

## Research Article

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# MW irradiation and ionic liquids as green tools in hydrolyses and alcoholyses

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**Abstract:** The optimized HCl-catalyzed hydrolysis of alkyl diphenylphosphinates is described. The reaction times and pseudo-first-order rate constants suggested the  $^i\text{Pr} > \text{Me} > \text{Et} \sim \text{Pr} \sim \text{Bu}$  order of reactivity in respect of the alkyl group of the phosphinates. The MW-assisted *p*-toluenesulfonic acid (PTSA)-catalyzed variation means a better alternative possibility due to the shorter reaction times, and the alkaline hydrolysis is another option. The transesterification of alkyl diphenylphosphinates took place only in the presence of suitable ionic liquids, such as butyl-methylimidazolium hexafluorophosphate ([bmim][PF<sub>6</sub>]) and butyl-methylimidazolium tetrafluoroborate ([bmim][BF<sub>4</sub>]). The application of ethyl-methylimidazolium hydrosulfate ([emim][HSO<sub>4</sub>]) and butyl-methylimidazolium chloride ([bmim][Cl]) was not too efficient, as the formation of the ester was accompanied by the fission of the O–C bond resulting in the formation of Ph<sub>2</sub>P(O)OH. This surprising transformation may be utilized in the phosphinate → phosphinic acid conversion.

**Keywords:** phosphinic derivatives, hydrolysis, alcoholysis, microwave irradiation, ionic liquids

widely applied starting materials and intermediates in syntheses [2]. They may also be the precursors of (potentially) biologically active derivatives [6–9]. Hydrolysis of the alkyl phosphinates (and in general *P*-esters including dialkyl phosphonates) is an often used and rather common transformation that may be performed under acidic conditions [10–13], but also in the presence of a base [14–17]. We have recently investigated the acidic hydrolysis of a series of cyclic alkyl phosphinates in detail [18]. Optimum conditions for the acidic hydrolysis of dialkyl arylphosphonates and  $\alpha$ -hydroxy-benzylphosphonates were also explored [19,20]. The reactivity of the starting *P*-esters along with the kinetics was also evaluated. In this paper, the acidic- or base-catalyzed hydrolyses of alkyl diphenylphosphinates are investigated and compared. We wished to find the optimum conditions and to characterize the processes by rate constants. The other purpose was to elaborate the transesterification of our “Ph<sub>2</sub>P(O)OR” model compounds by reaction with series of alcohols. We have had some experience on MW-assisted alcoholysis of dialkyl phosphites, which may lead to fully transesterified products via the intermediate with two different alkoxy groups [21,22]. Continuous flow accomplishments were also developed by us [23].

## 1 Introduction

The esters of phosphinic acids (alkyl phosphinates) prepared in most cases by the reaction of the corresponding phosphinic chloride with alcohol [1,2], or recently, by the microwave-assisted direct esterification of the phosphinic acids in the presence of an IL additive [2–5] are

## 2 Materials and methods

### 2.1 General

The <sup>31</sup>P, <sup>13</sup>C, <sup>1</sup>H NMR spectra were taken on a Bruker DRX-500 spectrometer operating at 202.4, 125.7, and 500 MHz, respectively. The couplings are given in Hz. LC-MS measurements were performed with an Agilent 1,200 liquid chromatography system coupled with a 6,130 quadrupole mass spectrometer equipped with an ESI ion source (Agilent Technologies, Palo Alto, CA, USA). High resolution mass spectrometric measurements were performed using a Thermo Velos Pro Orbitrap Elite hybrid mass spectrometer in positive electrospray mode.

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## 2.2 Preparation of the starting alkyl diphenylphosphinates

The C<sub>1</sub>–C<sub>4</sub> alkyl diphenylphosphinates (**1a–e**) were synthesized by the reaction of diphenylphosphinoyl chloride with the corresponding alcohols at 26°C in the presence of triethylamine in toluene (Scheme 1).

### 2.2.1 General procedure for the preparation of diphenyl phosphinates (**1a–e**)

10.5 mmol (2 mL) of diphenylphosphinic chloride was added to the mixture of 15 mL of toluene, 3 equivalents of alcohol (methanol: 1.27 mL, ethanol: 1.84 mL, propanol: 2.42 mL, isopropanol: 2.42 mL, butanol: 2.88 mL), and 1.61 mL (11.5 mmol) of triethylamine, and the reaction mixture was stirred at reflux for 2 h. After completion of the reaction, the amine salt was filtered off, the filtrate was concentrated in vacuum, and the crude product so obtained was purified by column chromatography (silica gel, hexane–ethyl acetate 7:3 as the eluent) to give the phosphinates (**1a–e**) in yields of 84–90%. The products were analyzed by <sup>31</sup>P NMR spectroscopy.

### 2.3 General procedure for the acidic hydrolysis of diphenylphosphinates (**1a–e**) under conventional conditions

A mixture of 3.7 mmol of diphenylphosphinate (**1a**: 0.86 g, **1b**: 0.91 g, **1c**: 0.96 g, **1d**: 0.96 g, **1e**: 0.99 g), 1.0 mL (6.0 mmol) of concentrated hydrochloric acid, and 2.0 mL of water was stirred at reflux (ca. 100°C) for 4–8 h. Concentration of an aliquot part of the reaction mixture afforded Ph<sub>2</sub>P(O)OH (**2**) as a solid powder in yields of

90–94%, which was analyzed by <sup>31</sup>P NMR spectroscopy and LC-MS.

