N-Heterocyclic Phosphines as Precatalysts for the Highly Selective Degradation of Poly(lactic acid)

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An N-heterocyclic phosphine (NHP) has been investigated as a catalyst for transesterification of a range of commercial polymer samples. NHP catalysed degradation of poly(lactic acid) with methanol provides access to methyl lactate (MeLA) in high yields over the course of days. In situ NMR spectroscopy and kinetic analysis has provided quantitative assessment of the yield over the course of days. Surprisingly attempts to depolymerise polycaprolactone (PCL) and polyethylene terephthalate (PET) were unsuccessful, and reactions mixed PLA/PCL and PLA/PET provided completely specific degradation of the PLA alone. NMR analysis of the catalyst provides insight into its solution speciation, indicating that the NHP does not remain intact under the transesterification conditions. The enediamine, tBuN(H)CH=CHN(H)tBu, was shown to be formed via methanolysis of the NHP and proved to be a selective catalyst for PLA degradation. Assessment of the depolymerisation activity of by-products of the NHP methanolysis suggest this is the active catalyst.

Introduction

In recent years there has been an explosion of interest in the production of polymers from renewable resources.[1] One such polymer that has garnered significant interest is poly(lactic acid) (PLA), this is due to its favourable properties and, under certain conditions, its ability to biodegrade.[2] PLA is prepared industrially by the ring opening polymerisation (ROP) of the cyclic ester, lactide (LA). The precursor for monomer synthesis is lactic acid, which can be prepared via fermentation of starch rich feedstocks. There are various initiators in the literature that have shown great promise for the ROP of LA to produce PLA with various physical properties of the resulting polymer, the most important initiators being based on groups 1–3,[3] group 4,[4] group 12,[5] group 13,[6] and the lanthanides.[7] The industrial method operates at temperatures around 180 °C and uses a Sn(II) based initiator. In recent years there has been a concerted effort in both academia and industry to develop catalysts that are capable of either upcycling waste polymers or converting them back to monomers, to further enhance the green credentials of PLA in-line with the concepts of the circular economy.[8] To this end several groups have focused on the chemical recycling of PLA.[5c,8b, 9] For example, Enthalier has shown it is possible to convert end-of-life PLA into LA using Zn(OAc)$_2$ at 200 °C.[10] The same group have also used alcoholysis for simple degradation of PLA to alkyl lactates.[11] The advantage of this approach is that the process is able to operate at milder conditions. Alkyl lactates have shown a multitude of uses including solvents and platform chemicals.[12] Jones has shown that a range of zinc complexes are able to form PLA via the controlled ROP of lactide at industrial conditions.[13] Moreover, the same catalysts are active for the degradation of PLA. As well as metal based systems organocatalysts are showing significant promise in this area.[9a,12] For example, Dove and Sardon have recently show that a protic ionic salt is able to selectively depolymerise a mixed PET:PC waste stream.[14] Jones and co-workers have shown that a simple ammonium carbonate salt is able to degrade a range of polyesters (e.g. PET, PLA, PCL) into monomer precursors which can then be repolymerised to new polymer, highlighting a truly circular economy approach.[15] There is a real desire to develop systems that are able to selectively degrade/depolymerisation mixed polymer feeds, which is more realistic of consumer waste streams.[16]

In this paper we report the application of an N-heterocyclic phosphine (NHP) catalyst for the chemical degradation of PLA to methyl lactate (MeLA). Interestingly, this catalyst was not able to degrade other polyesters (such as PET or PCL) which could have applications for mixed plastic recycling. The PLA selectivity is discussed in terms of hydrogen bonded intermediates.

Results and Discussion

NHPs have found increasing prominence as they display unusual chemistry originating from their charge separated character (Scheme 1).[17] We hoped this nature in NHP-OR compounds (R=CH$_2$Ph, 1; H, 2); a Lewis acidic P atom...
intimately associated with an oxanyan,[14] would provide an appropriate moiety to polymerise cyclic esters.

To investigate this, 10 mol% of compounds 1 and 2 were each reacted with the racemic lactide dimer (rac-LA) and varying equivalents of benzyl alcohol, a co-initiator, in \( d_8 \)-toluene at 80 °C. The results of these experiments are summarised in Table 1.

