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Enol Phosphates of Phosphorylated Derivatives of Furylacetic Aldehyde and Furylpiruvic Acid

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Abstract—Phosphorylated derivatives of isomeric furylacetic aldehydes and furylpiruvic acids have been synthesized via formylation and oxalylation of dialkyl (ethoxycarbonylfuryl)methanephosphonates under conditions of the Claisen reaction. ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy studies have shown that the products exist as equilibrium mixtures of the carbonyl compounds and its *E*- and *Z*-enol forms in chloroform solutions. Acylation of these substances with diethyl chlorophosphate has yielded the corresponding enol phosphates. Influence of the substituents location in the furan ring on predominance of *cis*- or *trans*-configuration has been demonstrated.

Keywords: furylmethanephosphonic acid, Claisen reaction, keto-enol tautomerism, enol phosphate

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Enol phosphates, in particular, phosphoenol pyruvate, have been recognized as phosphate group carriers in living organisms. These substances contain macroergic bonds, their cleavage producing energy necessary for occurring of biochemical reactions [1]. Influencing on the enzymes that ensure the phosphate groups transfer, it is possible to control the rate of various metabolic processes. In this regard, compounds containing both phosphate and phosphonate groups are of definite interest. Another attractive structure fragment is the furyl radical: it is found in aglycons of glycosides regulating the carbohydrate metabolism in living systems [2, 3]. Furthermore, furan derivatives generally exhibit low toxicity.

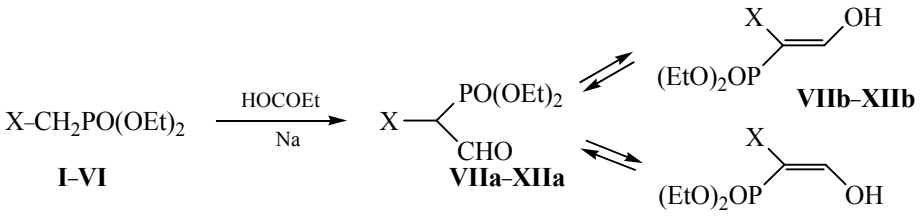
Recently [4, 5] we have shown that dialkyl furylmethanephosphonates can be acylated by the active methylene group under conditions of the Claisen reaction. The presence of ester or cyanide substituent in the furan ring increases CH-acidity of the methylene fragment, facilitating the ester condensation and enhancing stability of the obtained acylphosphonates towards hydrolysis. In view of that, it seemed promising to use isomeric esters of (ethoxycarbonylfuryl)methanephosphonates as parent substances for preparation of enol phosphates of phosphorylated derivatives of furylacetic aldehydes and furylpyruvic acids.

Enol phosphates of phosphorylated aldehydes and ketones have been practically unknown so far. To the best of our knowledge, the only related work [6] has been devoted to synthesis of phosphonoacetic aldehyde enol phosphate via the Perkov reaction. The product structure was characterized only by means of ^{13}C and ^{31}P NMR spectroscopy, but its configuration was not elucidated. According to the ^{31}P NMR, the prepared phosphonoacetic aldehyde enol phosphate was a pure individual isomer.

This work aimed to synthesize the derivatives of (furyl)(diethoxyphosphoryl)acetic aldehyde and (furyl)-(diethoxyphosphoryl)pyruvic acid and to prepare enol phosphates based on them.

Preliminary screening of biological activity of the target phosphorylated enol phopsphates, the derivatives of furylacetic aldehydes and furylpyruvic acids, was carried taking advantage of PASS software [7]. The analysis showed that with probability >0.7 those compounds inhibited the enzymatic activity of esterases cleaving fatty acid residues from glycerides (cutinase and carboxylesterase), of several phosphatases cleaving phosphorus acid residue from various substrates, and of transferase carrying *N*-acetylglucosamine derivatives, mannose, and dimethylallyl group of aspulvinone.

Scheme 1.



X = 5-ethoxycarbonylfur-2-yl (**I**, **VII**), 5-ethoxycarbonyl-2-methylfur-3-yl (**II**, **VIII**), 2-ethoxycarbonylfur-3-yl (**III**, **IX**), 3-ethoxycarbonylfur-2-yl (**IV**, **X**), 4-ethoxycarbonylfur-2-yl (**V**, **XI**), 4-ethoxycarbonylfur-3-yl (**VI**, **XII**).

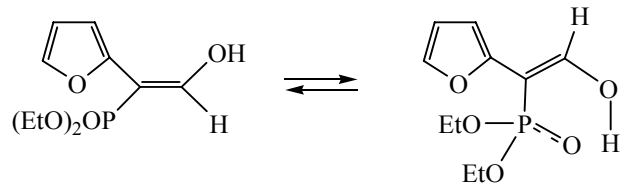
Phosphonates **I–VI** were chosen as starting substances. Their formylation was carried out in toluene in the presence of sodium foil according to the procedure given in [4], but pure formylation products **VII–XII** were isolated instead of sodium salts forming in the course of the reaction. The products were syrup-like or crystalline substances relatively stable in air at room temperature but noticeably hydrolyzing in the acidic or alkaline medium (Scheme 1).

Structure of the prepared compounds was elucidated using ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy. General synthetic procedure, yields, and spectral features of compounds **VII–XII** are given in the Experimental section and in Table 1.

The spectral data confirmed that phosphonates **VII–XII** existed in the form of equilibrium mixture of aldehyde and enol (*E*- or/and *Z*-configuration) forms **a–c** in chloroform solutions. NMR spectra of the aldehyde forms of compounds **VII–XII** differed significantly from the spectra of the corresponding enol forms. In particular, signal of the CHP proton was found at 5.2–5.5 ppm with the coupling constant J_{PH} of 27–32 Hz. Signal of the carbon atom directly bound to phosphorus was observed at 49–53 ppm with the coupling constant $^{1}J_{PC}$ of 128–132 Hz. The aldehyde group gave rise to signals at δ_H 9.7–9.8 ppm and δ_C 190–192 ppm.

In the case of enol forms, the signal at 86–93 ppm with the coupling constant $^{1}J_{PC}$ 180–200 Hz was assigned to the carbon atom directly bound to phosphorus. Signal of C^{2} carbon atom of the vinyl group was observed at 152–165 ppm, its coupling constant with phosphorus atom ranging 3 to 28 Hz and being not specific for the *E*- and *Z*-forms. The latter form could be distinguished using the proton signal of the =CHO fragment: that signal revealed the characteristic *trans*-constant J_{PH} 27–39 Hz in the case of *Z*-enols and *cis*-constant J_{PH} 6–11 Hz in the case of *E*-enols. The *Z*-enol **XIc** revealed special spectral features. In particular, the signal of proton at the double bond (δ 7.74 ppm) gave a doublet due to splitting at phosphorus with the coupling constant J_{PH} 39.2 Hz. It was additionally split with the coupling constant J_{HH} 12.8 Hz. Proton of the enol OH group gaves a doublet with J_{HH} 12.8 Hz at 11.37 ppm instead of a broad signal; hence, that proton did not take part in the exchange and interacted with the proton at the double bond. The enol nature of the compound was confirmed by the value of chemical shift of PC^{1} carbon atom and by the absence of the aldehyde group signal. Evidently, the proton of enol hydroxyl group formed strong H-bond with the oxygen atom of phosphoryl group.

The observations above brought new insight at the data reported in [5]: the product of condensation of diethyl 2-furylmethanephosphonate with ethyl formate was described in that work. The product existed as a mixture of two forms as well. One of them, *E*-enol, was elucidated correctly. The other one, previously claimed to be aldehyde, should be rather assigned to the *Z*-enol form.



Indeed, signal of the phosphorus atom of the latter form was observed at 21.78 ppm. Carbon atom directly bound to phosphorus gave a doublet at 92.01 ppm ($^{1}J_{PC}$ 177.7 Hz). Signal of the adjacent carbon atom of the side chain was found at 161.63 ppm. Two signals were observed in the downfield part of the ^{1}H NMR

Table 1. Yields and spectral features of compounds **VII–XII**

Comp. no.	Yield[a] (conversion), %	Content in the mixture	δ_H, ppm (J, Hz)		δ_C, ppm (J, Hz)		δ_P, ppm
			PC^{1}H	C^{2}HO	PC^{1}H	C^{2}HO	
VIIc	56 (89)	100		8.00 (J_{PH} 38.8)	91.57 ($^1J_{PC}$ 179.1)	152.40 ($^2J_{PC}$ 117.2)	20.85
VIIIa	36 (61)	18	5.52 (J_{PH} 32.0, J_{HH} 2.8)	9.77 (J_{PH} 5.6, J_{HH} 2.8)	50.42 ($^1J_{PC}$ 131.9)	192.25	17.74
VIIIb		62		7.37 (J_{PH} 6.0), 7.63 (J_{PH} 10.0)	90.54 ($^1J_{PC}$ 181.1)	163.02 ($^2J_{PC}$ 6.6	22.34
VIIIc		20		7.27 (J_{PH} 26.4)	93.15 ($^1J_{PC}$ 204.2)	158.07 ($^2J_{PC}$ 27.7)	23.20
IXa	35 (84)	60	5.42 (J_{PH} 28.8)	9.71	50.77 ($^1J_{PC}$ 129.2)	192.12 ($^2J_{PC}$ 3.8)	16.73
IXb		12		7.46 (J_{PH} 10.8)	93.23 ($^1J_{PC}$ 203.0)	159.04 ($^2J_{PC}$ 3.3)	21.44
IXc		28		7.48 (J_{PH} 39.6)	88.42 ($^1J_{PC}$ 180.4)	166.21 ($^2J_{PC}$ 4.6)	22.87
Xa	73 (72)	14	5.52 (J_{PH} 27.6)	9.77	53.07 ($^1J_{PC}$ 128.3)	190.98 ($^2J_{PC}$ 1.8)	14.59
Xc		86		7.81 (J_{PH} 38.8)	88.77 ($^1J_{PC}$ 176.9)	169.33 ($^2J_{PC}$ 2.6)	21.94
XIb	67 (63)	30		7.60 (J_{PH} 10.4)	92.70 ($^1J_{PC}$ 199.3)	163.11 ($^2J_{PC}$ 22.4)	20.19
XIc		70		7.74 (J_{PH} 39.2, J_{HH} 12.8)	91.70 ($^1J_{PC}$ 179.1)	158.89 ($^2J_{PC}$ 20.8)	20.84
XIIa	41 (70)	82	5.22 (J_{PH} 28.8)	9.71	48.93 ($^1J_{PC}$ 128.0)	192.32 ($^2J_{PC}$ 3.5)	17.50
XIIc		18		7.12 (J_{PH} 27.6), 7.14 (J_{PH} 28.0)	86.58 ($^1J_{PC}$ 180.2)	165.73 ($^2J_{PC}$ 4.8)	23.37

[a] Total yield of the mixture.

spectrum: a doublet of doublets at 7.76 ppm (J_{PH} 39.6 Hz, J_{HH} 13.3 Hz) and a doublet at 11.27 ppm (J_{HH} 13.3 Hz). The results coincided with the spectral data for enol **XIc** and disagreed with the features of aldehydes (see Table 1). Interestingly, position 5 of the furan ring of the both *Z*-enols was unsubstituted. If it was substituted with ethoxycarbonyl group (enol **VIIc**), the signal of OH proton at 11.53 ppm became broad. Rough modeling of molecular structure using typical bond lengths and bond angles showed that rotation of the phosphoryl group oxygen towards enol hydroxyl (to favor formation of strong hydrogen bond) brought the ethoxyl groups of phosphonate in contact with the esteric fragment in position 5 of the furan ring. The so emerged steric hindrance prevented the proton binding. That specific feature of five-member heterocycles is likely uncommon, and no reference about it was found in the literature.