### 2.4 General procedure for the acidic hydrolysis of diphenylphosphinates (**1a–e**) under MW conditions

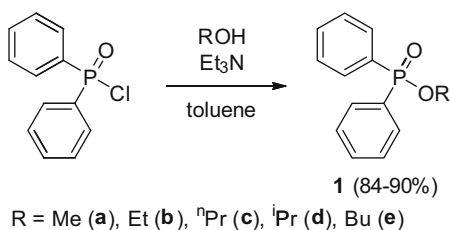
A mixture of 1.9 mmol of diphenylphosphinate (**1a**: 0.43 g, **1b**: 0.46 g, **1c**: 0.49 g, **1d**: 0.49 g, **1e**: 0.51 g), 0.04 g (0.19 mmol) of PTSA, and 1.0 mL of water was irradiated in a sealed tube placed in CEM MW reactor at 160–180°C (max. 100 W) for 0.5–6 h. After evaporating the water, the residue so obtained was washed 3 times with 3 mL of water and dried. Ph<sub>2</sub>P(O)OH (**2**) was obtained as a solid powder in yields of 93–97%, which was analyzed by <sup>31</sup>P NMR spectroscopy and LC-MS.

### 2.5 General procedure for the alkaline hydrolysis of diphenylphosphinates (**1a** and **1b**)

A mixture of 0.43 mmol of the diphenylphosphinate (**1a**: 0.10 g, **1b**: 0.11 g) and 0.38–0.42–0.69 mL of 5% NaOH solution (0.47–0.52–0.85 mmol of NaOH) was stirred at 50°C for 5–45 min. To liberate the free acid, hydrochloric acid was added dropwise to the Na-salt. After evaporating the water, the residue was washed 3 times with 2 mL of water and then dried. The product so obtained was analyzed by <sup>31</sup>P NMR spectroscopy.

### 2.6 General procedure for the alcoholysis of diphenylphosphinates (**1a–e**) with pentanol

0.43 mmol of alkyl diphenylphosphinate (**1a**: 0.10 g, **1b**: 0.11 g, **1c**: 0.11 g, **1d**: 0.11 g, **1e**: 0.12 g,) was added to 0.70 mL (6.5 mmol) *n*-pentanol and 0.043 mmol ([bmim][PF<sub>6</sub>]: 9 µL, [bmim][BF<sub>4</sub>]: 6.5 µL, [bmim][Cl]: 8 µL, [emim][HSO<sub>4</sub>]: 6.5 µL) ionic liquid. The mixture was irradiated in a sealed tube placed in CEM MW reactor at 220°C (max. 100 W) for 2 h. After evaporating the excess of the pentanol and purifying the residue by column chromatography (silica gel, hexane–ethyl acetate 7:3 as the



**Scheme 1:** Preparation of the starting alkyl diphenylphosphinates (**1a–e**).

eluent), the reaction mixture was analyzed by  $^{31}\text{P}$  NMR spectroscopy.

## 2.7 General procedure for the alcoholysis of methyl diphenylphosphinate (1a) with different alcohols

0.43 mmol of methyl diphenylphosphinate (**1a**) (0.10 g) was added to 6.5 mmol of the alcohol (*n*-propanol: 0.45 mL, *i*-propanol 0.48 mL, *n*-butanol 0.56 mL, *i*-butanol: 0.59 mL, cyclohexanol: 0.67 mL) and 9  $\mu\text{L}$  (0.043 mmol) [bmim][PF<sub>6</sub>]. The mixture was irradiated in a sealed tube placed in CEM MW reactor at 200–220°C (max. 100 W) for 2–3.5 h. After evaporating the excess of the alcohol, and purifying the residue so obtained by column chromatography (silica gel, hexane–ethyl acetate 7:3 as the eluent), the phosphinates (**1c–f, h**) were obtained in yields of 89–92%. The esters **1c–h** were analyzed by  $^{31}\text{P}$  NMR spectroscopy.

Identification of the starting material (**1a**) and the ester products (**1c–h**), as well as the acid (**2**), can be found in Table 1.

## 2.8 Use of the $^{31}\text{P}$ NMR spectra during monitoring the hydrolyses and alcoholyses

The composition of the reaction mixtures was determined by integration of the areas under the corresponding peaks of the starting material and product in the  $^{31}\text{P}$  NMR spectra.

## 2.9 Curve fitting on the time – relative quantity data pairs

The acidic hydrolyses were modelled assuming pseudo-first-order kinetics. The concentration of water and hydrochloric acid was constant during the reaction. The calculated time–composition curves were fitted to the experimental data using nonlinear least-squares method. The pseudo-first-order rate constants were optimized so that the sum of squares of the residuals (i.e., the difference of the experimental and the calculated composition) be the minimal. The approximate values of the rate constants were found iteratively, using the nonlinear generalized reduced gradient method of Microsoft Excel Solver.

