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## Tris(2,4,6-trimethoxyphenyl)phosphine – a Lewis base able to compete with phosphazene bases in catalysing oxa-Michael reactions†

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The performance of the strong Lewis base tris(2,4,6-trimethoxyphenyl)phosphine (TTMPP) in catalysing oxa-Michael reactions is assessed and compared with other electron-rich tertiary arylphosphines and, as the benchmark, with the Brønsted base 1-*tert*-butyl-2,2,4,4,4-pentakis-(dimethylamino)-2*λ*<sup>5</sup>,4*λ*<sup>5</sup>-catenadi-phosphazene (P<sub>2</sub>-tBu). A matrix of five varyingly strong Michael acceptors and four varyingly acidic alcohols is used to evaluate the activity of the catalysts. The study demonstrated that TTMPP shows a significant superiority over other arylphosphine based Lewis bases and a similar activity to P<sub>2</sub>-tBu under highly concentrated, quasi solvent free conditions. Furthermore, the performance of TTMPP and P<sub>2</sub>-tBu is compared in the oxa-Michael polymerisation reactions of 2-hydroxyethyl acrylate (HEA) and of 1,4-butanediol diacrylate (BDDA) with diols under solvent free conditions. In the case of HEA, TTMPP is preferred over P<sub>2</sub>-tBu because the latter gave a not fully soluble polymeric product. TTMPP is the first Lewis base capable of catalysing the oxa-Michael polymerisation of diacrylates and diols, albeit P<sub>2</sub>-tBu catalysis results in higher molar masses in this polymerisation reaction. Furthermore, the performance of the catalysts under diluted conditions was assessed and the activity of TTMPP is distinctly more concentration dependent than the activity of P<sub>2</sub>-tBu. The use of the polar protic solvent *t*-butanol mitigates the negative impact of dilution exerted by nonpolar aprotic and polar aprotic solvents such as toluene or dimethylformamide. Finally, data are shown confirming TTMPP to have limited but still acceptable stability to oxygen for practical work in air.

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## Introduction

Lewis base catalysis<sup>1</sup> with tertiary phosphines, often referred to as nucleophilic phosphine catalysis, relies on the conjugate addition of a sufficiently electron rich tertiary phosphine to an electron deficient multiple bond forming an energetically disfavoured zwitterionic species. This zwitterion can then be trapped with nucleophiles, electrophiles or a combination of both, resulting in manifold applications of this methodology in preparative chemistry.<sup>2</sup> A special case of a reaction with an electrophile is the proton transfer of an acidic proton from another reagent, *e.g.* an alcohol, to the zwitterion. This reaction results in the formation of an ion pair consisting of the corresponding phosphonium cation and the corresponding base of the acidic reagent as the newly formed

anion, *e.g.* an alkoxide (Fig. 1). In other words, the Lewis-basic phosphine is creating a zwitterionic Brønsted base, which in turn is protonated by another more acidic reagent.<sup>3</sup>

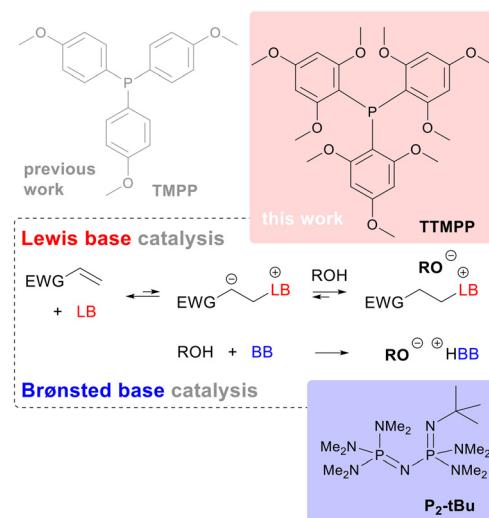


Fig. 1 Generation of alkoxides in Lewis base or in Brønsted base catalysis showing the Lewis and Brønsted bases used in this study.