Ratio of the aldehyde and enol forms strongly depended on the structure of heterocyclic radical, but we failed to generalize the trend strictly.

Oxalylation of phosphonates **I–VI** in the presence of sodium foil led to formation of the condensation products **XIII–XVIII**. The reaction was carried out in toluene at phosphonate : sodium : oxalate molar ratio of 1 : 1.1 : 1.3 as described in [5]. The so obtained products were syrups and did not crystallize on storage (Scheme 2).

Structures of the prepared products were elucidated using ^{1}H, ^{13}C, and ^{31}P NMR spectral data (Table 2). The data analysis showed that compounds **XIII-XVIII** existed as mixtures of the ketone and one of the enol forms (*E*- or *Z*-orientation of diethoxyphosphoryl and ethoxycarbonyl groups) in chloroform. Simultaneous formation of all three possible forms was not observed. In the case of ketoesters **XIII–XVIII**, spectral features of CHP fragment were close to that of aldehydes **VIIa–Xa, XIIa**. Noteworthily, if the ester group of the furan ring was adjacent to CHP fragment (compounds **XV, XVI, XVIII**), that proton signal shifted downfield by 0.7–1.0 ppm. That could be due to H-bonding with C=O carbon atom of ester group. Similar effect was observed in the case of phosphorylated derivatives of furylacetic acids [8].

In the case of enol forms, differentiation between the *E*- and *Z*- configurations was quite complicated.

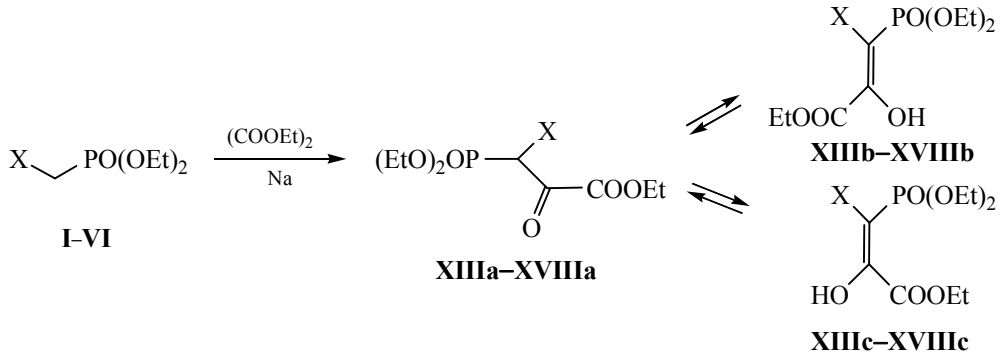
Table 2. Yields and spectral features of compounds **XIII–XVIII**

Comp. no.	Yield[a], %	Content in the mixture	δ_H, ppm (J, Hz)	δ_C, ppm (J, Hz)		δ_P, ppm
				PC^1	C^2O	
XIIIa	70 (59)	16	5.793 (J_{PH} 26.8)	48.73 ($^1J_{PC}$ 126.9)	184.26 ($^2J_{PC}$ 4.8)	12.84
XIIIb		84		90.41 ($^1J_{PC}$ 176.7)	162.61 ($^2J_{PC}$ 22.7)	20.86
XIVa	60 (61)	59	5.28 (J_{PH} 26.0)	43.97 ($^1J_{PC}$ 132.6)	186.27 ($^2J_{PC}$ 3.3)	16.52
XIVc		41		89.10 ($^1J_{PC}$ 192.0)	158.58 ($^2J_{PC}$ 10.5)	22.14
XVa	49 (47)	88	6.57 (J_{PH} 27.6)	44.49 ($^1J_{PC}$ 125.8)	186.49 ($^2J_{PC}$ 5.2)	15.43
XVc		12		86.39 ($^1J_{PC}$ 193.2)	159.08	21.76
XVIa	43 (41)	39	6.52 (J_{PH} 26.4)	47.52 ($^1J_{PC}$ 128.8)	184.71 ($^2J_{PC}$ 4.1)	13.74
XVIb		61		91.99 ($^1J_{PC}$ 176.3)	161.51 ($^2J_{PC}$ 22.9)	20.68
XVIIa	58 (54)	21	5.66 (J_{PH} 26.8)	47.63 ($^1J_{PC}$ 128.7)	184.32	13.42
XVIIb		79		90.72 ($^1J_{PC}$ 177.7)	162.46 ($^2J_{PC}$ 22.1)	20.92
XVIIIa	50 (50)	90	6.24 (J_{PH} 27.6)	43.29 ($^1J_{PC}$ 126.4)	186.66 ($^2J_{PC}$ 4.7)	16.40
XVIIIb		10		90.54 ($^1J_{PC}$ 184.5)	160.72 ($^2J_{PC}$ 22.9)	22.68

[a] Total yield of the mixture.

The most important indicator to judge about the configuration was the value of coupling constant between the carbonyl group carbon of ester group and phosphorus. In the compounds **XIIIb**, **XVIb,** and **XVIIb** signals of carbonyl groups were observed as doublets with the coupling constant $^3J_{PC}$ 5–9 Hz. In the spectra of compounds **XVc** and **XVIc** the signal of the carbonyl carbon was not split. Hence, the former group of substances was assigned to *E*-enols and the latter one was regarded as *Z*-enols. Moreover, in the ^{13}C NMR spectra of *E*-enols **XIIIb, XVIb,** and **XVIIb** the coupling constant $^2J_{PC}$ of the $=C^2O$ carbon atom was of 22–23 Hz. That could be used as an additional criterion to elucidate the configuration of alkenes bearing phosphoryl and carbonyl groups at the double bond. Analysis of the enol configuration on as function of the structure of heterocyclic fragment showed that *Z*-location of diethoxyphosphoryl and ethoxycarbonyl groups (compounds **XIVc** and **XVc**) was observed when phosphorus-containing substituent was located in the β-position of the furan ring, and the adjacent α-position was occupied. Evidently, only in that case rotation

Scheme 2.



I–VI

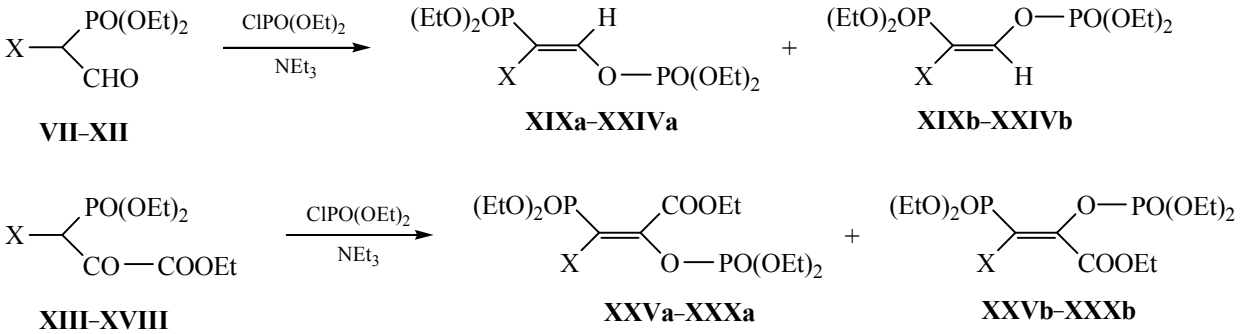
XIIIa–XVIIIa

XIIIb–XVIIIb

XIIIc–XVIIIc

X = 5-ethoxycarbonylfur-2-yl (**I**, **XIII**), 5-ethoxycarbonyl-2-methylfur-3-yl (**II**, **XIV**), 2-ethoxycarbonylfur-3-yl (**III**, **XV**), 3-ethoxycarbonylfur-2-yl (**IV**, **XVI**), 4-ethoxycarbonylfur-2-yl (**V**, **XVII**), 4-ethoxycarbonylfur-3-yl (**VI**, **XVIII**).

Scheme 3.



VII–XII **XIXa–XXIVa** **XIXb–XXIVb**

XIII–XVIII **XXVa–XXXa** **XXVb–XXXb**

X = 5-ethoxycarbonylfur-2-yl (**VII**, **XIII, XIX, XXV**), 5-ethoxycarbonyl-2-methylfur-3-yl (**VIII**, **XIV, XX, XXIV**), 2-ethoxycarbonylfur-3-yl (**IX**, **XV, XXII, XXVIII**), 3-ethoxycarbonylfur-2-yl (**X**, **XVI, XXII, XXVIII**), 4-ethoxycarbonylfur-2-yl (**XI**, **XVII, XXIII, XXIX**), 4-ethoxycarbonylfur-3-yl (**XII**, **XVIII, XXIV, XXX**).

of the groups towards the same side of the double bond was energetically favorable.

Reaction of compounds **VII–XVIII** with diethyl chlorophosphate in the presence of triethyamine gave the corresponding enol phosphates **XIX–XXX** that were isolated as viscous colored oils (Scheme 3).

In the majority of cases, mixtures of *E*- and *Z*-isomers of enol phosphates were obtained. Ratio of the isomers and spectral features of the enol phosphate fragment of compounds **XIX–XXIV** are listed in Table 3. The main criterion to elucidate the products configuretion was the value of the coupling constant between the olefin proton and the phosphonate phosphorus atom (30–33 Hz for *Z*-isomers and 9–11 Hz for *E*-isomers). The coupling constants reflecting the interaction between the olefin proton and the phosphate phosphorus atom in the both isomers were close (6–7 Hz). Signals of the double bond carbon atoms in the *E*-isomers appeared as weak doublets of doublets. Carbon atom

Table 3. Yields and spectral features of compounds **XIX–XXIV**

Comp. no.	Yield[a], %	Content in the mixture	δ_H(POCH), ppm (J, Hz)	δ_C, ppm (J, Hz)		δ_P, ppm (J, Hz)	
				PC=	POCH=	PC=	POCH=
XIXa	50	100	7.50 ($^3J_{PH}$ 10.4, 6.8)	105.60 ($^1J_{PC}$ 187.5, $^3J_{PC}$ 9.6)	148.12 ($^2J_{PC}$ 23.1, $^2J_{POC}$ 3.9)	13.64	–5.56
XXa	80	85	7.39 ($^3J_{PH}$ 10.0, 5.8)	107.48 ($^1J_{PC}$ 190.4, $^3J_{PC}$ 9.5)	147.43 ($^2J_{PC}$ 30.3, $^2J_{POC}$ 3.3)	16.18	–4.90
XXb		15	6.94 ($^3J_{PH}$ 32.8, 6.0)	–	147.41 ($^2J_{PC}$ 4.0)	11.88	–5.58
XXIa	84	91	7.39 ($^3J_{PH}$ 10.0, 6.0)	106.58 ($^1J_{PC}$ 192.6, $^3J_{PC}$ 10.6)	148.62 ($^2J_{PC}$ 28.7, $^2J_{PC}$ 3.1)	18.95	–4.31
XXIb		9	7.17 ($^3J_{PH}$ 32.4, 6.0)	–	–	15.57	–5.28
XXIIa	48	50	7.54 ($^3J_{PH}$ 9.2, 6.8)	[b]	152.64 ($^2J_{PC}$ 25.2, $^2J_{PC}$ 2.9)	[b]	[b]
XXIIb		50	7.41 ($^3J_{PH}$ 31.2, 6.4)	[b]	151.49 ($^2J_{PC}$ 4.2)	[b]	[b]
XXIIIa	50	94	7.42 ($^3J_{PH}$ 10.4, 6.8)	105.45 ($^1J_{PC}$ 186.0, $^3J_{PC}$ 9.6)	146.98 ($^2J_{PC}$ 23.2, $^2J_{PC}$ 4.4)	14.27	–5.24
XXIIIb		6	[b]	[b]	[b]	10.11	–5.38
XXIVa	85	34	7.29 ($^3J_{PH}$ 9.6, 6.0)	106.82 ($^1J_{PC}$ 186.3, $^3J_{PC}$ 12.4)	148.36 ($^2J_{PC}$ 35.4)	11.77	–5.83
XXIVb		66	7.02 ($^3J_{PH}$ 32.4, 6.0)	104.61 ($^1J_{PC}$ 192.9, $^3J_{PC}$ 10.6)	148.80 ($^2J_{PC}$ 2.8)	16.02	–5.45

[a] Total yield of the isomers mixture. [b] Pairs of signals of equal intensity. Their accurate reference to *E*- or *Z*-isomer is impossible.