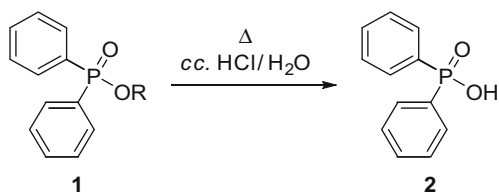
# 3 Results and discussion

## 3.1 Hydrolysis of alkyl diphenylphosphinates under acidic conditions on conventional heating

The hydrolyses of alkyl diphenylphosphinates (**1a–e**) were performed in water medium containing 12% of hydrochloric acid at reflux (Scheme 2). The reactions were monitored by  $^{31}\text{P}$  NMR. The concentration profiles for the components during the hydrolysis of the Me, Et,  $^n\text{Pr}$ ,  $^i\text{Pr}$ , and Bu esters (**1a–e**) are shown in Figures 1–5. The curves were fit by the nonlinear least-squares method. It can be seen that the reaction time fell in the range of 3–7 h. The pseudo-first-order rate constants calculated are listed in Table 2. The hydrolysis of the methyl ester (**1a**) was significantly faster ( $t_r = 4$  h and  $k = 1.36$  h<sup>−1</sup>)

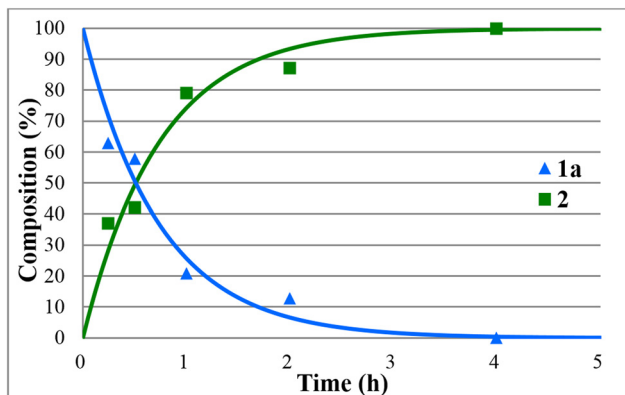
**Table 1:**  $^{31}\text{P}$  NMR characterization of diphenylphosphinates (**1a–h**) and diphenylphosphinic acid (**2**)

Compounds	R	$\delta^{31}\text{P}$ NMR	
		Found (solvent)	Literature (solvent)
<b>1a</b>	Me	33.3 (CDCl <sub>3</sub> )	33.3 [24] (CDCl <sub>3</sub> )
<b>1b</b>	Et	31.4 (CDCl <sub>3</sub> )	31.4 [24] (CDCl <sub>3</sub> )
<b>1c</b>	$^n\text{Pr}$	31.2 (CDCl <sub>3</sub> )	31.1 [24] (CDCl <sub>3</sub> )
<b>1d</b>	$^i\text{Pr}$	30.0 (CDCl <sub>3</sub> )	29.8 [24] (CDCl <sub>3</sub> )
<b>1e</b>	Bu	31.9 (CDCl <sub>3</sub> )	31.1 [24] (CDCl <sub>3</sub> )
<b>1f</b>	$^t\text{Bu}$	31.1 (CDCl <sub>3</sub> )	31.0 [25] (CDCl <sub>3</sub> )
<b>1g</b>	Pent	31.3 (CDCl <sub>3</sub> )	31.2 [24] (CDCl <sub>3</sub> )
<b>1h</b>	$^c\text{Hex}$	29.8 (CDCl <sub>3</sub> )	29.7 [24] (CDCl <sub>3</sub> )
<b>2</b>	H	23.5–23.7 (acidic) 23.6–23.8 (MW) 23.4–23.6 (alkaline) (DMSO)	23.4 [26] (DMSO)

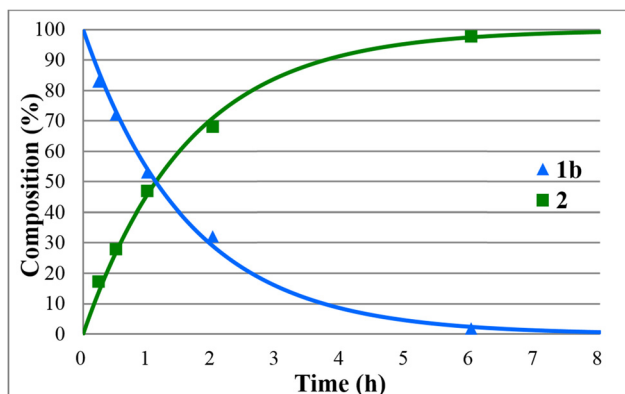


R = Me (a), Et (b), <sup>n</sup>Pr (c), <sup>i</sup>Pr (d), Bu (e)

**Scheme 2:** Acidic hydrolysis of diphenylphosphinates on conventional heating.

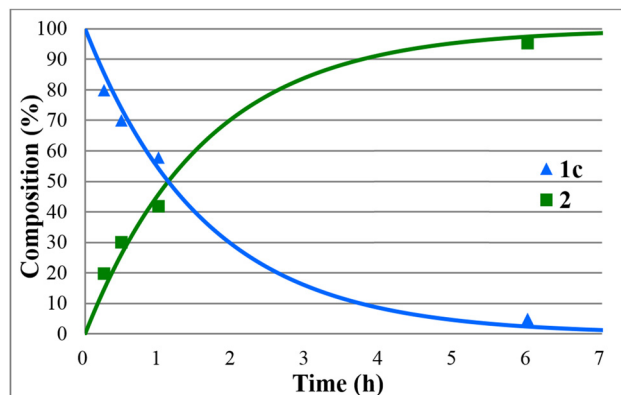


**Figure 1:** Concentration profile for the components (1a and 2) during the hydrolysis of methyl diphenylphosphinate (1a) under optimum conditions. The  $R^2$  measure of goodness of fit is 0.941.