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This mode of action is exploited in Michael addition chemistries where pronucleophiles, *i.e.* C–H acidic compounds like malonates or thiols, have to be activated upon deprotonation. Since the first demonstration in 1973,<sup>4</sup> phosphine catalysed Michael reactions of carbon, sulphur and oxygen donors have been frequently employed in all areas of organic chemistry,<sup>2</sup> including polymer synthesis.<sup>5</sup> Among Michael donor reagents, oxygen based Michael donors are less frequently used, which has been rationalized by a lack of reactivity and selectivity of these reagents compared to *e.g.* carbon or sulphur based Michael donors.<sup>6</sup> However, within the last decades more and more oxa-Michael reactions were reported<sup>6</sup> and oxa-Michael polymerisations, also named hydrogen-transfer polymerisations,<sup>7</sup> were conducted. Typically, oxa-Michael reactions are Brønsted base catalysed<sup>8,9</sup> and the most potent catalysts for oxa-Michael polymerisations are phosphazene bases.<sup>10</sup> Phosphazene bases are extremely strong, uncharged Brønsted bases that contain a phosphorous atom bonded to four nitrogen atoms and were disclosed by Schwesinger.<sup>11</sup> Some of them, like 1-*tert*-butyl-2,2,4,4,4-penta-kis-(dimethylamino)-2<sup>5</sup>,4<sup>5</sup>-catenadi-(phosphazene) (P<sub>2</sub>-*t*Bu, Fig. 1), are stable in an ambient atmosphere making their use particularly attractive. The toxicity and the relatively high prices of phosphazene bases can be regarded as their downsides. Furthermore, their high basicity might be problematic when base labile substrates need to be used. In such cases, a Lewis base catalyst might be the better choice. Commonly used Lewis base catalysts are tertiary phosphines,<sup>3,12</sup> amines like 4-dimethylaminopyridine<sup>13</sup> and *N*-heterocyclic carbenes.<sup>14</sup> Highly reactive nucleophiles such as trialkylphosphines or NHCs often suffer from poor air and moisture stability or require a strong base to form from their precursors. Therefore, the quest for an air and moisture insensitive Lewis base catalyst with high activity is ongoing. Recently, we have reported a step towards this direction by showing that the electron rich tris(4-methoxyphenyl)-phosphine (TMPP, Fig. 1) is more active in converting poor and intermediate Michael acceptors than triphenylphosphine (TPP).<sup>15</sup> Regrettably, the improvement in activity was not that pronounced that TMPP could rival the performance of phosphazene bases.

Herein, we wish to report the activity of tris(2,4,6-trimethoxyphenyl)phosphine (TTMPP, Fig. 1) as a Lewis base catalyst in oxa-Michael reactions and compare its performance with that of the phosphazene base P<sub>2</sub>-*t*Bu. Moreover, we investigate the oxidation stability of TTMPP.

TTMPP was first disclosed in 1984 by Wada and Higashizaki and has been described as a very strong nucleophile.<sup>16</sup> It acts as a Lewis base catalyst in various reactions such as chemo- and stereoselective deacetylations, ring opening of aziridines, and Henry and sila-Morita–Baylis–Hillman reactions.<sup>17</sup> In polymerisation reactions, the group transfer polymerisation and, in another work, the Lewis-pair catalysed polymerisation of alkyl methacrylates were demonstrated using TTMPP.<sup>18</sup> Epoxy-phenol resins were cured with TTMPP as the catalyst<sup>19</sup> and the reaction of

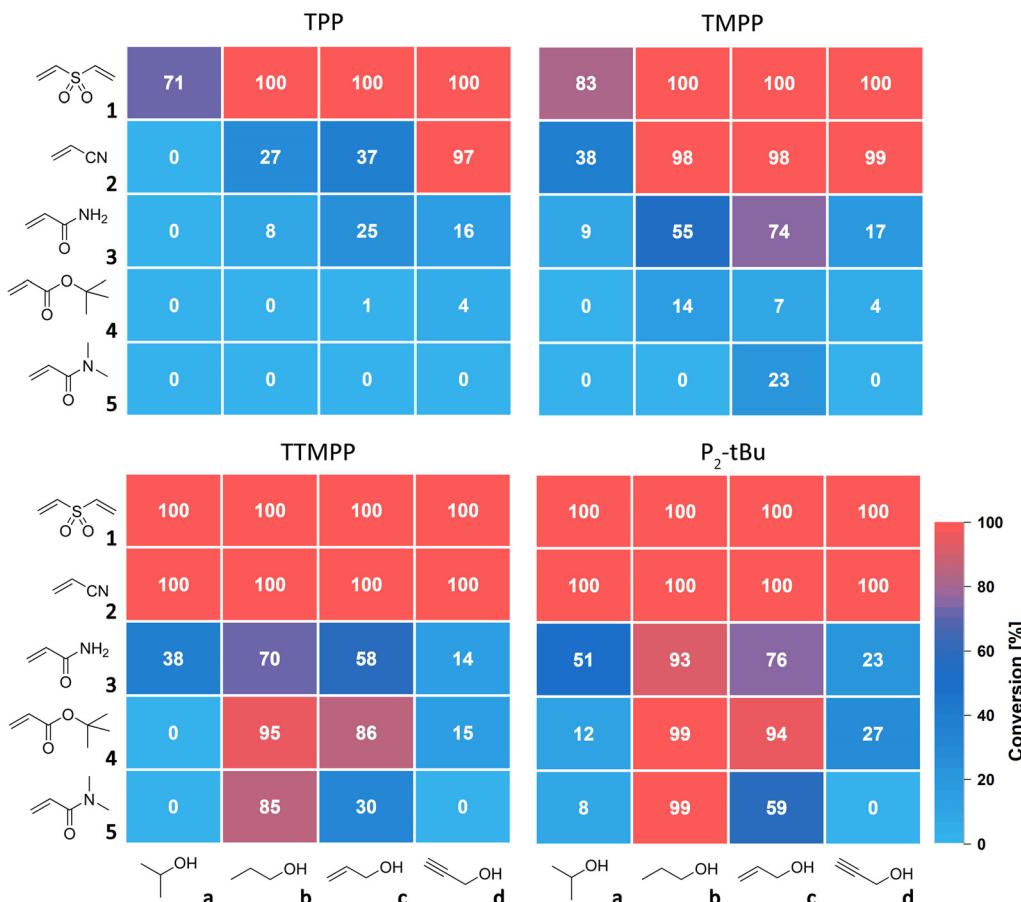
TTMPP with epoxides has been described.<sup>20</sup> Another important application of TTMPP is as a reagent for the preparation of alkali-stable phosphonium cation bearing hydroxide exchange membranes.<sup>21</sup> Recently, also ionic liquids have been prepared from TTMPP.<sup>22</sup> Considering that TTMPP is commercially available from major specialty chemical suppliers, the relatively small number of reports on the use of this compound as a Lewis base catalyst is surprising.