Table 4. Yields and spectral features of compounds **XXV–XXX**[a]

Comp. no.	Yield[b], %	Content in the mixture	δ_P, ppm (J, Hz)		δ_C, ppm (J, Hz)		
			=CP	=COP	=CP	=COP	C=O
XXVa	90	48	10.03	–8.98	110.24 ($^1J_{PC}$ 235.9, $^3J_{PC}$ 9.2)	150.13 ($^2J_{PC}$ 24.8, $^2J_{PC}$ 6.7)	158.21 ($^2J_{PC}$ 5.2)
XXVb		52	9.14 ($^4J_{PP}$ 2.3)	–8.41 ($^4J_{PP}$ 2.3)	108.42 ($^1J_{PC}$ 240.0, $^3J_{PC}$ 9.0)	149.78 ($^2J_{PC}$ 3.7)	161.92 ($^3J_{PC}$ 17.0)
XXVIa	95	7	11.97	–8.50	112.93 ($^1J_{PC}$ 147.5, $^3J_{PC}$ 9.2)	155.60 ($^2J_{PC}$ ~30, $^3J_{PC}$ ~9.6)	158.65
XXVIb		93	10.71 ($^4J_{PP}$ 3.4)	–7.89 ($^4J_{PP}$ 3.4)	112.77 ($^1J_{PC}$ 180.5, $^3J_{PC}$ 9.1)	155.23 ($^2J_{PC}$ 7.3)	161.77 ($^3J_{PC}$ 18.4)
XXVIIa	74	11	10.94	–8.91	–	–	158.34
XXVIIb		89	9.84 ($^4J_{PP}$ 2.9)	–7.84 ($^4J_{PP}$ 2.9)	114.52 ($^1J_{PC}$ 179.8, $^3J_{PC}$ 9.4)	146.81 ($^2J_{PC}$ 6.1)	161.32 ($^3J_{PC}$ 17.8)
XXVIIIa	55	10	9.80	–9.09	–	–	–
XXVIIIb		90	8.77 ($^4J_{PP}$ 2.8)	–8.10 ($^4J_{PP}$ 2.8)	116.70 ($^1J_{PC}$ 262.0, $^3J_{PC}$ 7.5)	149.51 ($^2J_{PC}$ 4.3)	152.42 ($^3J_{PC}$ 13.6)
XXIXa	85	69	9.27 ($^4J_{PP}$ 2.7)	–8.29 ($^4J_{PP}$ 2.7)	109.033 ($^1J_{PC}$ 173.9, $^3J_{PC}$ 8.6)	[c]	162.54 ($^2J_{PC}$ 3.7)
XXIXb		31	10.72	–8.73	108.31 ($^1J_{PC}$ 183.2, $^3J_{PC}$ 7.0)	149.76 ($^2J_{PC}$ 5.2)	161.99 ($^3J_{PC}$ 16.5)
XXXa	80	11	11.70	–8.76	–	–	159.15
XXXb		89	10.58 ($^4J_{PP}$ 3.4)	–7.84 ($^4J_{PP}$ 3.4)	113.06 ($^1J_{PC}$ 183.4, $^3J_{PC}$ 9.5)	146.90 ($^2J_{PC}$ 6.0)	161.64 ($^3J_{PC}$ 18.1)

[a] ("–") is a signal not found. [b] Total yield of the mixture. [c] Signal overlaps with the signals of C^2 and C^5 atoms of the furan ring.

of the PC= fragment gave signals at 105–107 ppm with the coupling constants $^1J_{PC}$ 185–190 Hz and $^3J_{PC}$ 9–10 Hz. Signals of the PC= fragment of *Z*-isomers revealed similar features. Carbon atom of the =CHOP fragment gave a doublet of doublets at 148–152 ppm with the coupling constants $^2J_{PC}$ 23–37 and 0–4 Hz in the spectra of the *E*-isomers. In the case of *Z*-isomers, the corresponding signal was found at the same position but one of the coupling constants was absent. The described spectral differences can be probably used in future to establish the structure of the new compounds. Analysis the *E*-/*Z*-ratio as function of the structure of the furan fragment showed that if ethoxycarbonyl group was far from the phosphorus-containing fragment (compounds **XIX**, **XX**, and **XXIII**), the *E*-isomer was preferable. Methyl group in the adjacent α-position of the furan ring did not prevent *trans*-orientation of phosphonate and phosphate groups. Preference of *E*-isomer in the case of enol phosphate **XXI** was unexpected because in two other cases when the ester group was adjacent to the phosphorus-containing substituent (compounds **XXII** and **XXIV**) *E*- and *Z*-isomers were formed in equal amounts or the latter one predominated.

In the case of enol phosphates **XXV–XXX,** the main criterion to discriminate between *E*- and *Z*-configurations (defined by location of phosphorus-containing groups with respect to the double bond) was the value of the coupling constant between the phosphorus and the ester carbonyl carbon atom $^3J_{PC}$ (Table 4). In the case of *trans*-location of phosphoryl and carbonyl groups, $^3J_{PC}$ was of 13–18 Hz, being of 3.7–5.2 Hz in the case of *cis*-location. In the case of compounds **XXVIa, XXVIIa,** and **XXXa** the constant was not revealed at all. Hence, spectral features of phosphonates **XIII-XVIII** practically coincided with those of phosphoenolpyruvates **XXV–XXX**. The shape of carbon signals of the =COP fragment were noticeably different in the cases of *E*- and *Z*-isomers. The differrences were similar to those in the case of furylacetaldehyde enol phosphates. In particular, the signals were either doublets of doublets with the coupling constants $^2J_{PC}$ 24–30 and $^2J_{PC}$ 6–10 Hz (*E*-isomers) or doublets with the coupling constant $^2J_{PC}$ 4–8 Hz (*Z*-isomers). Therefore, $^2J_{PC}$ constant values can be used to elucidate configuration of the P–C=C–O–P fragment.

Relative location of the phosphonate and carboxyl groups in phosphoenol pyruvates **XXV–XXX** directly depended on the character of substitution in the furan ring (Table 4). If a substituent was located in the position adjacent to that of the phosphorus-containing

fragment, the phosphoryl group tended to take *trans*-position with respect to the carboxyl function. If the position adjacent to the phosphorus-containing fragment was unoccupied (**XXV** and **XXIX**), *cis*- and *trans*-location of the phosphoryl group and carbonyl became almost equally probable.

Let us note another remarkable feature of ^{31}P NMR spectra of compounds **XXV–XXX**. In the case of thermodynamically most stable isomer, the coupling constant between the phosphonate and phosphate phosphorus nuclei ($^4J_{PP}$ 2.3–3.4 Hz) was revealed. It was not stereospecific, as it was observed in both *E*- and *Z*-isomers. To the best of our knowledge, the effect was not reported about previously.

To conclude, it was shown that phosphorylated derivatives of furylacetic aldehyde and furylpyruvic acid formed in the course of ester condensation existed as mixtures of carbonyl compounds with their *E*- and *Z*-enols in chloroform solutions. Spectral data allowed elucidation of the structure and configuration of the tautomers. Further, enol phosphates were synthesized based on the above-listed compounds. They also existed as mixtures of *E*- and *Z*-isomers. Spectral data allowed elucidation of the configuration of the phosphorus-containing fragment. Previously unknown interaction between phosphorus nuclei through four bonds was observed. The effect of the furan ring substitution pattern on configuration of enols and their phosphates was demonstrated.

EXPERIMENTAL

^{1}H, ^{13}C, and ^{31}P NMR spectra were recorded using a Bruker DPX-400 spectrometer [400.13 (^{1}H), 161.97 (^{31}P), 100.16 (^{13}C) MHz] in $CDCl_3$.

Formylation of dialkyl (ethoxycarbonylfuryl) methanephosphonates with ethyl formate *(general procedure)*. Freshly prepared sodium foil, 0.012 g-at was added to a mixture of 0.01 mol of dialkyl (ethoxycarbonylfuryl)methanephosphonate and 0.02 mol of ethyl formate in 20 mL of toluene. The reaction mixture was stirred till complete dissolution of sodium and left overnight. Then the reaction products were extracted with water (2 × 10 mL). The water extract was saturated with sodium chloride and acidified to pH 2–3 with hydrochloric acid. The reaction product was extracted with chloroform, washed with 10 mL of water, and dried over sodium sulfate. The solvent was removed, and the residue was kept in vacuum at room temperature for 1 h at 1 mmHg. Yields and isomeric composition of products are presented in Table 1.

Diethyl *Z*-1-(5-ethoxycarbonylfur-2-yl)-2-hydroxyvinylphosphonate (VIIc). mp 86°C. ^{1}H NMR spectrum, δ, ppm: *Z*-enol **VIIc:** 1.23–1.35 m (CH_3-ethyl); 4.02–4.18 m (CH_2OP); 4.30–4.35 m (CH_2OC); 6.21 br.s (H^3-furan); 7.11 br.s (H^4-furan); 8.00 d (=CH–O, J_{PH} 38.8 Hz); 11.53 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: 14.32 (CH_3); 16.04 (CH_3, $^3J_{PC}$ 6.5 Hz); 60.73 (CH_2O); 62.87 (CH_2OP, $^2J_{PC}$ 4.1 Hz); 91.57 (P–C=, $^1J_{PC}$ 179.1 Hz); 106.81 (C^3-furan); 119.54 (C^4-furan); 142.58 (C^5-furan); 152.39 (=CH–O, $^2J_{PC}$ 17.2 Hz); 158.61 (C^2-furan); 163.97 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 20.85.

(5-Ethoxycarbonyl-2-methylfur-3-yl)(diethoxyphosphoryl)acetic aldehyde (VIII). ^{1}H NMR spectrum, δ, ppm: common signals: 1.14–1.34 m (CH_3); 3.99–4.15 m (CH_2OP); 4.29–4.36 m (CH_2OC); aldehyde **VIIIa**: 2.28 d (CH_3-furan, J_{PH} 1.2 Hz); 5.52 d.d (CHP, J_{PH} 32.0 Hz, J_{HH} 2.8 Hz); 7.17 d (H^4-furan J_{PH} 5.6 Hz); 9.77 d.d (CHO, J_{PH} 5.6 Hz, J_{HH} 2.8 Hz); *E*-enol **VIIIb**: 2.32 d (CH_3-furan, J_{PH} 2.0 Hz); 7.07 s (H^4-furan); 7.34 d (=CH–O, J_{PH} 6.0 Hz), 7.63 d (=CH–O, J_{PH} 10.0 Hz) (two forms); 9.60–9.99 br.s (OH); *Z*-enol **VIIIc**: 2.35 d (CH_3-furan, J_{PH} 1.2 Hz); 6.70 s (H^4-furan); 7.27 d (=CH–O, J_{PH} 26.4 Hz); 9.60–9.99 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: common signals: 14.30 (CH_3), 16.13 (CH_3, $^3J_{PC}$ 6.7 Hz); 16.25 (CH_3, $^3J_{PC}$ 4.7 Hz); 60.71 (CH_2O); 60.89 (CH_2O); 61.97 (CH_2OP, $^2J_{PC}$ 5.3 Hz) 62.57 (CH_2OP, $^2J_{PC}$ 4.7 Hz); aldehyde **VIIIa**: 13.32 (CH_3-furan); 50.42 (CH–P, $^1J_{PC}$ 131.9 Hz); 110.31 (C^3-furan, $^2J_{PC}$ 8.5 Hz); 119.68 (C^4-furan); 142.93 (C^5-furan); 155.14 (C^2-enol, $^3J_{PC}$ 10.4 Hz); 158.63 (C=O-ester); 192.25 (C=O-aldehyde); *E*-enol **VIIIb**: 12.48 (CH_3-furan); 90.54 (P–C=, $^1J_{PC}$ 181.1 Hz); 115.39 (C^3-furan, $^2J_{PC}$ 6.9 Hz); 120.41 (C^4-furan); 142.41 (C^5-furan); 153.85 (C^2-furan, $^3J_{PC}$ 9.5 Hz); 158.79 (C=O); 163.02 (=CH–O, $^2J_{PC}$ 6.6 Hz); *Z*-enol **VIIIc**: 12.24 (CH_3-furan); 93.15 (P–C=, $^1J_{PC}$ 204.2 Hz); 113.28 (C^3-furan, $^2J_{PC}$ 6.9 Hz); 120.69 (C^4-furan); 142.08 (C^5-furan); 155.284 (C^2-furan, $^3J_{PC}$ 10.5 Hz); 158.07(=CH–O, $^2J_{PC}$ 27.7 Hz; 158.94 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 17.74 (**VIIIa**); 22.34 (**VIIIb**); 23.20 (**VIIIc**).