As shown, the presence of the alcohol co-initiator was required to see any conversion (Table 1, Entries 1 and 3 versus Entries 2 and 4) at all and conversions remained poor, with even extended heating only marginally providing greater conversion than that provided by the co-initiator (Table 1, Entry 3, 39% after 8 days in the presence of 2 versus Entry 5, 19% after 7 days in the presence of benzyl alcohol alone). Postulating that mass-transfer in the NMR tube may be contributing to these unremarkable conversions, repetition of the reaction catalysed by 2 in toluene on a preparative scale provided only 82% conversion in 7 days (Table 1, Entry 6). Moreover, GPC analysis on the material produced indicated it to be oligomeric, with DP \( \approx \)7. In a related reaction, an attempt to generate polycaprolactone from \( \varepsilon \)-caprolactone in the presence of 10 mol% 2 and methanol in \( d_8 \)-toluene showed no sign of conversion of the \( \varepsilon \)-caprolactone even at 80 °C over the course of days. These results indicated that, under these conditions, NHPs are not competitive ROP catalysts for these cyclic esters, but during the course of the reactions between 1 or 2 and lactide, resonances at 4.22 and 1.08 ppm in the \(^1\)H NMR spectrum were noted. These were attributed as the methine and methyl of ring-opened products such as lactic acid or benzyl lactate by comparison to literature data.[15] This was interpreted as evidence that 1 and 2 may be viable PLA transesterification catalysts and thus able to effect the degradation of PLA to lactate esters.

To investigate this, pieces of PLA were suspended in \( d_8 \)-toluene in the presence of 5 wt% of 2, and 7 equivalents of methanol per ester unit was added to this. The resultant suspension was heated to 80 °C and repeatedly subjected to analysis by NMR spectroscopy. After 3 days the \(^1\)H NMR spectrum reflected a 95% conversion of the polymer to degraded products which were obtained in a 97:3 ratio of MeLA to oligolactide. Catalyst 2 is attractive over its benzoxy analogue, 1, as it is stable to air and moisture at ambient temperature, whilst providing slightly higher conversions (see SI, Table S1). Furthermore, during reactions with 1 the formation of 2 from the action of residual moisture was observed (see SI, Figure S14). Further optimisation of the conditions indicated that increases in temperature, and catalyst loading were unproductive towards improved activity, whilst decreasing them resulted in diminished conversions (see SI, Table S1). The optimised system was found to be reusable; after 3 days at 80 °C additional PLA was added, without the addition of any further equivalents of methanol. Heating of this suspension provided complete degradation in a further 3 days at 80 °C. Furthermore, the reaction proceeded without rigorous exclusion of air with only a minor reduction in conversion (see SI, Table S1).

In order to gain mechanistic insight into the reaction, \textit{in situ} \(^1\)H NMR spectroscopy over the course of 70 hours was used, the results of which are summarised in Figure 1. The reaction was shown to proceed via a two-step consecutive reaction with

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**Table 1.** Polymerisation of LA to PLA catalysed by NHPs (See SI Figures S1–S10).

| Entry | Catalyst | Catalyst loading [mol%] | BzOH loading [mol%] | Time [days] | Conversion of rac-LA to PLA [%] [a] |
|-------|----------|-------------------------|---------------------|-------------|-----------------------------------|
| 1     | 1        | 10                      | 10                  | 8           | 28                                |
| 2     | 1        | 10                      | 0                   | 4           | 0                                 |
| 3     | 2        | 10                      | 10                  | 3           | 0                                 |
| 4     | 2        | 10                      | 0                   | 7           | 19                                |
| 5     | None     | –                       | 10                  | 7           | 82 [b]                            |
| 6     | 2        | 10                      | 10                  | 7           | 82 [b]                            |

[a] Determined by \(^1\)H NMR spectroscopy, reaction of rac-LA (347 mmol) at 80 °C in \( d_8 \)-toluene (500 μL). [b] Preparative scale experiment with rac-lactide (10.4 mmol) at 80 °C in toluene (15 mL). BzOH = PhCH₂OH.
essentially no evidence for chain-coupling reactions, a result unsurprising in the light of the poor polymerisation ability of 2. Kinetic analysis of this data provided kinetic constants for this mechanism constants ($k_1 = 5.86 \times 10^{-4} \text{ min}^{-1}$, $k_2 = 3.48 \times 10^{-4} \text{ min}^{-1}$), which were found to be lower than those reported for other PLA degradation catalysts, resulting in a result consistent with the observed reaction times required to achieve appreciable degradation.

2 was also found to be active towards transesterification of PLA with other alcohols, and replacement of the MeOH with EtOH provided 95% conversion to a 96:4 ratio of ethyl lactate to oligolactide after 10 days. These reduced reaction rates are consistent with other catalytic system wherein ethanol is found to be a less active degradation reagent than methanol.

The solvent scope was investigated with reactions in toluene, tetrahydrofuran (THF), acetonitrile (MeCN), acetone and ethyl acetate (EtOAc) attempted. The solvents were, with the exception of toluene, used as received with no further purification or drying attempted and activity was seen in all cases. Whilst activity was generally consistent (Figure 2), workup to isolate the methyl lactate proved a significant differentiator between the solvents, with the significant boiling point difference of MeLA to the solvent favouring THF (78% isolated yield) and acetone (70% isolated yield), the latter of which showed marginally improved selectivity for MeLA formation.