## Results and discussion

The catalytic activity of TTMPP was evaluated by reacting varyingly strong Michael acceptors, namely divinyl sulfone (**1**), acrylonitrile (**2**), acrylamide (**3**), *t*-butyl acrylate (**4**) and *N*,*N*-dimethylacrylamide (**5**), with alcohols of different acidity. All reactions were carried out with 2.0 equiv. alcohol (3.0 equiv. for **1**) and 1 mol% catalyst (with respect to the Michael acceptor) at 25 °C. The conversion of double bonds after 24 h was determined by <sup>1</sup>H NMR spectroscopy. Results for TTMPP are compared with those for TPP, TMPP and the phosphazene base P<sub>2</sub>-*t*Bu and are displayed in Fig. 2.

Strong Michael acceptors like divinyl sulfone (*E* = −18.36, for phenyl vinyl sulfone<sup>23</sup>) and acrylonitrile (*E* = −19.05 (ref. 23)) are fully converted by the Lewis base TTMPP and the Brønsted base P<sub>2</sub>-*t*Bu after 24 h. In contrast, less electron rich TMPP gives (almost) full conversion with primary alcohols (**b–d**), but not with *i*-propanol (**a**). Least active TPP fully converts the most reactive Michael acceptor **1** using primary alcohols.<sup>15</sup> Interestingly, acrylonitrile and *i*-propanol did not react within 24 h using TPP as the catalyst. Weaker Michael acceptors **3**, **4** and **5** are not or only marginally converted with TPP as the catalyst. With TMPP, the situation improves, in particular for acrylamide (no *E* value available) but with *t*-butyl acrylate (*E* = −20.22 (ref. 23)) and *N,N*-dimethylacrylamide (*E* = −23.54 (ref. 23)) no or very low conversions with all alcohols under investigation are obtained. In contrast, TTMPP and P<sub>2</sub>-*t*Bu with propanol and allyl alcohol give satisfactory conversions of all weak Michael acceptors, but not with *i*-propanol and propargyl alcohol. For *t*-butyl acrylate, transesterification was observed as a side reaction (see ESI†). Importantly, TTMPP and P<sub>2</sub>-*t*Bu perform similarly in all investigated combinations and the activity of TTMPP was found to be only slightly lower than that of P<sub>2</sub>-*t*Bu. These findings indicate that alkoxide generation by Lewis base catalysis with TTMPP under the selected conditions is similarly efficient to using the strong Brønsted base and not dependent on the acidity of the alcohol. This is in contrast to reactions of strong acceptors like **1** and **2** catalysed with the weaker Lewis bases TPP and TMPP. In these cases, the acidity of the alcohol was found to be decisive for the speed of the reaction. As particularly evident from the reaction of **2** catalysed with TPP, the least acidic alcohol **a** gave the lowest conversion and the most acidic alcohol **d** the highest conversion after 24 h (Fig. 2).<sup>15</sup> This correlation between the alcohol's acidity and the obtained