(2-Ethoxycarbonylfur-3-yl)(diethoxyphosphoryl)-acetic aldehyde (IX). ^{1}H NMR spectrum, δ, ppm: common signals: 1.16–1.33 m (CH_3); 3.96–4.13 m (CH_2OP); 4.03–4.19 m (CH_2OC); aldehyde **IXa**: 5.42 d (CHP, J_{PH} 28.8 Hz); 6.74 s (H^4-furan); 9.71 s (CHO); *E*-enol **IXb**: 6.43 s (H^4-furan); 7.43 s (H^5-furan); 7.46 d (=CH–O, J_{PH} 10.8 Hz), 11.27 br.s (OH); *Z*-enol **IXc**: 6.44 s (H^4-furan); 7.41 s (H^5-furan); 7.48 d (=CH–O,

J_{PH} 39.6 Hz); 11.27 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: common signals: 14.07 (CH_3); 14.16 (CH_3); 16.01 (CH_3, $^3J_{PC}$ 6.7 Hz); aldehyde **IXa**: 50.77 (CH–P, $^1J_{PC}$ 129.2 Hz); 61.07 (CH_2O); 63.27 (CH_2OP, $^2J_{PC}$ 6.6 Hz); 63.40 (CH_2OP, $^2J_{PC}$ 6.8 Hz); 114.27 (C^4-furan, $^3J_{PC}$ 1.2 Hz); 123.14 (C^3-furan, $^2J_{PC}$ 7.7 Hz); 141.01 (C^2-furan, $^3J_{PC}$ 10.4 Hz); 145.10 (C^5-furan); 158.83 (C=O-ester); 192.12 (C=O-aldehyde, $^2J_{PC}$ 3.8 Hz); *E*-enol **IXb**: 60.59 (CH_2O); 61.66 (CH_2OP, $^2J_{PC}$ 4.8 Hz) 93.28 (P–C=, $^1J_{PC}$ 203.0 Hz); 114.59 (C^4-furan); 123.68 (C^3-furan, $^2J_{PC}$ 10.9 Hz); 141.24 (C^2-furan, $^3J_{PC}$ 10.9 Hz); 144.72(C^5-furan); 159.02 (C=O); 159.04 (=CH–O, $^2J_{PC}$ 3.3 Hz); *Z*-enol **IXc**: 60.73 (CH_2O); 62.37 (CH_2OP, $^2J_{PC}$ 4.4 Hz); 88.42 (P–C=, $^1J_{PC}$ 180.4 Hz); 114.45 (C^4-furan); 127.24 (C^3-furan, $^2J_{PC}$ 8.4 Hz); 139.46 (C^2-furan, $^3J_{PC}$ 11.4 Hz); 144.98 (C^5-furan); 159.02 (C=O); 166.21 (=CH–O, $^2J_{PC}$ 4.6 Hz). ^{31}P NMR spectrum, δ_P, ppm: 16.73 (**IXa**); 21.44 (**IXb**); 22.87 (**Ixc**).

(3-Ethoxycarbonylfur-2-yl)(diethoxyphosphoryl)-acetic aldehyde (X). ^1H NMR spectrum, δ, ppm: common signals: 1.23–1.34 m (CH_3); 4.05–4.13 m (CH_2OP); 4.22–4.30 m (CH_2OC); aldehyde **Xa**: 5.52 d (CHP, J_{PH} 27.6 Hz); 6.73 s (H^4-furan); 7.36 s (H^5-furan), 9.77 s (CHO); *Z*-enol **Xc**: 6.72 s (H^4-furan); 7.31 s (H^5-furan); 7.81 d (=CH–O, J_{PH} 38.8 Hz); 11.85 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: common signals: 14.21 (CH_3); 16.00 (CH_3, $^3J_{PC}$ 7.0 Hz); 16.07 (CH_3, $^3J_{PC}$ 7.1 Hz); 60.37 (CH_2O); 61.81 (CH_2OP, $^2J_{PC}$ 3.9 Hz); 62.40 (CH_2OP, $^2J_{PC}$ 6.4 Hz); aldehyde **Xa**: 53.07 (CH–P, $^1J_{PC}$ 128.3 Hz); 110.87 (C^4-furan); 115.48 (C^3-furan, $^3J_{PC}$ 8.4 Hz); 143.17(C^5-furan); 152.39 (C^2-furan, $^3J_{PC}$ 14.0 Hz)); 163.05 (C=O-ester); 190.98 (C=O-aldehyde, $^2J_{PC}$ 1.8 Hz); *Z*-enol **Xc**: 88.77 (P–C=, $^1J_{PC}$ 176.9 Hz); 111.81 (C^4-furan); 114.41 (C^3-furan, $^3J_{PC}$ 7.0 Hz); 141.41 (C^5-furan); 153.53 (C^2-furan, $^2J_{PC}$ 8.5 Hz); 163.28 (C=O); 169.24 (=CH–O, $^2J_{PC}$ 2.6 Hz). ^{31}P NMR spectrum, δ_P, ppm: 14.60 (**Xa**); 21.93 (**Xc**).

(4-Ethoxycarbonylfur-2-yl)(diethoxyphosphoryl)-acetic aldehyde (XI). mp 89–90°C. ^1H NMR spectrum, δ, ppm: common signals: 1.24–1.31 m (CH_3); 3.99–4.15 m (CH_2OP); 4.25 q CH_2OC, J_{HH} 7.0 Hz); *E*-enol **XIb**: 6.90 s (H^3-furan); 7.60 d (=CH–O, J_{PH} 10.4 Hz); 7.91 s (H^4-furan); *Z*-enol **XIc**: 6.42 s (H^3-furan); 7.74 d. (=CH–O, J_{PH} 39.2 Hz, J_{HH} 12.8 Hz); 7.82 s (H^5-furan); 11.37 d (OH, J_{HH} 12.8 Hz). ^{13}C NMR spectrum, δ_C, ppm: common signals: 14.24 (CH_3); 16.03 (CH_3, $^3J_{PC}$ 6.1 Hz); *E*-enol **XIb**: 60.35 (CH_2O); 62.34 (CH_2OP, $^2J_{PC}$ 4.6 Hz); 92.70 (P–C=, $^1J_{PC}$ 199.3 Hz); 108.07 (C^3-furan, $^3J_{PC}$ 6.8 Hz); 120.57 (C^4-furan); 145.98 (C^5-furan); 148.96 (C^2-furan, $^2J_{PC}$ 6.6 Hz); 162.89 (C=O); 163.11 (=CH–O, $^2J_{PC}$ 22.4 Hz); *Z*-enol **XIc**: 60.42 (CH_2O); 62.80 (CH_2OP, $^2J_{PC}$ 4.2 Hz); 91.70 (P–C=, $^1J_{PC}$ 179.1 Hz); 104.48 (C^3-furan); 120.83 (C^4-furan); 145.63 (C^5-furan); 149.54 (C^2-furan, $^2J_{PC}$ 16.2 Hz); 158.89 (=CH–O, $^2J_{PC}$ 20.8 Hz); 158.94 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 20.19 (**XIb**); 20.84 (**XIc**).

(4-Ethoxycarbonylfur-3-yl)(diethoxyphosphoryl)-acetic aldehyde (XII). ^1H NMR spectrum, δ, ppm: common signals: 1.20–1.29 m (CH_3); 3.90–4.15 m (CH_2OP); 4.22 q (CH_2OC, J_{HH} 7.0 Hz); aldehyde **XIIa**: 5.22 d (CHP, J_{PH} 28.8 Hz); 7.69 br.s (H^2-furan); 7.97 br.s (H^5-furan), 9.71 s (CHO); *Z*-enol **XIIc**: 7.12 d (=CH–O, J_{PH} 27.6 Hz), 7.14 d (=CH–O, J_{PH} 28.0 Hz) (2 forms); 7.31 s (H^2-furan); 8.00 s (H^5-furan); 11.16 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: aldehyde **XIIa**: 14.14 (CH_3); 16.19 (CH_3, $^3J_{PC}$ 4.5 Hz); 16.07 (CH_3, $^3J_{PC}$ 7.1 Hz); 48.93 (CH–P, $^1J_{PC}$ 128.0 Hz); 60.43 (CH_2O); 63.15 (CH_2OP, $^2J_{PC}$ 6.8 Hz); 63.36 (CH_2OP, $^2J_{PC}$ 6.8 Hz); 112.92 (C^3-furan, $^3J_{PC}$ 7.2 Hz); 117.40 (C^4-furan, $^3J_{PC}$ 6.2 Hz); 144.26 (C^2-furan, $^3J_{PC}$ 6.0 Hz); 148.27 (C^5-furan); 163.05 (C=O - ester); 192.32 (C=O-aldehyde, $^2J_{PC}$ 3.5 Hz); *Z*-enol **XIIc**: 14.05 (CH_3); 16.04 (CH_3, $^3J_{PC}$ 6.9 Hz); 60.25 (CH_2O); 62.07 (CH_2OP, $^2J_{PC}$ 6.5 Hz); 62.27 (CH_2OP, $^2J_{PC}$ 4.3 Hz); 86.58 (P–C=, $^1J_{PC}$ 180.2 Hz); 115.05 (C^3-furan, $^3J_{PC}$ 8.6 Hz); 117.91 (C^4-furan, $^2J_{PC}$ 6.2 Hz); 142.73 (C^2-furan, $^3J_{PC}$ 4.1 Hz); 149.19 (C^5-furan); 163.12 (C=O); 165.73 (=CH–O, $^2J_{PC}$ 4.8 Hz). ^{31}P NMR spectrum, δ_P, ppm: 17.5 (**XIIa**); 23.37 (**XIIc**).

Reaction of diethyl (ethoxycarbonylfuryl)methanephosphonates with diethyl oxalate *(general procedure)*. Diethyl (ethoxycarbonylfuryl)methanephosphonate (0.01 mol) and diethyl oxalate (0.013 mol) were dissolved in 20 mL of toluene, and 0.011 mol of freshly prepared sodium foil was added under vigorous stirring. The reaction mixture was stirred till complete dissolution of sodium and left overnight. The reaction products were extracted with water (2 × 25 mL), the water phase was saturated with sodium chloride and acidified with concentrated hydrochloric acid to pH 2–3. The formed oil was extracted with chloroform (3 × 20 mL), the extract was washed with water (10 mL) and dried over sodium sulfate. The solvent was removed on a rotary evaporator, and the residue was kept in vacuum (1 mmHg) for 1 h at room temperature. Yields and isomeric composition of the products are listed in the Table 2.