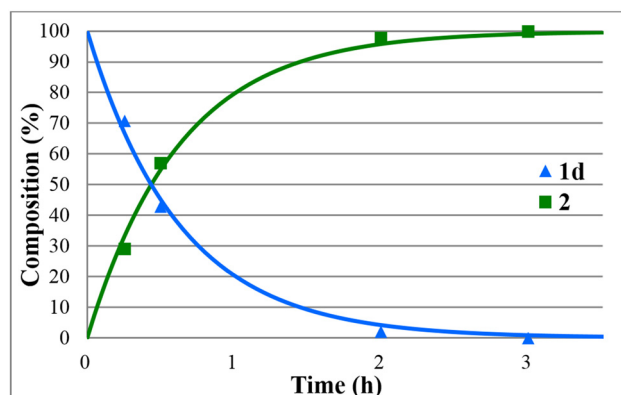


**Figure 2:** Concentration profile for the components (1b and 2) during the hydrolysis of ethyl diphenylphosphinate (1b) under optimum conditions. The  $R^2$  measure of goodness of fit is 0.995.

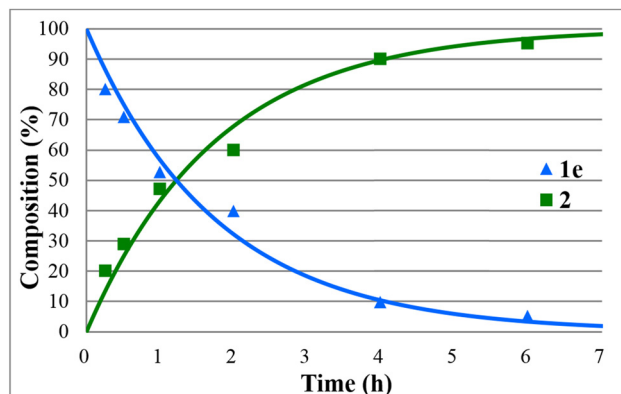
than that of the *n*-alkyl esters (1b,c,e) ( $t_r = 6.5\text{--}7\text{ h}$  and  $k = 0.57\text{--}0.62\text{ h}^{-1}$ ). It is noteworthy that the <sup>i</sup>Pr ester (1d) was hydrolyzed more than twice as much faster than the <sup>n</sup>Pr derivative (1c) (compare  $t_r = 3\text{ to }7\text{ h}$ , and  $k = 1.6\text{ h}^{-1}$  to  $k = 0.62\text{ h}^{-1}$ ). In the latter case, obviously the  $A_{Al}1$  mechanism operates.



**Figure 3:** Concentration profile for the components (1c and 2) during the hydrolysis of propyl diphenylphosphinate (1c) under optimum conditions. The  $R^2$  measure of goodness of fit is 0.980.



**Figure 4:** Concentration profile for the components (1d and 2) during the hydrolysis of isopropyl diphenylphosphinate (1d) under optimum conditions. The  $R^2$  measure of goodness of fit is 0.993.



**Figure 5:** Concentration profile for the components (1e and 2) during the hydrolysis of butyl diphenylphosphinate (1e) under optimum conditions. The  $R^2$  measure of goodness of fit is 0.958.

**Table 2:** Pseudo-first-order rate constants ( $k_A$  and  $k_{MW}$ ) obtained for the thermal HCl-catalyzed and MW-assisted PTSA-catalyzed hydrolyses

Entry	R	$k_A$ ( $h^{-1}$ )	$k_{MW}$ ( $h^{-1}$ )
1	Me ( <b>1a</b> )	1.36	1.52
2	Et ( <b>1b</b> )	0.62	0.86
3	<sup>n</sup> Pr ( <b>1c</b> )	0.62	—
4	<sup>i</sup> Pr ( <b>1d</b> )	1.60	1.92
5	<sup>n</sup> Bu ( <b>1e</b> )	0.57	—

The HCl-catalyzed hydrolyses of phosphinates **1a–e** furnished diphenylphosphinic acid (**2**) in yields of 90–94%; however, the reaction times were in most cases (**1b–d**) as long as 7–8 h. The hydrolysis of the Me and <sup>i</sup>Pr diphenylphosphinate (**1a** and **1e**) was complete after 4 and 3 h, respectively.

### 3.2 Hydrolysis of alkyl diphenylphosphinates under acidic conditions on microwave irradiation

In the second phase of our study, the alkyl diphenylphosphinates (**1a–e**) were hydrolyzed under microwave (MW) irradiation. To avoid corrosion problems caused by the HCl, in these experiments PTSA served as the catalyst. The experimental data are summarized in Table 3.