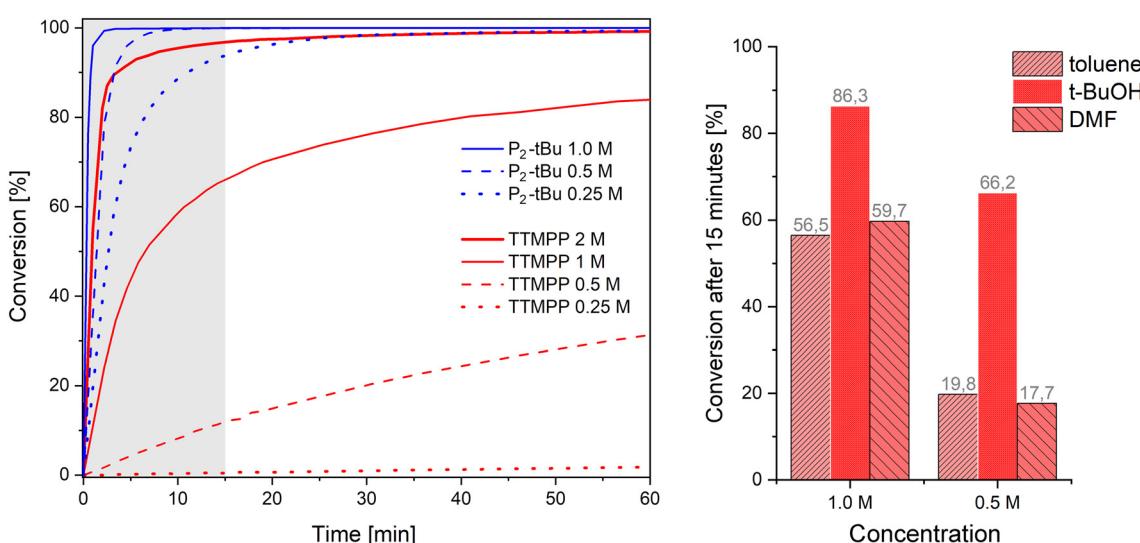




**Fig. 2** Heatmap visualization of the double bond conversion obtained in the benchmarking of different catalysts in the oxa-Michael addition of alcohols with Michael acceptors; reaction conditions: 1.0 equiv. Michael acceptor, 2.0 equiv. alcohol (3 equiv. when reacted with 1), 0.01 equiv. catalyst, solvent-free, 25 °C, 24 h.

conversion can be rationalized by a more efficient trapping of the intermediately formed zwitterion by more acidic alcohols

and thus a faster formation of alkoxide. When strong Michael acceptors react, all alkoxides are nucleophilic enough to form



**Fig. 3** Left: conversion over time of the reaction of acrylonitrile (1 equiv.) with *n*-propanol (1.5 equiv.) in the presence of 1 mol% catalyst at various concentrations (solvent: benzene-*d*<sub>6</sub>) and room temperature; right: bar graph showing the conversion of the same reaction at 15 min vs. the concentration; toluene, *t*-butanol and dimethylformamide were used as the solvents.

the desired Michael adducts. However, when going to weaker Michael acceptors like 3–5, the nucleophilicity of the alkoxides becomes the critical factor for the reaction to proceed. The poor conversions of **4** and **5** with alcohols **a** and **d** can be explained by the relatively poor nucleophilicity of the corresponding alkoxides. Moreover, the obtained conversions correlate with the thermodynamic stabilities of the products (see ESI,† Tables S1 and S2). *n*-Propoxide is the most potent oxa-Michael donor studied here. Its high nucleophilicity is rationalized by a low steric congestion and the lack of stabilization of the negative charge through electronic effects like in **c** or **d**.<sup>24</sup>

### Solvents and dilution

Although the solvent-free conditions used so far are desirable, it is sometimes unavoidable to use solvents, for example, when the donor and acceptor are not soluble in each other. Therefore, the performance of TTMPP and  $P_2-tBu$  (0.01 equiv.) in solution was studied by monitoring the conversion of differently concentrated solutions of acrylonitrile (1 equiv.,  $[2] = 2.0, 1.0, 0.50$  or  $0.25 \text{ mol L}^{-1}$ ) in benzene- $d_6$  upon reaction with *n*-propanol (1.5 fold excess) by  $^1\text{H}$  NMR spectroscopy (Fig. 3, left). At a relatively high concentration of  $2 \text{ mol L}^{-1}$ , the use of TTMPP results in a fast reaction (half-life period  $\tau_{1/2} = 1 \text{ min } 20 \text{ s}$ ). However, upon increasing the dilution, a pronounced deceleration of the reaction is observed. This deceleration is particularly striking when compared to the  $P_2-tBu$  catalysed variants at the same dilution. At a concentration of  $1 \text{ mol L}^{-1}$ ,  $\tau_{1/2}$  increased to  $6 \text{ min } 30 \text{ s}$  when TTMPP is used while the  $P_2-tBu$  catalysed reaction is distinctly faster ( $\tau_{1/2} < 1 \text{ min}$ ).<sup>25</sup> Further halving the concentration of 2 to  $0.5 \text{ mol L}^{-1}$  resulted in a  $\tau_{1/2}$  value of  $162 \text{ min}$  for the TTMPP catalysed reaction. For  $P_2-tBu$ , the Michael addition is still fast ( $\tau_{1/2} = 1 \text{ min } 20 \text{ s}$ ). In other words, all differently diluted Brønsted base catalysed reactions reached conversions  $>95\%$  after 15 min reaction time ( $[2] = 1\text{--}0.25 \text{ mol L}^{-1}$ ). In sharp contrast, the speed of Lewis base catalysed reactions is strongly concentration dependent. Only the 2 M reaction reaches a conversion  $>90\%$  within 15 min and more diluted reactions exhibit conversions of 66% ( $[2] = 1 \text{ mol L}^{-1}$ ), 12% ( $[2] = 0.5 \text{ mol L}^{-1}$ ) and 0.5% ( $[2] = 0.25 \text{ mol L}^{-1}$ ), at that time. These observations suggest a strong concentration dependence of the speed of alkoxide formation through protonation of the intermediate zwitterion by the alcohol (Fig. 1).<sup>26</sup> This hypothesis is based on the results obtained in the study of different solvents at the same dilution. The same reaction was carried out in either toluene (apolar aprotic), *N,N*-dimethylformamide (polar aprotic) or *t*-butanol (polar protic) in a dilution of 1.0 and 0.5 mol L<sup>-1</sup> (Fig. 3, right). After 15 min, a significantly higher conversion of 2 could be observed when the reaction was carried out in *t*-butanol (66.2% at 0.5 M) instead of toluene (19.8% at 0.5 M) or *N,N*-dimethylformamide (17.7% at 0.5 mol L<sup>-1</sup>). Only the desired product **2b** formed in all cases and no evidence for a conjugate addition of *t*-butanol under these conditions

