.91 (3H, $C\underline{H}_3CH_2CH$, t, J_{HH} = 7.5 Hz), 1.29 (2H, $CH_3C\underline{H}_2CH$, m), 2.22 (1H, $CH_2CHC\underline{H}CO$, dd, J_{HH} = 8.1 Hz, J_{HH} = 5.1 Hz), 2.53 (1H, $CH_2C\underline{H}$, m), 3.35

(1H, COCHCHP, m), 3.45 (1H, CHP, m), 5.61 (1H, CH_2CH-CH=CH, dd, J_{HH} = 6.1 Hz, J_{HH} = 4.3 Hz), 5.79 (1H, CH=CH-CHP, m), 7.12-7.31 (10H, C_6H_5 Aromatic, overlap); ^{13}C NMR (75.5 MHz, $CDCl_3$, Me_4Si): δ 15.0, 16.6, 21.0 32.9, 33.8 (d, $^2J_{PC}$ = 8.8 Hz), 41.0, 43.2 (d, $^1J_{PC}$ = 171.0 Hz), 120.4 (d, $^3J_{PC}$ = 10.1 Hz), 120.5, 125.8, 132.1, 134.2 (d, $^2J_{PC}$ = 9.1 Hz), 150.1, 178.2, 178.8; ^{31}P NMR (125 MHz, $CDCl_3$, Me_4Si): δ 28.41. MS (EI): *m/z* (%) 28.0 (31.9), 77.0 (30.8), 92.0 (35.2), 95.0 (53.8), 105.0 (100), 133.0 (6.6), 207.0 (8.8), 263.0 (25.3), 291.0 (6.6), 319.0 (46.2), 412.0 (2.2). Anal. Calcd for $C_{22}H_{21}O_6P$: C, 64.08; H, 5.13; P, 7.51. Found: C, 64.04; H, 5.13; P, 7.50.

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