Ethyl 3-(5-ethoxycarbonylfur-2-yl)-3-(diethoxyphosphoryl)-2-oxopropanoate (XIII). ^1H NMR spec-

trum, δ, ppm: common signals: 1.23 t (CH_3, J_{HH} 7.2 Hz); 1.31 t (CH_3, J_{HH} 7.2 Hz); 1.33 t (CH_3, J_{HH} 7.2 Hz); 4.06–4.19 m (CH_2OP); 4.25–4.46 m (CH_2OC); ketone **XIIIa**: 5.79 d (CHP, J_{PH} 26.8 Hz); 6.75 br.s (H^3-furan); 7.15 d (H^4-furan, J_{HH} 3.2 Hz); *E*-enol **XIIIb**: 6.33 br.s (H^3-furan); 7.12 d (H^4-furan, J_{HH} 3.2 Hz); 12.33 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: ketone **XIIIa**: 13.90 (CH_3); 14.29 (CH_3); 16.15 (CH_3, $^3J_{PC}$ 5.9 Hz); 48.73 (CH–P, $^1J_{PC}$ 126.9 Hz); 60.98 (CH_2O); 62.45 (CH_2O-furan); 63.96 (CH_2OP, $^2J_{PC}$ 6.6 Hz); 64.18 (CH_2OP, $^2J_{PC}$ 6.9 Hz); 112.82 (C^3-furan, $^3J_{PC}$ 4.7 Hz); 118.91 (C^4-furan); 144.63 (C^5-furan); 147.66 (C^2-furan, $^2J_{PC}$ 7.3 Hz); 159.91 (C=O-furan); 162.08 (C=O-ester); 184.26 (C=O-ketone, $^2J_{PC}$ 4.8 Hz); *E*-enol **XIIIb**: 13.79 (CH_3); 14.29 (CH_3); 16.01 (CH_3, $^3J_{PC}$ 6.6 Hz); 60.78 (CH_2O); 62.95 (CH_2O-furan); 63.50 (CH_2OP, $^2J_{PC}$ 4.4 Hz); 90.41 (P–C=, $^1J_{PC}$ 176.7 Hz); 110.56 (C^3-furan, $^3J_{PC}$ 2.1 Hz); 119.12 (C^4-furan); 143.94 (C^5-furan); 149.88 (C^2-furan, $^2J_{PC}$ 10.0 Hz); 158.35 (C=O-furan); 162.61 (=C–O, $^2J_{PC}$ 22.7 Hz); 162.85 (C=O-ester, $^3J_{PC}$ 5.1 Hz). ^{31}P NMR spectrum, δ_P, ppm: 12.83 (**XIIIa**); 20.86 (**XIIIb**).

Ethyl 3-(5-ethoxycarbonyl-2-methylfur-3-yl)-3-(diethoxyphosphoryl)-2-oxopropanoate (XIV). ^1H NMR spectrum, δ, ppm: common signals: 1.21–1.26 m (CH_3, J_{HH} 6.8 Hz); 1.29–1.37 m (CH_3, J_{HH} 6.8 Hz); 4.02–4.07 m (CH_2OP); 4.26-4.31 m (CH_2OC); ketone **XIVa**: 2.36 s (CH_3); 5.28 d (CHP, J_{PH} 26.0 Hz); 7.38 d (H^4-furan); *Z*-enol **XIVc**: 2.20 s (CH_3); 6.89 s (H^4-furan); 11.62 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: common signals: 13.69 (CH_3); 13.85 (CH_3); 14.27 (CH_3); 16.14 (CH_3, $^3J_{PC}$ 7.1 Hz); 16.20 (CH_3, $^3J_{PC}$ 6.0 Hz); 60.78 (CH_2O); 62.90 (CH_2O); 63.16 (CH_2O); 63.48 (CH_2OP, $^2J_{PC}$ 7.0 Hz); 63.65 (CH_2OP, $^2J_{PC}$ 6.7 Hz); ketone **XIVa**: 12.18 (CH_3-furan); 43.97(CH–P, $^1J_{PC}$ 132.6 Hz); 111.33 (C^3-furan, $^2J_{PC}$ 8.9 Hz); 119.97 (C^4-furan); 142.73 (C^5-furan); 154.98 (C^2-furan, $^3J_{PC}$ 9.6 Hz); 158.63 (C=O-ester); 160.05 (C=O-furan); 186.27 (C=O-ketone, $^2J_{PC}$ 3.3 Hz); *Z*-enol **XIVc**: 12.37 (CH_3); 89.10 (P–C=, $^1J_{PC}$ 192.0 Hz); 112.00 (C^3 – furan, $^2J_{PC}$ 9.8 Hz); 121.08 (C^4-furan); 142.38 (C^5-furan); 155.45 (C^2-furan, $^3J_{PC}$ 7.4 Hz); 158.58 (=C–O, $^2J_{PC}$ 10.5 Hz); 158.63 (C=O-ester); 160.05 (C=O-furan). ^{31}P NMR spectrum, δ_P, ppm: 16.52 (**XIVa**); 22.14 (**XIVc**).

Ethyl 3-(2-ethoxycarbonylfur-3-yl)-3-(diethoxyphosphoryl)-2-oxopropanoate (XV). ^1H NMR spectrum, δ, ppm: common signals: 1.25 t (CH_3, J_{HH} 6.8 Hz); 1.27 t (CH_3, J_{HH} 6.8 Hz); 1.37 t (CH_3, J_{HH} 7.2 Hz); 1.38 t (CH_3, J_{HH} 7.2 Hz); 4.04–4.16 m (CH_2OP); 4.32–4.39 m (CH_2OC); ketone **XVa**: 6.57 d (CHP, J_{PH} 27.6 Hz); 6.98 s (H^4-furan); 7.52 s (H^5-furan); *Z*-enol **XVc**: 6.61 s (H^4-furan); 7.52 s (H^5-furan); 11.92 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: common signals: 13.11 (CH_3); 13.91 (CH_3); 14.13 (CH_3); 14.23 (CH_3); 16.15 (CH_3, $^3J_{PC}$ 6.0 Hz); 16.30 (CH_3, $^3J_{PC}$ 6.0 Hz); 60.83 (CH_2O); 61.18 (CH_2O); 61.69 (CH_2O); 63.03 (CH_2O-furan); 60.86 (CH_2OP, $^2J_{PC}$ 6.6 Hz); 62.14 (CH_2OP, $^2J_{PC}$ 6.6 Hz); 63.39 (CH_2OP, $^2J_{PC}$ 6.6 Hz); 63.74 (CH_2OP, $^2J_{PC}$ 6.6 Hz); ketone **XVa**: 44.49 (CH–P, $^1J_{PC}$ 125.8 Hz); 114.87 (C^4-furan, $^3J_{PC}$ 2.0 Hz); 123.76 (C^3-furan, $^2J_{PC}$ 8.9 Hz); 140.82 (C^2-furan, $^2J_{PC}$ 10.3 Hz); 144.95 (C^5-furan) 158.74 (C=O-ester); 160.30 (C=O-furan); 186.49 (C=O-ktone, $^2J_{PC}$ 5.2 Hz); *Z*-enol **XVc**: 86.39 (P–C=, $^1J_{PC}$ 193.2 Hz); 115.00 (C^4-furan); other signals overlap with **XVa**; 158.52 (C=O-ester); 159.08 (=C–O); 160.30 (C=O-furan). ^{31}P NMR spectrum, δ_P, ppm: 15.43 (**XVa**); 21.76 (**XVc**).

Ethyl 3-(3-ethoxycarbonylfur-2-yl)-3-(diethoxyphosphoryl)-2-oxopropanoate (XVI). ^1H NMR spectrum, δ, ppm: common signals: 1.26–1.41 m (CH_3); 4.13 m (CH_2OP, J_{HH} 7.0 Hz, J_{PH} 13.6 Hz); 4.22 q (CH_2OC, J_{HH} 7.2 Hz); 4.305 q (CH_2OC, J_{HH} 7.2 Hz); ketone **XVIa**: 6.52 d (CHP, J_{PH} 26.4 Hz); 6.69 br.s (H^4-furan); 7.47 br.s (H^5-furan); *E*-enol **XVIb**: 6.26 br.s (H^4-furan); 7.42 br.s (H^5-furan); 9.03 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: common signals 13.68 (CH_3); 13.89 (CH_3); 14.15 (CH_3); 14.21 (CH_3); 16.00 (CH_3, $^3J_{PC}$ 7.1 Hz); 16.07 (CH_3, $^3J_{PC}$ 7.1 Hz); 16.25 (CH_3, $^3J_{PC}$ 6.3 Hz); 60.49 (CH_2O); 60.81 (CH_2O); 62.06 (CH_2O); 63.11 (CH_2O); 63.44 (CH_2OP, $^2J_{PC}$ 4.2 Hz); 63.82 (CH_2OP, $^2J_{PC}$ 5.7 Hz); ketone **XVIa**: 47.52 (CH–P, $^1J_{PC}$ 128.8 Hz); 110.90 (C^4-furan); 116.72 (C^3-furan, $^3J_{PC}$ 6.6 Hz); 141.49 (C^2-furan, $^2J_{PC}$ 4.9 Hz); 143.20 (C^5-furan); 160.55 (C=O-ester); 162.93 (C=O-furan); 184.71 (C=O-ketone, $^2J_{PC}$ 4.1 Hz); *E*-enol **XVIb**: 91.99 (P–C=, $^1J_{PC}$ 176.3 Hz); 111.63 (C^4-furan); 117.11 (C^3-furan, $^3J_{PC}$ 5.4 Hz); 141.81 (C^2-furan $^2J_{PC}$ 2.4 Hz); 142.26 (C^5-furan); 159.90 (C=O, $^3J_{PC}$ 6.7 Hz); 161.51 (=C-O, $^2J_{PC}$ 22.9 Hz); 162.93 (C=O-furan). ^{31}P NMR spectrum, δ_P, ppm: 13.74 (**XVIa**); 20.68 (**XVIb**).

Ethyl 3-(4-ethoxycarbonylfur-2-yl)-3-(diethoxyphosphoryl)-2-oxopropanoate (XVII). ^1H NMR spectrum, δ, ppm: common signals: 1.25–1.39 m (CH_3); 4.13–4.17 m (CH_2OP); 4.18 q (CH_2OC, J_{HH} 7.2 Hz); 4.34 q (CH_2OC, J_{HH} 7.2 Hz); ketone **XVIIa**: 5.66 d (CHP, J_{PH} 26.8 Hz); 6.91 s (H^3-furan); 7.94 s (H^5-furan); *E*-enol **XVIIb**: 6.53 s (H^3-furan); 7.86 s (H^5-furan); 11.18 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: common signals: 13.82 (CH_3); 14.23 (CH_3); 60.39 (CH_2O);

60.48 (CH_2O); 62.19 (CH_2O); ketone **XVIIa**: 16.29 (CH_3, $^3J_{PC}$ 5.9 Hz); 47.63 (CH–P, $^1J_{PC}$ 128.7 Hz); 62.52 (CH_2OP, $^2J_{PC}$ 6.5 Hz); 108.18 (C^3-furan, $^3J_{PC}$ 7.2 Hz); 120.60 (C^4-furan); 147.40 (C^2-furan, $^2J_{PC}$ 7.3 Hz); 147.47 (C^5-furan); 162.35 (C=O-ester); 162.90 (C=O-furan); 184.32 (C=O-ketone); E-enol **XVIIb**: 16.01 (CH_3, $^3J_{PC}$ 6.3 Hz); 63.39 (CH_2OP, $^2J_{PC}$ 4.1 Hz); 90.72 (P–C=, $^1J_{PC}$ 177.7 Hz); 108.93 (C^3-furan, $^3J_{PC}$ 2.6 Hz); 120.89 (C^4-furan); 146.89 (C^5-furan); 147.22 (C^2-furan, $^2J_{PC}$ 8.4 Hz); 162.46 (=C-O, $^2J_{PC}$ 22.1 Hz); 162.46 (C=O, $^3J_{PC}$ 6.3 Hz); 162.76 (C=O-furan). ^{31}P NMR spectrum, δ_P, ppm: 13.42 (**XVIIa**); 20.91 (**XVIIb**).