could be retrieved. The superiority of *t*-butanol as the solvent can be rationalized by its hydrogen bonding donor ability, which activates the Michael acceptor, stabilizes anionic intermediates and promotes the hydrogen transfer to trap the zwitterionic intermediate (Fig. 1).<sup>27</sup> Accordingly, the speed of alkoxide formation in Lewis base catalysis increases with increasing nucleophilicity of the Lewis base, increasing electrophilicity of the Michael acceptor, increasing acidity of the alcohol and decreasing dilution of the reaction mixture. The negative effect of dilution can be mitigated to some extent by using polar protic solvents (of low nucleophilicity and lower acidity than the alcohol intended for carrying out the addition reaction).

### Nucleophile or base?

The above described results strongly suggest that TTMPP acts as a Lewis base catalyst and  $P_2-tBu$  as a Brønsted base catalyst. Also theoretically, TTMPP should not be able to deprotonate the most acidic alcohol in this study, propargyl alcohol ( $pK_a$  14.1), because the  $pK_a$  value of its conjugated acid is calculated to be 4.9.<sup>28</sup> Nevertheless, to retrieve further evidence, the reaction of acrylonitrile with 2.0 equiv. allyl alcohol and 5 mol% catalyst (TPP, TTMPP and  $P_2-tBu$ ) was monitored with an IR thermal imaging camera. In Fig. 4, the temperature profiles are displayed. The respective catalyst was added to the alcohol and in the case of TPP and TTMPP, no increase of the temperature of the reaction mixture was noted. In contrast, the addition of  $P_2-tBu$  to the alcohol resulted in a significant temperature rise due to the acid base reaction between **c** and the phosphazene base. Finally, upon addition of the Michael acceptor, a temperature surge was detected for the TTMPP and  $P_2-tBu$  catalysed runs, indicating the rapid oxa-Michael addition reaction, whereas no

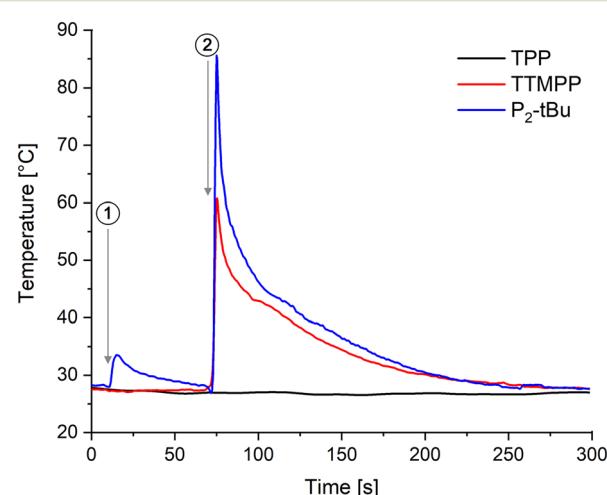


Fig. 4 Temperature profiles of the reaction of allyl alcohol with acrylonitrile and TPP, TTMPP or  $P_2-tBu$  as the catalysts. Reaction conditions: 2 equiv. allyl alcohol, 0.05 equiv. of catalyst was added at point in time 1; afterwards, at point in time 2, 1 equiv. acrylonitrile was added.