Applying 1 equivalent of PTSA, the hydrolysis of methyl phosphinate **1a** was complete at 140°C after 3.75 h or at 160°C after 0.75 h (Table 3, entries 1 and 2). Using only 0.5 equivalents of PTSA at 160°C, the completion required 1.5 h (Table 3, entry 3). Decreasing the quantity of the catalyst to 0.1 equivalents, there was need for a reaction time of 4 h (Table 3, entry 4). Increasing the temperature to 180°C, an irradiation of 1.5 h was enough (Table 3, entry 5). The hydrolysis of the ethyl ester (**1b**) was somewhat slower; in the presence of 0.1 equivalents of PTSA at 160°C and 180°C, the completion took 6 and 2 h, respectively (Table 3, entries 6 and 7). Similar results were obtained for the hydrolysis of the *n*-propyl and the *n*-butyl phosphinate (**1c** and **1e**) (Table 3, entries 8, 9, 12, and 13). In the Me (**1a**), Et (**1b**), <sup>n</sup>Pr (**1c**), and Bu (**1e**) cases, the hydrolyses were about 3-times faster at 180°C than at 160°C. It is noteworthy that the hydrolysis of isopropyl diphenylphosphinate (**1d**) was again significantly faster: at 160°C and 180°C, the completion required 2 and 0.5 h, respectively (Table 3, entries 10 and 11). This is the consequence of the A<sub>AC</sub>1 mechanism.

**Table 3:** MW-assisted hydrolysis of alkyl phenylphosphinates (**1a–e**) in the presence of PTSA catalyst

Entry	R	Temperature (°C)	PTSA (equiv.)	Reaction time (h)	Yield (%)
1	Me	140	1	3.75	
2	Me	160	1	0.75	
3	Me	160	0.5	1.5	
4	Me	160	0.1	4	
5	Me	180	0.1	1.5	94
6	Et	160	0.1	6	
7	Et	180	0.1	2	96
8	<sup>n</sup> Pr	160	0.1	6.5	
9	<sup>n</sup> Pr	180	0.1	2.1	95
10	<sup>i</sup> Pr	160	0.1	2	
11	<sup>i</sup> Pr	180	0.1	0.5	97
12	Bu	160	0.1	6	
13	Bu	180	0.1	2.2	94

A comparative thermal experiment corresponding to entry 5 of Table 3 afforded phosphinic acid **2** in a significantly lower conversion of 24% referring to the role of MWs. This observation may be the consequence of local overheatings [27] and the better MW absorbing ability of PTSA. Earlier, the beneficial effect of onium salts was demonstrated [28].

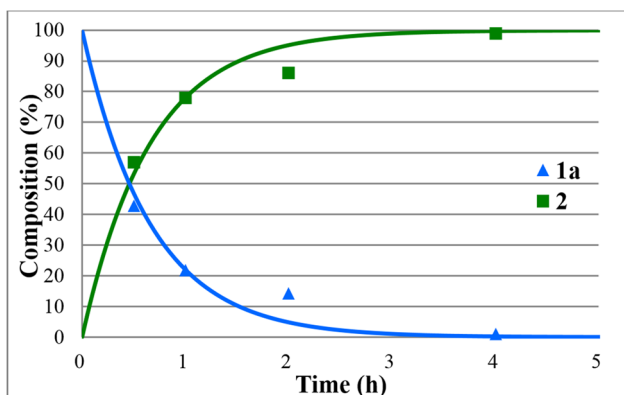
The MW-assisted hydrolyses performed at 180°C in the presence of 10% of PTSA can be regarded as robust and green affording diphenylphosphinic acid (**2**) practically quantitatively (in yields of 93–97%) after removing the PTSA catalyst by washing with water.

To determine the corresponding pseudo-first-order rate constants, the hydrolyses of phosphinates **1a**, **1b**, and **1d** performed at 160°C in the presence of 0.1 equivalents of PTSA were monitored by <sup>31</sup>P NMR (Figures 6–8). The rate constants are listed in Table 2.

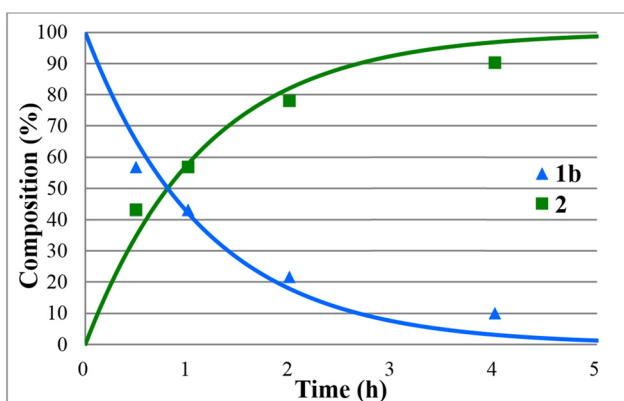
It can be seen that the rate constants obtained under MW conditions at 160°C applying 0.1 equivalents of PTSA were significantly higher than those determined on conventional heating at 100°C in the presence of 12% aqueous HCl.