Ethyl 3-(4-ethoxycarbonylfur-3-yl)-3-(diethoxyphosphoryl)-2-oxopropanoate (XVIII). ^{1}H NMR spectrum, δ, ppm: common signals: 1.25–1.29 m (CH_3); 1.31 t (CH_3, J_{HH} 7.2 Hz); 1.34 t (CH_3, J_{HH} 7.2 Hz); 4.07–4.18 m (CH_2OP); 4.26 q (CH_2OC, J_{HH} 7.2 Hz); 4.37 q (CH_2OC, J_{HH} 7.2 Hz); ketone **XVIIIa**: 6.24 d (CHP, J_{PH} 27.6 Hz); 7.84 s (H^2-furan); 7.98 s (H^5-furan); *E*-enol **XVIIIb**: 7.49 s (H^2-furan); 7.95 s (H^5-furan); 11.89 br.s (OH). ^{13}C NMR spectrum, δ_C, ppm: ketone **XVIIIa**: 13.92 (CH_3); 14.12 (CH_3); 16.15 (CH_3, $^3J_{PC}$ 4.7 Hz); 43.29 (CH–P, $^1J_{PC}$ 126.4 Hz); 60.52 (CH_2O); 62.90 (CH_2O); 63.33 (CH_2OP, $^2J_{PC}$ 6.8 Hz); 63.76 (CH_2OP, $^2J_{PC}$ 6.5 Hz); 114.06 (C^3-furan, $^2J_{PC}$ 7.6 Hz); 117.29 (C^4-furan, $^3J_{PC}$ 7.2 Hz); 144.89 (C^2-furan, $^3J_{PC}$ 5.9 Hz); 148.17 (C^5-furan); 160.26 (C=O-ester); 162.98 (C=O-furan); 186.66 (C=O-ketone, $^2J_{PC}$ 4.7 Hz); *E*-enol **XVIIIb**: 13.67 (CH_3); 16.29 (CH_3, $^3J_{PC}$ 6.2 Hz); 60.29 (CH_2O); 61.69 (CH_2O); 62.12 (CH_2OP, $^2J_{PC}$ 6.7 Hz); 90.54 (P–C=, $^1J_{PC}$ 184.5 Hz); 114.579 (C^3-furan, $^2J_{PC}$ 9.7 Hz); 118.91 (C^4-furan); 142.53 (C^2-furan, $^3J_{PC}$ 8.4 Hz); 148.50 (C^5-furan); 160.72 (=C–O, $^2J_{PC}$ 22.9 Hz); 162.13 (C=O, $^3J_{PC}$ 9.7 Hz); 163.25 (C=O-furan). ^{31}P NMR spectrum, δ_P, ppm: 16.40 (**XVIIIa**); 22.68 (**XVIIIb**).

Synthesis of enol phosphates of phosphorylated derivatives of furylacetic aldehyde and furylpyruvic acid *(general procedure)*. Triethylamine, 0.011 mol, and a solution of 0.01 mol of diethyl chlorophosphate in 10 mL of ethyl acetate were added to a solution of 0.01 mol of the carbonyl compound in 40 mL of ethyl acetate. The obtained mixture was stirred during 4 h at room temperature and left overnight. Triethylamine hydrochloride was filtered off, and the filtrate was washed sequentially with 15 mL of water, 15 mL of 5% sodium carbonate, and 15 mL of water; and then dried over sodium sulfate. The solvent was removed at reduced pressure, and the residue was kept in vacuum (1 mmHg) during 1 h at room temperature. Enol phosphates were viscous liquids readily soluble in chloroform, ethyl acetate, acetone, and ethanol; poorly soluble in water. Yields and isomeric composition of the reaction products are presented in the Tables 3 and 4.

Diethyl *E*-1-(5-ethoxycarbonylfur-2-yl)-2-(diethoxyphosphoryloxy)ethenephosphonate (XIXa). ^{1}H NMR spectrum, δ, ppm: 1.29–1.39 m (CH_3); 4.09–4.19 m (CH_2OP-phosphonate); 4.20–4.27 m (CH_2OP-phosphate); 4.303 q (CH_2OC, J_{HH} 7.2 Hz); 6.74 d (H^3-furan, J_{HH} 3.2 Hz); 7.15 d (H^4-furan, J_{HH} 3.2 Hz); 7.50 d (=CH–O, J_{PH} 10.4 Hz, J_{POH} 6.8 Hz). ^{13}C NMR spectrum, δ_C, ppm: 14.27 (CH_3); 15.94 (CH_3, $^3J_{PC}$ 6.4 Hz); 16.20 (CH_3, $^3J_{PC}$ 6.3 Hz); 60.78 (CH_2OC); 62.86 (CH_2OP-phosphonate, $^2J_{PC}$ 5.5 Hz); 65.40 (CH_2OP-phosphate, $^2J_{PC}$ 6.0 Hz); 105.60 (P–C=, $^1J_{PC}$ 187.5 Hz, $^3J_{POC}$ 9.6 Hz); 113.14 (C^3-furan, $^3J_{PC}$ 3.9 Hz); 118.78 (C^4-furan); 143.95 (C^5-furan); 148.11 (=CH–O, $^2J_{PC}$ 23.1 Hz, $^2J_{POC}$ 3.9 Hz); 149.35 (C^2-furan, $^2J_{PC}$ 9.2 Hz); 158.38 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 13.64, –5.56.

Diethyl 1-(5-ethoxycarbonyl-2-methylfur-3-yl)-2-(diethoxyphosphoryloxy)ethenephosphonate (XX). ^{1}H NMR spectrum, δ, ppm: common signals: 1.17–1.33 m (CH_3); 3.99–4.18 m (CH_2OP); 4.25–4.30 m (CH_2OC); *E*-isomer **XXa**: 2.23 d (CH_3-furan, J_{PH} 1.2 Hz); 7.04 s (H^4-furan); 7.37 d.d (=CH–, J_{PH} 10.0 Hz, J_{POH} 5.8 Hz); *Z*-isomer **XXb**: 2.22 d (CH_3-furan, J_{PH} 1.6 Hz); 6.94 d.d (=CH–, J_{PH} 32.8 Hz, J_{POH} 6.0 Hz); 7.06 s (H^4-furan). ^{13}C NMR spectrum, δ_C, ppm: common signals: 14.08 (CH_3); 14.33 (CH_3); 16.00 (CH_3, $^3J_{PC}$ 5.9 Hz); 16.28 (CH_3, $^3J_{PC}$ 5.7 Hz); 60.85 (CH_2O); 62.40 (CH_2OP-phosphonate, $^2J_{PC}$ 5.2 Hz); 65.11 (CH_2OP-phosphate, $^2J_{PC}$ 5.9 Hz); *E*-isomer **XXa**: 13.36 (CH_3-furan); 107.48 (P–C=, $^1J_{PC}$ 190.4 Hz, $^3J_{POC}$ 9.5 Hz); 112.58 (C^3-furan, $^2J_{PC}$ 4.2 Hz); 119.92 (C^4-furan); 142.79 (C^5-furan); 147.43 (=CH–O, $^2J_{PC}$ 30.3 Hz, $^2J_{POC}$ 3.3 Hz); 155.09 (C^2-furan, $^3J_{PC}$ 10.6 Hz); 158.67 (C=O); *Z*-isomer **XXb**: 12.61 (CH_3-furan); 120.12 (C^4-furan); 142.17 (C^5-furan); 147.41 (=CH–O, $^2J_{PC}$ 4.0 Hz); 158.67 (C=O); ^{31}P NMR spectrum, δ_P, ppm: 16.18, –4.90 (**XXa**); 11.88, –5.57 (**XXb**).

Diethyl 1-(2-ethoxycarbonylfur-3-yl)-2-(diethoxyphosphoryloxy)ethenephosphonate (XXI). ^{1}H NMR spectrum, δ, ppm: common signals: 1.17–1.29 m (CH_3); 4.00–4.08 m (CH_2OP); 4.24 q (CH_2OC, J_{HH} 7.2 Hz); *E*-isomer **XXIa**: 6.44 d (H^4-furan, J_{HH} 3.6 Hz); 7.39 d.d (=CH–, J_{PH} 10.0 Hz, J_{POH} 6.0 Hz); 7.43 d (H^5-furan, J_{HH} 3.6 Hz); *Z*-isomer **XXIb**: 6.41 br.s (H^4-furan); 7.17 d.d (=CH–, J_{PH} 32.4 Hz, J_{POH} 6.0 Hz); 7.43 d. (H^5-furan, J_{HH} 3.6 Hz). ^{13}C NMR spectrum, δ_C,

ppm: common signals: 14.11 (CH_3); 15.87 (CH_3, $^3J_{PC}$ 6.4 Hz); 16.14 (CH_3, $^3J_{PC}$ 6.4 Hz); *E*-isomer **XXIa**: 60.84 (CH_2O); 62.28 (CH_2OP-phosphonate, $^2J_{PC}$ 5.3 Hz); 64.91 (CH_2OP-phosphate, $^2J_{PC}$ 5.9 Hz); 106.58 (P–C=, $^1J_{PC}$ 192.6 Hz, $^3J_{POC}$ 10.6 Hz); 114.08 (C^4-furan); 122.28 (C^3-furan, $^2J_{PC}$ 5.9 Hz); 141.23 (C^2-furan, $^3J_{PC}$ 9.6 Hz); 144.98 (C^5-furan); 148.62 (=CH–O, $^2J_{PC}$ 28.7 Hz, $^2J_{POC}$ 3.1 Hz); 158.30 (C=O); *Z*-isomer **XXIb**: 60.64 (CH_2O); 61.78 (CH_2OP-phosphonate, $^2J_{PC}$ 4.8 Hz); 65.11 (CH_2OP-phosphate, $^2J_{PC}$ 6.0 Hz); 115.44 (C^4-furan); 123.31 (C^3-furan, $^2J_{PC}$ 4.0 Hz); 140.31 (C^2-furan, $^3J_{PC}$ 11.6 Hz); 144.70 (C^5-furan); 158.69 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 18.50, –4.306 (**XXIa**); 15.57, –5.28 (**XXIb**).