temperature increase was observed in the case of TPP. The reaction was also studied by  $^{31}\text{P}$ -NMR spectroscopy revealing that the signal for TTMPP (at  $-65.8$  ppm relative to  $85\%$   $\text{H}_3\text{PO}_4$  in  $\text{DMSO}-d_6$ ) is not changed when allyl alcohol was added. This disagrees with the formation of a phosphonium species since protonation of TTMPP causes a deshielding of the phosphorous atom (ESI,† Fig. S19). Only upon addition of acrylonitrile a new peak at  $5.1$  ppm appeared in the  $^{31}\text{P}$  spectrum, which increased in intensity after  $24$  h. This signal is tentatively attributed to the  $\beta$ -phosphonium species forming after conjugate addition to acrylonitrile. For comparison, chemical shifts of zwitterions of TTMPP and methacrylates were reported to be located at  $2.4$  and  $2.9$  ppm (in toluene- $d_8$ )<sup>18b</sup> and the chloromethyl phosphonium salt of TTMPP has a  $^{31}\text{P}$  NMR shift of  $8.5$  ppm (in  $\text{DMSO}-d_6$ , ESI,† Fig. S22). Moreover, the formation of the corresponding phosphine oxide ( $7.10$  ppm) was observed. Accordingly, solid evidence for TTMPP being a Lewis base catalyst in these reactions is available.

### Oxa-Michael polymerisation

The performance of TTMPP (0.05 equiv.) was further evaluated in the oxa-Michael polymerisation of 2-hydroxyethyl acrylate (HEA). The reaction progress was checked after  $1$  h and  $24$  h by sampling an aliquot and analyzing it by  $^1\text{H}$  NMR spectroscopy and size exclusion chromatography (SEC). The double bond conversions reached a high value of  $95\%$  already after  $1$  h, which further increased to  $97\text{--}98\%$  after  $24$  h. Using TTMPP or  $\text{P}_2\text{-}t\text{Bu}$  catalysis resulted in the same double bond conversions, which were higher than that

obtained with TPP (1 h:  $48\%$ ; 24 h:  $75\%$ ) or TMPP (1 h:  $80\%$ ; 24 h:  $90\%$ ).<sup>15</sup> Number average molecular masses ( $M_n$ ) and dispersities ( $D$ ) were obtained by subjecting the reaction mixture to an SEC machine after  $24$  h reaction time and  $M_n$  and  $D$  values of  $1280 \pm 100 \text{ g mol}^{-1}$  and  $2.1 \pm 0.1$  were determined for the TTMPP catalysed reactions (ESI,† Fig. S27). The use of phosphazene base resulted in lower  $M_n$  values of  $770 \pm 50 \text{ g mol}^{-1}$  and in higher  $D$  values of  $2.7 \pm 0.1$ . However, the reaction mixture in these cases is not fully soluble in THF since a small residue was noticed in the syringe filter used during sample injection. Accordingly, the results from SEC have to be considered with precaution. Performing the polymerisation of HEA at higher temperatures resulted in partly insoluble polymers for both catalysts. For comparison, the HEA polymerisation with TMPP at room temperature resulted in similar molecular masses ( $M_n = 1160 \text{ g mol}^{-1}$ ,  $D = 1.8$ ) to TTMPP.<sup>15</sup>

Next, the oxa-Michael polymerisation of 1,4-butanediol diacrylate (BDDA) and butane-1,4-diol was investigated. The performance of TTMPP and  $\text{P}_2\text{-}t\text{Bu}$  was compared with that of other commonly used organocatalysts, namely the triarylphosphines TPP and TMPP and amine based nucleophiles such as 1-azabicyclo[2.2.2]octane (ABCO), 4-dimethylaminopyridine (DMAP), 1,8-diazabicyclo(5.4.0)-undec-7-ene (DBU), and 1,1,3,3-tetramethylguanidine (TMG). All reactions were performed with  $5 \text{ mol}\%$  catalyst loading and at room temperature without any solvent. Results are displayed in Fig. 5. Double bond conversions higher than  $85\%$  could only be observed in the polymerisations catalysed by TTMPP ( $86 \pm 1\%$ ) and by  $\text{P}_2\text{-}t\text{Bu}$  ( $93 \pm 1\%$ ) after  $1$  h. Other catalysts clearly fall behind with TMPP