As a comparison, the MW-assisted PTSA-catalyzed hydrolyses seem to be more advantageous than the HCl-promoted conversions on conventional heating, as

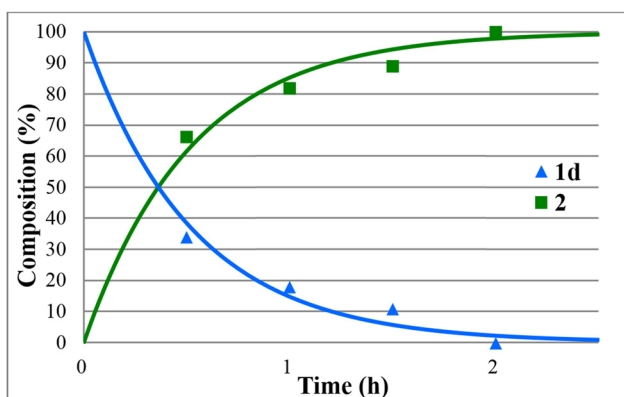




**Figure 6:** Concentration profile for the components (**1a** and **2**) during the hydrolysis of methyl diphenylphosphinate (**1a**) under MW conditions at 160°C. The  $R^2$  measure of goodness of fit is 0.977.



**Figure 7:** Concentration profile for the components (**1b** and **2**) during the hydrolysis of ethyl diphenylphosphinate (**1b**) under MW conditions at 160°C. The  $R^2$  measure of goodness of fit is 0.903.



**Figure 8:** Concentration profile for the components (**1d** and **2**) during the hydrolysis of isopropyl diphenylphosphinate (**1d**) under MW conditions at 160°C. The  $R^2$  measure of goodness of fit is 0.896.

**Table 4:** Alkaline hydrolysis of alkyl diphenylphosphinates (**1a–b**) under different conditions

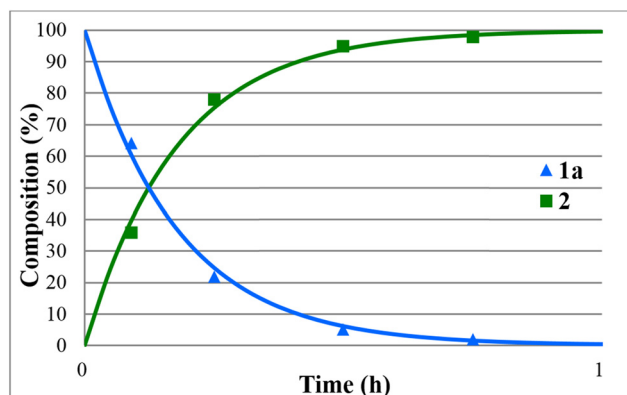
Entry	R	NaOH (equiv.)	Time	Conversion to <b>2</b> (%)	$k$ (dm <sup>3</sup> /mol h)
1	Me	1.1	45 min	98	4.31
2	Me	1.2	35 min	100	—
3	Me	2	15 min	100	—
4	Et	1.2	7 h	100	0.31
5	Et	2	4 h	98	—

the reaction times were significantly shorter, especially for the hydrolyses of the esters with *n*-alkyl substituent (ca. 5 h at 160°C vs 7–8 h at 100°C).

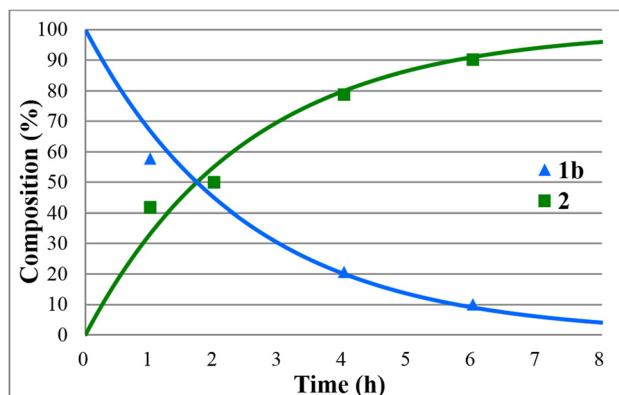
### 3.3 Alkaline hydrolysis of alkyl diphenylphosphinates

Beside acidic hydrolysis, the alkaline version is also a good option to convert P-esters to P-acids. The methyl and ethyl diphenylphosphinates (**1a** and **1b**) were hydrolyzed at 50°C using aqueous 5% NaOH solution in different portions (Table 4). Applying 1.1, 1.2, and 2 equivalents of NaOH in reaction with methyl diphenylphosphinate (**1a**), the hydrolysis was complete after 45, 35, and 15 min, respectively (Table 4, entries 1–3). It is noteworthy that the conversion of the ethyl ester (**1b**) to diphenylphosphinic acid (**2**) was much slower under similar conditions and took 7 and 4 h using 1.2 equivalents and 2 equivalents of NaOH, respectively (Table 4, entries 4 and 5). The sensitivity of the basic hydrolysis on the substituents is in accord with earlier observations [29]. Two selected cases marked by entries 1 and 4 of Table 4 were monitored by <sup>31</sup>P NMR. The resulting curves are shown in Figures 9 and 10, respectively. The second order rate constants were obtained as 4.31 and 0.31 dm<sup>3</sup>/mol h, respectively.

The alkaline hydrolysis is an alternative possibility to the option performed in the presence of an acid. It required a lower temperature of 50°C, but the rate was sensitive to the nature of the alkyl substituent: the



**Figure 9:** Concentration profile for the components (**1a** and **2**) during the alkaline hydrolysis of methyl diphenylphosphinate (**1a**) at 50°C, in the presence of 1.1 equiv. NaOH. The  $R^2$  measure of goodness of fit is 0.991.