Diethyl 1-(3-ethoxycarbonylfur-2-yl)-2-(diethoxyphosphoryloxy)ethenephosphonate (XXII). ^{1}H NMR spectrum, δ, ppm: common signals: 1.17–1.39 m (CH_3); 4.04–4.10 m (CH_2OP); 4.17–4.25 m (CH_2OC); signals of equal intensity: 6.69 br.s, 6.71 br.s (H^4-furan, *E* + *Z*-isomers); 7.35 br.s + 7.39 br.s (H^5-furan, *E* + *Z*-isomers); *E*-isomer **XXIIa**: 7.54 d.d (=CH–, J_{PH} 9.2 Hz, J_{POH} 6.8 Hz); *Z*-isomer **XXIIb**: 7.41 d.d (=CH–, J_{PH} 31.2 Hz, J_{POH} 6.4 Hz). ^{13}C NMR spectrum, δ_C, ppm: common signals: 14.09 (CH_3); 14.15 (CH_3); 16.23 (CH_3, $^3J_{PC}$ 6.8 Hz); 16.05 (CH_3, $^3J_{PC}$ 6.1 Hz); 16.23 (CH_3, $^3J_{PC}$ 6.8 Hz); 104.00 (P–C=, $^1J_{PC}$ 215.7 Hz, $^3J_{POC}$ 7.8 Hz) + 104.70 (P–C=, $^1J_{PC}$ 233.6 Hz, $^3J_{POC}$ 8.3 Hz); 111.45 + 111.61 (C^4-furan, *E* + *Z*-isomers); 116.70 ($^3J_{PC}$ 6.5 Hz) + 117.99 ($^3J_{PC}$ 6.0 Hz) (C^3-furan, *E* + *Z*-isomers); 142.42 + 142.78 (C^5-furan, *E* + *Z*-isomers); 152.05 ($^2J_{PC}$ 2.0 Hz) + 152.31 ($^2J_{PC}$ 3.3 Hz) (C^2-furan, *E* + *Z*-isomers); 162.51 + 162.76 (C=O, *E* + *Z*-isomers); *E*-isomer **XXIIa**: 152.64 (=CH–O, $^2J_{PC}$ 25.2 Hz, $^2J_{POC}$ 2.9 Hz); *Z*-isomer **XXIIb**: 151.47 (=CH–O, $^2J_{PC}$ 4.2 Hz). ^{31}P NMR spectrum, δ_P, ppm: 13.77; 9.76; –5.53; –5.82.

Diethyl 1-(4-ethoxycarbonylfur-2-yl)-2-(diethoxyphosphoryloxy)ethenephosphonate (XXIII). ^{1}H NMR spectrum, δ, ppm: common signals: 1.26–1.40 m (CH_3); 4.02-4.15 m (CH_2OP-phosphonate); 4.21 m (CH_2OP-phosphate, J_{HH} 7.6 Hz, J_{PH} 15.2 Hz,); 4.27 q (CH_2OC, J_{HH} 7.2 Hz); *E*-isomer **XXIIIa**: 6.96 s (H^3-furan); 7.42 d.d (=CH–, J_{PH} 10.4 Hz, J_{POH} 6.8 Hz); 7.96 s (H^5-furan). ^{13}C NMR spectrum, δ_C, ppm: *E*-isomer **XXIIIa**: 14.24 (CH_3); 15.98 (CH_3, $^3J_{PC}$ 6.2 Hz); 16.17 (CH_3, $^3J_{PC}$ 6.2 Hz); 60.51 (CH_2O); 62.24 (CH_2OP, $^2J_{PC}$ 5.9 Hz); 62.61 (CH_2OP, $^2J_{PC}$ 5.2 Hz); 105.45 (P–C=, $^1J_{PC}$ 186.0 Hz, $^3J_{POC}$ 9.6 Hz); 111.13 (C^3-furan, $^3J_{PC}$ 5.2 Hz); 120.77 (C^4-furan); 146.77 (C^5-furan); 146.93 (C^2-furan, $^3J_{PC}$ 7.8 Hz); 146.98 (=CH–O, $^2J_{PC}$ 23.2 Hz, $^2J_{POC}$ 4.4 Hz); 162.71 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 14.27, –5.24 (**XXIIIa**); 10.11, –5.38 (**XXIIIb**).

Diethyl 1-(4-ethoxycarbonylfur-3-yl)-2-(diethoxyphosphoryloxy)ethenephosphonate (XXIV). ^{1}H NMR spectrum, δ, ppm: common signals: 1.07–1.26 m (CH_3); 3.91–4.02 m (CH_2OP); 4.07–4.15 m (CH_2OC); *E*-isomer **XXIVa**: 7.29 d.d (=CH–, J_{PH} 9.6 Hz, J_{POH} 6.0 Hz); 7.30 s (H^2-furan); 7.82 s (H^5-furan); *Z*-isomer **XXIV**b: 7.02 d.d (=CH–, J_{PH} 32.4 Hz, J_{POH} 6.0 Hz); 7.30 s (H^2-furan); 7.85 s (H^5-furan). ^{13}C NMR spectrum, δ_C, ppm: common signals: 15.76 (CH_3); 16.06 (CH_3, $^3J_{PC}$ 5.7 Hz); 60.84(CH_2O); *E*-isomer **XXIVa**: 14.02 (CH_3); 61.991(CH_2OP-phosphonate, $^2J_{PC}$ 5.6 Hz); 64.95 (CH_2OP-phosphate, $^2J_{PC}$ 6.3 Hz); 106.82 (P–C=, $^1J_{PC}$ 186.3 Hz, $^3J_{POC}$ 12.4 Hz); 115.06 (C^3-furan, $^2J_{PC}$ 8.6 Hz); 117.95 (C^4-furan, $^3J_{PC}$ 12.4 Hz); 142.80 (C^2-furan, $^3J_{PC}$ 7.0 Hz); 148.36 (=CH–O, $^2J_{PC}$ 35.4 Hz); 148.55 (C^5-furan); 162.37 (C=O); *Z*-isomer **XXIVb**: 13.99 (CH_3); 62.16 (CH_2OP-phosphonate, $^2J_{PC}$ 4.8 Hz); 64.77 (CH_2OP-phosphate, $^2J_{PC}$ 5.7 Hz); 104.61 (P–C=, $^1J_{PC}$ 192.9 Hz, $^3J_{POC}$ 10.6 Hz); 114.23 (C^3-furan, $^2J_{PC}$ 5.9 Hz); 118.31 (C^4-furan, $^3J_{PC}$ 5.5 Hz); 142.62 (C^2-furan, $^3J_{PC}$ 3.6 Hz); 148.17 (C^5-furan); 148.80 (=CH–O, $^2J_{PC}$ 2.8 Hz); 162.26 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 11.77, –5.83 (**XXIVa**); 16.02, –5.45 (**XXIVb**).

Diethyl 1-(5-ethoxycarbonylfur-2-yl)-2-(diethoxyphosphoryloxy)-2-(ethoxycarbonyl)ethenephosphonate (XXV). ^{1}H NMR spectrum, δ, ppm: common signals: 1.22–1.33 m (CH_3); 4.05–4.17 m (CH_2OP); 4.24–4.34 m (CH_2OP); *E*-isomer **XXVa**: 6.62 d.d (H^3-furan, J_{HH} 3.6 Hz, J_{PH} 2.4 Hz); 7.09 d (H^4-furan, J_{HH} 3.6 Hz); *Z*-isomer **XXVb:** 6.72 d.d (H^3-furan, J_{HH} 3.6 Hz, J_{PH} 1.6 Hz); 7.13 d (H^4-furan, J_{HH} 3.6 Hz). ^{13}C NMR spectrum, δ_C, ppm: common signals: 15.81 (CH_3 $^3J_{PC}$ 7.1 Hz); 15.89 (CH_3, $^3J_{PC}$ 7.2 Hz); 16.06 (CH_3 $^3J_{PC}$ 7.2 Hz); 16.13 (CH_3, $^3J_{PC}$ 7.2 Hz); *E*-isomer **XXVa**: 14.21 (CH_3); 60.87 (CH_2O); 62.57 (CH_2O); 62.91 (CH_2OP-phosphonate, $^2J_{PC}$ 5.6 Hz); 65.40 (CH_2OP-phosphate, $^2J_{PC}$ 6.7 Hz); 110.24 (P–C=, $^1J_{PC}$ 235.9 Hz, $^3J_{POC}$ 9.2 Hz); 113.93 (C^3-furan, $^2J_{PC}$ 8.6 Hz); 118.67 (C^4-furan); 144.57 (C^5-furan); 149.23 (C^2-furan, $^2J_{PC}$ 10.7 Hz); 150.13 (=CH–O, $^2J_{PC}$ 24.8 Hz, $^2J_{POC}$ 6.7 Hz); 158.21 (C=O, $^3J_{PC}$ 5.2 Hz); 161.78 (C=O); *Z*-isomer **XXVb**: 13.59 (CH_3); 60.87 (CH_2O); 63.05 (CH_2OP-phosphonate, $^2J_{PC}$ 5.2 Hz); 65.03 (CH_2OP-phosphate, $^2J_{PC}$ 6.5 Hz; 108.44 (P–C=, $^1J_{PC}$ 240.0 Hz, $^3J_{POC}$ 9.0 Hz); 114.41 (C^3-furan, $^3J_{PC}$ 9.7 Hz); 118.93 (C^4-furan); 144.57 (C^5-furan); 148.67 (C^2-furan, $^2J_{PC}$ 6.2 Hz); 149.77 (=CH–O, $^2J_{PC}$ 3.7 Hz); 161.78 (C=O); 161.92 (C=O, $^3J_{PC}$ 17.0 Hz).

^{31}P NMR spectrum, δ_P, ppm: 11.03, –8.98 (**XXVa**); 9.14 ($^4J_{PP}$ 2.3 Hz), –8.405 ($^4J_{PP}$ 2.3 Hz) (**XXVb**).

Diethyl 1-(5-ethoxycarbonyl-2methylfur-3-yl)-2-(diethoxyphosphoryloxy)-2-(ethoxycarbonyl)ethenephosphonate (XXVI). ^{1}H NMR spectrum, δ, ppm: common signals: 1.10–1.33 m (CH_3); 3.99–4.11 m (CH_2OP); 4.23–4.30 m (CH_2O); *E*-isomer **XXVIa**: 7.06 s (H^4-furan); *Z*-isomer **XXVIb**: 7.06 s (H^4-furan). ^{13}C NMR spectrum, δ_C, ppm: common signals: 14.24 (CH_3); 16.23 (CH_3 $^3J_{PC}$ 6.2 Hz); 62.64 (CH_2OP-phosphonate, $^2J_{PC}$ 6.0 Hz); 62.67 (CH_2O); *E*-isomer **XXVIa**: 12.01 (CH_3-furan); 13.65 (CH_3); 15.75 (CH_3, $^3J_{PC}$ 7.3 Hz); 60.65 (CH_2O); 64.95 (CH_2OP-phosphate, $^2J_{PC}$ 6.0 Hz); 112.93 (P–C=, $^1J_{PC}$ 147.5 Hz, $^3J_{POC}$ 9.2 Hz); 115.03 (C^3-furan, $^2J_{PC}$ 5.2 Hz); 120.22 (C^4-furan); 142.71 (C^5-furan); 148.39 (C^2-furan, $^3J_{PC}$ 8.9 Hz); 155.60 (=CH–O, $^2J_{PC}$ 30.0 Hz, $^2J_{POC}$ 9.0 Hz); 158.53 (C=O); 158.65 (=C–C=O); *Z*-isomer **XXVIb:** 12.54 (CH_3-furan); 13.50 (CH_3); 15.92 (CH_3,$^3J_{PC}$ 7.1 Hz); 60.81 (CH_2O); 65.35 (CH_2OP-phosphate, $^2J_{PC}$ 6.0 Hz); 112.77 (P–C=, $^1J_{PC}$ 180.5 Hz, $^3J_{POC}$ 9.1 Hz); 114.76 (C^3-furan, $^2J_{PC}$ 3.9 Hz); 120.761 (C^4-furan); 142.57 (C^5-furan); 147.96 (C^2-furan, $^3J_{PC}$ 5.9 Hz); 155.23 (=CH–O, $^2J_{PC}$ 7.3 Hz); 158.53 (C=O); 161.74 (=C–C=O, $^3J_{PC}$ 18.4 Hz). ^{31}P NMR spectrum, δ_P, ppm: 11.95, –8.50 (**XXVIa**); 10.71 ($^4J_{PP}$ 3.4 Hz), –7.89 ($^4J_{PP}$ 3.4 Hz) (**XXVIb**).