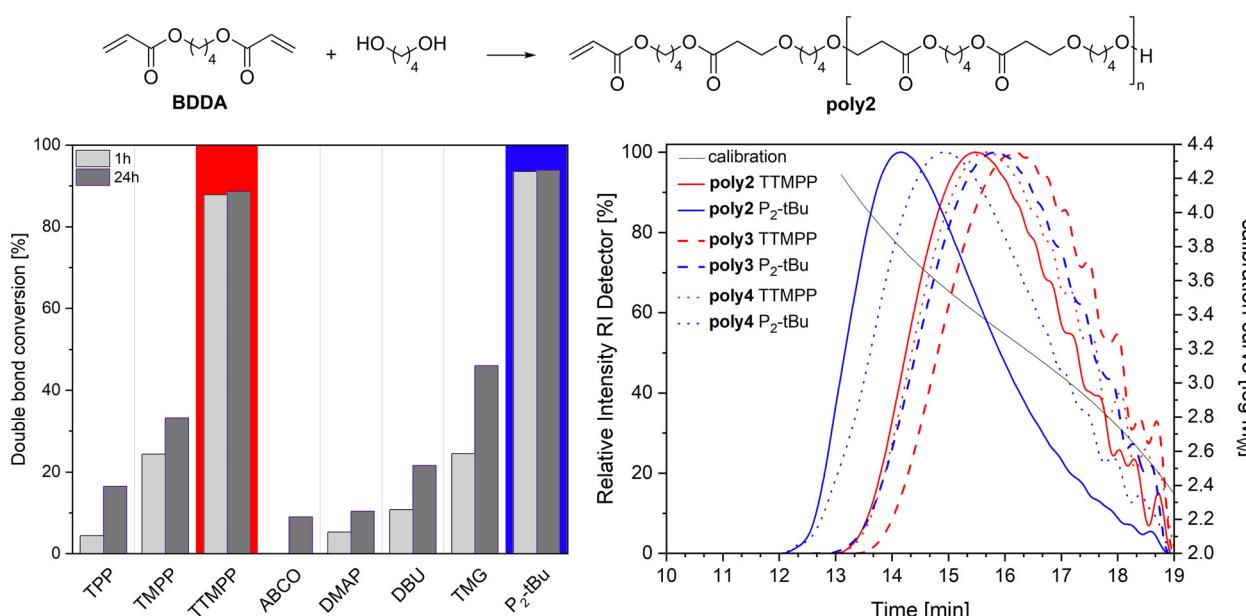


Fig. 5 Left: double bond conversion of 1,4-butanediol diacrylate (1 equiv.) in the reaction with butane-1,4-diol (1 equiv.) in the presence of a catalyst (0.05 equiv.) after  $1$  h and  $24$  h; polymerisation performed at  $25\text{ }^\circ\text{C}$ ; no solvent used. Right: size exclusion chromatograms of **poly2** (alcohol = butane-1,4-diol), **poly3** (alcohol = butene-1,4-diol), and **poly4** (alcohol = butyne-1,4-diol) obtained after  $24$  h without any workup of the polymerisation reaction.

and TMG giving the best results as evident from double bond conversions of about  $25 \pm 2\%$  after 1 h. This situation does not significantly change after 24 h, as double bond conversions increase only slightly in the case of TTMPP ( $88 \pm 1\%$ ) or stay unaltered as in the case of  $P_2-tBu$ . The other catalysts somewhat improved the double bond conversion over time, but in all cases no values higher than 50% were obtained. After 24 h reaction time, SEC was performed for all reaction mixtures and only TTMPP and  $P_2-tBu$  catalysed reactions resulted in the formation of macromolecules. Lewis base catalysis gave **poly2** at  $1400 \pm 150 \text{ g mol}^{-1}$  and relatively small  $D$  values of  $1.6 \pm 0.1$  while  $P_2-tBu$  catalysis produced somewhat higher molar masses ( $M_n = 2500 \pm 150 \text{ g mol}^{-1}$ ,  $D = 2.0 \pm 0.1$ ). Switching to other diols, namely more acidic (*Z*)-butene-1,4-diol and butyne-1,4-diol, yielded the corresponding polymers **poly3** and **poly4**. NMR spectroscopy investigations revealed significant amounts of repeating units derived from transesterification reactions and the oxa-Michael addition of released butane-1,4-diol which has already been observed before for alkyl acrylates (*cf.* ESI† for details).<sup>13</sup> SEC performed after 24 h revealed  $M_n$  values of  $1150 \pm 50 \text{ g mol}^{-1}$  ( $D = 1.6$ ) for **poly3** and  $1350 \pm 50 \text{ g mol}^{-1}$  ( $D = 1.7$ ) for **poly4** when TTMPP catalysis is used. In the case of  $P_2-tBu$  catalysis, somewhat higher values were obtained for **poly3** ( $1400 \pm 100 \text{ g mol}^{-1}$ ,  $D = 1.8$ ) and **poly4** ( $1650 \pm 250 \text{ g mol}$ ,  $D = 2.0$ ). Accordingly, it can be said that TTMPP is the first Lewis base capable of catalysing the oxa-Michael polymerisation of diacrylates and diols.