**Figure 10:** Concentration profile for the components (**1b** and **2**) during the alkaline hydrolysis of ethyl diphenylphosphinate (**1b**) at 50°C, in the presence of 1.2 equiv. NaOH. The  $R^2$  measure of goodness of fit is 0.931.

hydrolysis of the methyl diphenylphosphinate (**1a**) was complete after 1 h, while that of the ethyl ester (**1b**) required a prolonged reaction time of 8 h. Moreover, after the hydrolysis, there was need to liberate the free acid (**2**) by an acidic treatment.

### 3.4 The alcoholysis of alkyl diphenylphosphinates

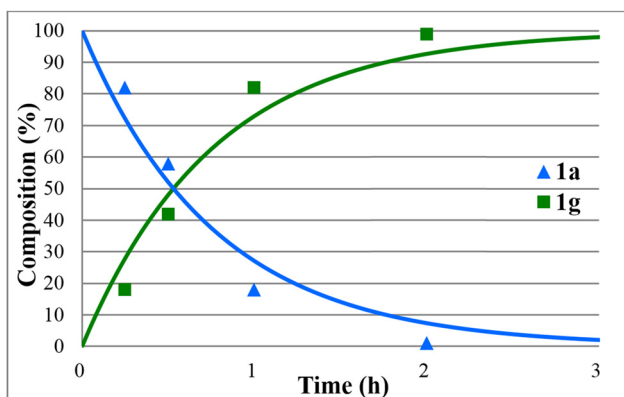
Phosphinic esters may also participate in alcoholysis reactions. The first model reaction was the transesterification of methyl diphenylphosphinate (**1a**) with pentanol. The results are summarized in Table 5. As can be

seen, at 220°C, there was no reaction between phosphinate **1a** and PentOH after a 2 h MW irradiation (Table 5, entry 1). On the basis of our earlier experiences, ionic liquid additives promoted the direct esterification of *P*-acids [4,5,30]. For this, the alcoholysis was also attempted in the presence of 10 mol% of the selected ionic liquids. Applying 10 mol% of [bmim][BF<sub>4</sub>] or [bmim][PF<sub>6</sub>] as an additive at 220°C, the conversion was 63% and 100%, respectively (Table 5, entries 2 and 3), meaning that the use of 10 mol% [bmim][PF<sub>6</sub>] is the method of choice for an efficient transesterification. The latter reaction was monitored by <sup>31</sup>P NMR (Figure 11). The pseudo-first-order rate constant was obtained as 1.47 h<sup>-1</sup>. However, carrying out the model reaction in the presence of [bmim][Cl] and [emim][HSO<sub>4</sub>], surprisingly a side reaction comprising

**Table 5:** Alcoholysis of methyl diphenylphosphinate (**1a**) with pentanol under MW conditions in the presence of different ILs

Entry	IL	Composition <sup>a</sup>		
		1a (%)	1g (%)	2 (%)
1	—	99	1	0
2	[bmim][BF <sub>4</sub> ]	37	63	0
3	[bmim][PF <sub>6</sub> ]	0	100	0
4	[bmim][Cl]	42	2	56
5	[emim][HSO <sub>4</sub> ] <sup>b</sup>	0	18	82

<sup>a</sup> On the basis of relative <sup>31</sup>P NMR intensities. <sup>b</sup> The reaction time was 130 min.



**Figure 11:** Concentration profile for the components (**1a** and **1g**) during the alcoholysis of methyl diphenylphosphinate (**1a**) with pentanol under MW condition at 220°C, in the presence of 10% of [bmim][PF<sub>6</sub>] monitored by LC-MS. The  $R^2$  measure of goodness of fit is 0.938 ( $k = 1.31 \text{ h}^{-1}$ ).

the fission of the ester group to the acid function predominated (Table 5, entries 4 and 5). The [emim][HSO<sub>4</sub>] additive was so efficient that the ratio of the ester (**1g**) and acid (**2**) was 18:82. In other words, instead of transesterification, the fission of the ester function took place with a selectivity of 82%. This novel transformation can be regarded as an alternative for hydrolysis and will be studied in detail in due course.

In the next stage, methyl diphenylphosphinate (**1a**) was reacted with different alcohols under MW irradiation in the presence of 10 mol% of [bmim][PF<sub>6</sub>] (Table 6). The alcoholysis of phosphinate **1a** with *n*-propyl alcohol was

complete after a 2 h heating at 200°C (Table 6, entry 1). At the same time, the similar reaction with *i*-propyl alcohol was not successful, as the product (**1d**) formed decomposed almost quantitatively under the conditions of the reaction (Table 6, entry 2). The unstability of *i*-propyl diphenylphosphinate (**1d**) on heating has been described [31]. Completion of the transesterification of phosphinate **1a** with *n*- and *i*-butyl alcohol required 2 h at 220°C (Table 6, entries 3 and 4). The similar reaction of ester **1a** with cyclohexanol required a longer reaction time of 3.5 h at 220°C (Table 6, entry 5). This is the consequence of steric hindrance. After flash column chromatography, the phosphinates were obtained in yields of 89–92%.