Diethyl 1-(2-ethoxycarbonylfur-3-yl)-2-(diethoxyphosphoryloxy)-2-(ethoxycarbonyl)ethenephosphonate (XXVII). ^{1}H NMR spectrum, δ, ppm: common signals: 1.16–1.21 m (CH_3); 1.23–1.31 m (CH_3); 3.94–4.05 m (CH_2OP); 4.18–4.29 m (CH_2O); *E*-isomer **XXVIIa**: 6.42 s (H^4-furan); 7.50 s (H^5-furan); *Z*-isomer **XXVIIb:** 6.42 s (H^4-furan); 7.46 s (H^5-furan). ^{13}C NMR spectrum, δ_C, ppm: *E*-isomer **XXVIIa**: 13.59 (CH_3); 14.22 (CH_3); 15.66 (CH_3, $^3J_{PC}$ 6.8 Hz); 61.16 (CH_2O); 62.06 (CH_2O); 63.47 (CH_2OP-phosphonate, $^2J_{PC}$ 5.6 Hz); 64.81 (CH_2OP-phosphate, $^2J_{PC}$ 6.2 Hz); 114.31 (C^4-furan); 125.23 (C^3-furan, $^2J_{PC}$ 3.0 Hz); 141.15 (C^2-furan, $^3J_{PC}$ 6.7 Hz); 145.16 (C^5-furan); 158.33 (=C–C=O); 161.93 (C=O); *Z*-isomer **XXVIIb**: 13.27 (CH_3); 13.96 (CH_3); 15.88 (CH_3, $^3J_{PC}$ 7.2 Hz); 16.11 (CH_3, $^3J_{PC}$ 6.3 Hz); 60.99 (CH_2O); 61.91 (CH_2O); 62.97 (CH_2OP-phosphonate, $^2J_{PC}$ 6.1 Hz); 65.11 (CH_2OP-phosphate, $^2J_{PC}$ 6.1 Hz); 114.51 (P–C=, $^1J_{PC}$ 179.8 Hz, $^3J_{POC}$ 9.4 Hz); 115.06 (C^4-furan); 125.34 (C^3-furan, $^2J_{PC}$ 3.8 Hz); 140.90 (C^2-furan, $^3J_{PC}$ 7.2 Hz); 144.80 (C^5-furan); 146.81 (=CH–O, $^2J_{PC}$ 6.1 Hz); 158.99 (C=O); 161.32 (=C–C=O, $^3J_{PC}$ 17.8 Hz). ^{31}P NMR spectrum, δ_P, ppm: 10.99, –8.91 (**XXVIIa**); 9.84 ($^4J_{PP}$ 2.9 Hz), –7.84 ($^4J_{PP}$ 2.9 Hz) (**XXVIIb**).

Diethyl 1-(3-ethoxycarbonylfur-2-yl)-2-(diethoxyphosphoryloxy)-2-(ethoxycarbonyl)ethenephosphonate (XXVIII). ^{1}H NMR spectrum, δ, ppm: common signals: 1.27–1.39 m (CH_3); 4.06–4.15 m (CH_2OP); 4.33–4.43 m (CH_2O); *E*-isomer **XXVIIIa**: 6.830 br.s (H^4-furan); 7.49 br.s (H^5-furan); *Z*-isomer **XXVIIIb**: 6.78 d (H^4-furan, J_{HH} 1.8 Hz); 7.46 d.d (H^5-furan, J_{HH} 1.8 Hz, J_{PH} 1.6 Hz). ^{13}C NMR spectrum, δ_C, ppm: common signals: 13.97 (CH_3); 15.85 (CH_3); 16.03 (CH_3, $^3J_{PC}$ 6.6 Hz); 16.17 (CH_3, $^3J_{PC}$ 7.1 Hz); 60.21 (CH_2O); 60.73 (CH_2O); 62.24 (CH_2OP-phosphonate, $^2J_{PC}$ 5.8 Hz); 63.45 (CH_2OP, $^2J_{PC}$ 5.5 Hz); *Z*-isomer **XXVIIIb**: 110.80 (C^4-furan); 115.32 (C^3-furan); 116.70 (P–C=, $^1J_{PC}$ 262.8 Hz, $^3J_{POC}$ 7.5 Hz); 141.66 (C^5-furan); 149.51 (=CH–O, $^2J_{PC}$ 4.3 Hz); 150.85 (C^2-furan, $^2J_{PC}$ 5.3 Hz); 152.42 (=C–C=O, $^3J_{PC}$ 13.6 Hz); 162.74 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 9.80, –9.09 (**XXVIIIa)**; 8.77 ($^4J_{PP}$ 2.8 Hz), –8.10 ($^4J_{PP}$ 2.8 Hz) (**XXVIIIb)**.

Diethyl 1-(4-ethoxycarbonylfur-2-yl)-2-(diethoxyphosphoryloxy)-2-(ethoxycarbonyl)ethenephosphonate (XXIX). ^{1}H NMR spectrum, δ, ppm: common signals: 1.22–1.31 m (CH_3); 1.35 m (CH_3, J_{HH} 7.0 Hz); 4.07–4.16 m (CH_2OP); 4.20–4.37 m (CH_2O); *E*-isomer **XXIXa**: 6.78 d (H^4-furan, J_{PH} 2.4 Hz); 7.95 s (H^5-furan); *Z*-isomer **XXIXb**: 6.99 br.s (H^4-furan); 8.00 s (H^5-furan). ^{13}C NMR spectrum, δ_C, ppm: common signals: 15.91 (CH_3 $^3J_{PC}$ 6.0 Hz); 16.11 (CH_3, $^3J_{PC}$ 8.2 Hz); 16.18 (CH_3, $^3J_{PC}$ 6.6 Hz); 16.32 (CH_3, $^3J_{PC}$ 6.1 Hz); *E*-isomer **XXIXa**: 13.69 (CH_3); 14.22 (CH_3); 60.55 (CH_2O); 62.47 (CH_2O); 62.89 (CH_2OP-phosphonate, $^2J_{PC}$ 5.4 Hz); 65.44 (CH_2OP-phosphate, $^2J_{PC}$ 6.2 Hz); 109.03 (P–C=, $^1J_{PC}$ 173.9 Hz, $^3J_{POC}$ 8.6 Hz); 111.64 (C^3-furan, $^3J_{PC}$ 3.7 Hz); 121.13 (C^4-furan); 146.97 (C^2-furan, $^3J_{PC}$ 8.3 Hz); 147.55 (C^5-furan); 162.53 (C=O); 162.54 (=C–C=O, $^3J_{PC}$ 3.7 Hz); Z-isomer XXIXb: 13.63 (CH_3); 14.22 (CH_3); 60.34 (CH_2O); 62.34 (CH_2O); 62.82 (CH_2OP-phosohonate, $^2J_{PC}$ 8.8 Hz); 65.26 (CH_2OP-phosphate, $^2J_{PC}$ 6.0 Hz); 108.31 (P–C=, $^1J_{PC}$ 183.2 Hz, $^3J_{POC}$ 7.0 Hz); 112.55 (C^3-furan, $^2J_{PC}$ 4.2 Hz); 120.84 (C^4-furan); 146.38 (C^2-furan, $^2J_{PC}$ 5.1 Hz); 147.34 (C^5-furan); 149.76 (=CH–O, $^2J_{PC}$ 5.2 Hz); 161.99 (=C–C=O, $^3J_{PC}$ 16.5 Hz); 162.91 (C=O). ^{31}P NMR soectrum, δ_P, m.d.: 9.273($^4J_{PP}$ 2.7 Hz), –8.294 ($^4J_{PP}$ 2.7 Hz) (**XXIXa**); 10.72–8.73 (**XXIXb**).

Diethyl 1-(4-ethoxycarbonylfur-3-yl)-2-(diethoxyphosphoryloxy)-2-(ethoxycarbonyl)ethenephosphonate (XXX). ^{1}H NMR spectrum, δ, ppm: common

signals: 1.04 t (CH_3, J_{HH} 7.2 Hz); 1.19–1.27 m (CH_3); 1.30 t (CH_3, J_{HH} 7.2 Hz); 1.36 t (CH_3, J_{HH} 6.8 Hz); 4.03–4.15 m (CH_2OP); 4.22–4.37 m (CH_2O); *E*-isomer **XXXa**: 7.37 br.s (H^2-furan); 8.02 br.s (H^5-furan); *Z*-isomer **XXXb**: 7.32 br.s (H^2-furan); 7.97 br.s (H^5-furan). ^{13}C NMR spectrum, δ_C, ppm: common signals: 13.39 (CH_3); 13.92 (CH_3); 14.18 (CH_3); 15.73 (CH_3, $^3J_{PC}$ 6.9 Hz); 15.96 (CH_3, $^3J_{PC}$ 6.8 Hz); 16.20 (CH_3, $^3J_{PC}$ 6.2 Hz); 60.32 (CH_2O); 60.43 (CH_2O); 60.65 (CH_2O); 61.94 (CH_2O); 62.53 (CH_2OP-phosphonate, $^2J_{PC}$ 5.8 Hz); 62.61 (CH_2OP-phosphonate, $^2J_{PC}$ 5.8 Hz); 63.27 (CH_2OP-phosphonate, $^2J_{PC}$ 6.8 Hz); 63.69 (CH_2OP-phosphonate, $^2J_{PC}$ 6.4 Hz); 64.871 (CH_2OP-phosphate, $^2J_{PC}$ 6.3 Hz); 65.14 (CH_2OP-phosphate, $^2J_{PC}$ 5.4 Hz); *E*-isomer **XXXa**: 117.28 (C^3-furan, $^2J_{PC}$ 7.0 Hz); 119.45 (C^4-furan); 142.749 (C^2-furan, $^3J_{PC}$ 7.7 Hz); 148.15 (C^5-furan); 159.15 (=C–<u>C</u>=O); 162.97 (C=O); *Z*-isomer **XXXb**: 113.06 (P–C=, $^1J_{PC}$ 183.4 Hz, $^3J_{POC}$ 9.5 Hz); 117.47 (C^3-furan, $^2J_{PC}$ 3.6 Hz); 119.84 (C^4-furan); 142.49 (C^2-furan, $^3J_{PC}$ 7.3 Hz); 146.90 (=CH–O, $^2J_{PC}$ 6.0 Hz); 148.15 (C^5-furan); 161.64 (=C–<u>C</u>=O, $^3J_{PC}$ 18.1 Hz); 162.62 (C=O). ^{31}P NMR spectrum, δ_P, ppm: 11.70, –8.76 (**XXXa**); 10.58 ($^4J_{PP}$ 3.4 Hz), –7.842 ($^4J_{PP}$ 3.4 Hz) (**XXXb**).

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REFERENCES

1. Marry, G., Grenner, D., Mayes, P., and Radwell, M, *Biokhimiya cheloveka* (Biochemistry of Man), Moscow: Mir, 1993, vol. 1.
2. Ohana, P., Delmer, D.P., Steffens, J.C., Matthews, D.E., Mayer, R., Benziman, M., *J. Biol. Chem*., 1991, vol. 266, no. 21, p. 13742.
3. Robina, I., Moreno-Vargas, A.J., Fernandez-Bolanos, J.G., Fuentes, J., Demange, R., and Vogel, P., *Bioorg. And Medicinal Chem. Lett*., 2001, vol 11, p. 2555. DOI: org/10.1016/S0960-894X(01)00497-8.
4. Pevzner, L.M., *Russ. J. Gen. Chem*., 2012, vol. 82, no. 12, p. 1938. DOI: 10.1134/S1070363412067.
5. Pevzner, L.M., *Russ. J. Gen. Chem*., 2014, vol. 84, no. 4, p. 658. DOI: 109.1134/S1070363214040100.
6. Ismailov, V.M., Moskva V.V., Guseinov, F.I., Zykova, T.V., and Sadykov, I.S., *Zh. Obshch. Khim.*, 1986, vol. 56, no. 9, p. 2005.
7. *www.pharmaexpert.ru/PASSOnline.*
8. Pevzner, L.M., *Russ. J. Gen. Chem*., 2014, vol. 84, no. 7, p. 1143. DOI: 10.1134/S1070363214070159.