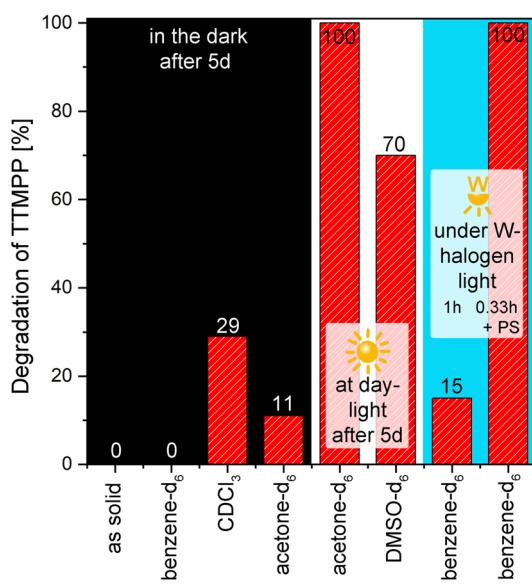
## Oxidation stability of TTMPP

Finally, the oxidation stability of TTMPP was tested. For this purpose, re-crystallized TTMPP was exposed to air for 5 d at room temperature under different conditions. The samples were either stored in the dark, under daylight or were irradiated with a 250 W tungsten-halogen lamp. The samples were dissolved in benzene- $d_6$ , DMSO- $d_6$ , chloroform- $d$  and acetone- $d_6$  or were stored as solids. The amount of phosphine oxide was then determined *via*  $^{31}\text{P}$ -NMR spectroscopy (Fig. 6). First, the results obtained from the samples stored in the dark are discussed. In contrast to our expectations, TTMPP is relatively stable as a solid and in solution when stored in the dark. As a solid and dissolved in benzene, no phosphine oxide can be detected after 5 d. In acetone- $d_6$ , 11% phosphine oxide forms, indicating that the amount of phosphine oxide is dependent on the oxygen solubility of the solvent.<sup>29</sup> When the samples are stored under light, oxidation stability is significantly decreased. The sample stored in acetone- $d_6$  under daylight was determined to be fully oxidized after 5 d. In DMSO, the relative amount of phosphine oxide is with 70% slightly lower. Finally, turning to the results obtained in chloroform- $d$ . After 5 d in the dark, 16% phosphine oxide and 13% of another species (characterized by a  $^{31}\text{P}$ -NMR shift of 24.9 ppm) formed. Considering the high nucleophilicity of TTMPP, a reaction with chloroform is conceivable, as TTMPP is known to react with dichloromethane to give the chloromethyl phosphonium salt within 15 min at room temperature (see ESI† for the full characterization of this species).<sup>16b</sup> Moreover, another side reaction, namely the formation of the corresponding phosphinate, could potentially occur in the presence of singlet oxygen.<sup>30</sup> To obtain some evidence for such phosphinate species, a solution containing the singlet oxygen sensitizer Pd(II) *meso*-tetra(4-fluorophenyl)tetrabenzoporphyrin (Pd4F) and TTMPP in benzene- $d_6$  was irradiated with a 250 W metal-halogen lamp for 20 min. In  $^{31}\text{P}$  NMR spectroscopy, a new signal with a chemical shift of 22.05 ppm was observed (approx. 5% with respect to TTMPP) and mass spectrometry revealed a newly formed compound with a mass of  $565.5 \text{ g mol}^{-1}$  (ESI† S34). Both findings point to the formation of the phosphinate species, particularly because the irradiation of a solution of TTMPP without Pd4F results in the formation of 14% phosphine oxide, but no phosphinate species.

Overall, TTMPP is not particularly sensitive towards oxidation and it can be used as a catalyst without the unconditional need to exclude oxygen. However, aliphatic halogenated solvents, in particular dichloromethane, should be avoided.

## Conclusion

The activity of the Lewis base TTMPP in catalysing oxa-Michael reactions was evaluated and benchmarked against the strong Brønsted base  $P_2-tBu$ . Under solvent free or highly concentrated conditions, TTMPP is only slightly less active than  $P_2-tBu$  but considerably more active than other Lewis



**Fig. 6** Degradation of TTMPP in the presence of air as investigated by  $^{31}\text{P}$ -NMR spectroscopy at room temperature after storage of TTMPP as a solid or dissolved in the solvent (x-axis) for 5 d in the dark (black background), for 5 d under daylight (white background) and upon illumination with a tungsten-halogen lamp (blue background) for 1 h and for 20 min in the presence of a photosensitizer (PS).



bases investigated so far. Upon dilution of the reaction mixture, the favourable activity of TTMPP is quickly lost and  $P_2\text{-}t\text{Bu}$  becomes clearly superior under these conditions. This phenomenon can be understood by the underlying mechanism of the Lewis base catalysed oxa-Michael reaction, which involves the formation of an energetically disfavoured intermediate zwitterion. This zwitterion either decomposes again or is trapped upon protonation by an alcohol, thus generating an alkoxide stabilized by the corresponding phosphonium cation. Under concentrated conditions, the alkoxide generation is, thanks to the high nucleophilicity of TTMPP, fast and not the rate determining step of the overall oxa-Michael reaction, while under diluted conditions the trapping of the zwitterion, *i.e.* alkoxide generation, becomes the rate determining step. Considering that TTMPP is fairly air-stable and exclusion of atmospheric oxygen is not mandatory for typical reactions carried out with this catalyst, this commercially available Lewis base is a powerful alternative to previously established Lewis base catalysts.

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## Conflicts of interest

There are no conflicts to declare.

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