Finally, different alkyl phosphinates (**1b–e**) were subjected to alcoholysis with *n*-pentanol in the presence of 10 mol% of [bmim][PF<sub>6</sub>]. The case starting from the methyl ester (**1a**) is recalled (Table 5, entry 3). The alcoholysis of the ethyl phosphinate **1b** hardly proceeded after a treatment at 220°C for 4 h (Table 7, entry 1). However, after an irradiation at 225°C for 4 h in the presence of 20 mol% of the additive, the conversion was 97% (Table 7, entry 2). Alcoholyses of the *n*-propyl and *n*-butyl esters (**1c** and **1e**) at 225°C remained incomplete after 4 h, when only 10 mol% of the additive was used. The conversions were ca. 43% (Table 7, entries 3 and 6). Repeating the reaction at 225°C using 20 mol% of the additive, the conversion amounted to 80% (Table 7, entry 7). As regards the transesterification of *i*-propyl phosphinate **1d**, it was faster than that of the *n*-propyl derivative (**1c**) (Table 7, entries 4 and 5 vs entry 3). Performing the reaction at

**Table 6:** Alcoholysis of methyl diphenylphosphinate with different alcohols under MW conditions in the presence of 10 mol% of [bmim][PF<sub>6</sub>]

<p style="text-align: center;"> <math>\text{1a} + \text{ROH} \xrightarrow[10 \text{ mol\% [bmim][PF}_6\text{]}]{\text{MW, 200-220}^\circ\text{C, 2 h}} \text{1c-f,h}</math> </p> <p style="text-align: center;">R = Pr (<b>c</b>), <i>i</i>Pr (<b>d</b>), Bu (<b>e</b>), <i>i</i>Bu (<b>f</b>), <sup>c</sup>Hex (<b>h</b>)</p>						
Entry	R	T (°C)	Time (h)	Composition <sup>a</sup>		Yield (%)
				1a (%)	1c–h (%)	
1	<i>n</i> Pr	200	2	5 ( <b>1c</b> )	95	89
2	<i>i</i> Pr	200 <sup>b</sup>	3	3 ( <b>1d</b> )	16	—
3	Bu	220	2	1 ( <b>1e</b> )	99	92
4	<i>i</i> Bu	220	2	1 ( <b>1f</b> )	99	90
5	<sup>c</sup> Hex	220	3.5	3 ( <b>1h</b> )	97	90

<sup>a</sup> On the basis of relative <sup>31</sup>P NMR intensities. <sup>b</sup> 81% of Ph<sub>2</sub>P(O)OH (**2**) was present in the mixture ( $\delta_{\text{P}} = 22.7$  (DMSO),  $\delta_{\text{P}}[26] = 23.4$  (DMSO); M + H = 219).



**Table 7:** Alcoholysis of alkyl diphenylphosphinates with pentanol under MW conditions in the presence of [bmim][PF<sub>6</sub>] as the catalyst

1 + PentOH  $\xrightarrow[\text{[bmim][PF}_6\text{]}]{\text{MW, T, 4 h}}$  1g

R = Et (**b**), <sup>n</sup>Pr (**c**), <sup>i</sup>Pr (**d**), Bu (**e**)

Entry	R	T (°C)	IL (mol%)	Composition <sup>a</sup>	
				1b–e (%)	1g (%)
1	Et	220	10	81 ( <b>1b</b> )	19
2	Et	225	20	3 ( <b>1b</b> )	97
3	<sup>n</sup> Pr	225	10	56 ( <b>1c</b> )	44
4	<sup>i</sup> Pr	220	10	16 ( <b>1d</b> )	70 <sup>b</sup>
5	<sup>i</sup> Pr	225	10	0 ( <b>1d</b> )	77 <sup>c</sup>
6	Bu	225	10	58 ( <b>1e</b> )	42
7	Bu	225	20	20 ( <b>1e</b> )	80

<sup>a</sup> On the basis of relative <sup>31</sup>P NMR intensities. <sup>b</sup> There was 14% of Ph<sub>2</sub>P(O)OH in the crude mixture. <sup>c</sup> There was 23% of Ph<sub>2</sub>P(O)OH in the crude mixture.

220°C for 4 h, only 16% starting material (**1d**) remained in the mixture, while at 225°C all **1d** was consumed. This surprising result can be explained assuming a different mechanism. In the case under discussion, the *i*-propyl ester (**1d**) is converted to the corresponding acid (**2**), and the latter species take part in a direct MW-assisted and IL-catalyzed esterification. This was confirmed by the fact that some Ph<sub>2</sub>P(O)OH could be detected in the crude mixtures (see footnotes “b” and “c” of entries 4 and 5 of Table 7). The reactivity of the ethyl, *n*-propyl, and *n*-butyl phosphinates **1a**, **1b**, and **1e** seemed to be comparable (see entries 1, 3, and 6, as well as entries 2 and 7 of Table 7).

## 4 Conclusions

In summary, from among the three possibilities of the hydrolysis of alkyl diphenylphosphinates, the MW-assisted and PTSA-catalyzed method seems to be the best due to the shorter reaction times, but the HCl-promoted option on conventional heating, as well as the alkaline hydrolysis, may also be applied as these are also efficient, but, with one exception, are somewhat slower. The reactivity of the alkyl phosphinates was also mapped and rate constants were determined. In case of the *i*-propyl ester, the A<sub>Al</sub>1 mechanism was

substantiated. The alcoholyses of alkyl diphenylphosphinates may be performed under the effect of MWs in the presence of [bmim][PF<sub>6</sub>] as the catalyst. The application of [bmim][HSO<sub>4</sub>] led to the fission of the ester moiety to the acid function. This novel reactivity will be explored in due course.

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