Attempts to depolymerise other polyesters gave surprising results. Exposure of PCL or PET to identical conditions as PLA provided no evidence of depolymerisation. Moreover, when PLA was observed with conversions and oligomer to MeLA-ether side-products in the reaction mixture was responsible for the reduced reaction rates. These results from the optimised depolymerisation conditions showed no sign of the precatalyst, 2, or its P-OH methanolysis product MeOP(N(tBu)CH)₃, which might be expected from transalkoxidation of 2 in the presence of excess MeOH. Instead, three resonances in the $^{31}$P NMR spectrum were observed as shown in Figure 3. Two of these resonances, a broad multiplet at 26.5 ppm, and a doublet of septets around 11.1 ppm could be attributed to (MeO)$_2$POH in its three-coordinate phosphorus- and four-coordinate phosphate-tautomers respectively. The dominant peaks of this species were also observed in the $^1$H NMR spectrum (see SI, Figure S35). This is the product of complete methanolysis of the alkoxiphosphamide bonds in 2 to generate dimethyl phosphite and the protonated ligand, tBuN(H)CH=NH(tBu) (compound 3), which could be identified in the mass spectrum of the reaction mixtures by an [M + H]$^+$ ion with an m/z of 171.1856. With these data in hand, we set out to identify which of these species in the reaction mixture was responsible for the depolymerisation activity.

Initially, 10 wt% of dimethylphosphite was reacted with PLA and methanol in 4-toluene on an NMR scale. After 3 days at 80°C no evidence of depolymerisation was observed. We first interpreted this to suggest the other resonances in the $^{31}$P NMR spectrum...
spectrum might reflect the catalytically active species, which comprised a doublet of quartets around 6.3 ppm. Addition of (MeO)₂P(=O)H to a sample of compound 3 followed by a depolymerisation reaction under standard conditions resulted in a ³¹P NMR spectrum containing an equivalent resonance at 6.3 ppm which we thus identify as compound 4, the open-chain partial methanolysis product of 2 (see SI, Figure S40). With these data in hand, we inferred that 4 may be the active species, however addition of an isolated sample of 3 to PLA in the presence of methanol produced rapid depolymerisation at 80 °C. Furthermore, this species showed identically selectivity for PLA over PCL as observed for 2 (see SI, Figure S43). We thus propose that compound 3, tBuN(CH)(CH₂)₂N(tBu), is the active depolymerisation catalyst, and that 2 acts as an air-stable precatalyst for its generation, albeit through a reversible activation via 4, which diminishes its activity compared to isolated samples of 3. Compound 3 is sensitive to ambient atmosphere, thus its protection via coordination to phosphorus in 2 provides the benefit of easier handling at the cost of reduced activity.

Compound 3 proved significantly more active than compound 2, providing > 99% of MeLA and oligomer in a 98:2 ratio overnight when used in the reaction of MeOH and PLA in d₆-toluene at 80 °C. To quantify this increased consumption of PLA by 3 versus 2, it was applied in a range of depolymerisation reactions using the conditions optimised for 2. Kinetic analysis under equivalent conditions to 2 indicated reaction proceeded via the same two-step mechanism as observed for the NHP, but with much larger rate constants (k₁ = 0.0081 min⁻¹, k₂ = 0.0039 min⁻¹, see SI, Figure S47). Furthermore, 3 was also found to be active for ethanolyis of PLA, but on shorter timescales than required for 2 providing 99% conversion of PLA to ethyl lactate in 3 days (see SI, Figure S45).

With evidence towards the solution speciation in hand, we propose that the specificity of this system towards the depolymerisation of PLA reflects the rigid nature of the catalyst, which provides a set of hydrogen bond donor groups in a specific spatial arrangement. We thus hypothesise that an element of molecular recognition between the PLA backbone, comprising an ester carbonyl in the β-position of an ester alkoxide, with the N–H bonds of catalyst system might be responsible for the activation, with subsequent transesterification of an expedient methoxy group delivered from the bulk solvent (Figure 4).

**Experimental Section**

**General Information**

Unless otherwise stated reactions were carried out under argon or nitrogen atmosphere using standard Schlenk line and glovebox techniques. NMR experiments using air-sensitive compounds were conducted in NMR tubes equipped with J. Young’s valves, prepared and sealed in a glovebox under nitrogen. Toluene and hexane were purified using an MBraun Solvent Purification System and stored over 4 Å molecular sieves, all other solvents were used as received. Commercially available reagents were used as received with the exception of methanol, ethanol, and benzyl alcohol, which were dried over magnesium before distillation and stored in sealed ampoules; rac-lactide which was recrystallised from toluene and stored in the glovebox under nitrogen; e-caprolactone which was dried over calcium hydride before distillation and stored in a glovebox under nitrogen. d₆-Benzene and d₆-toluene were dried over a potassium mirror prior to vacuum transfer into a sealed ampoule and storage in the glove box under nitrogen. d₆-Chloroform was used as received. All NMR data were acquired at 298 K on an Agilent ProPulse instrument for ¹H (500 MHz) and ³¹P (202 MHz), a Bruker AV400 instrument for ¹H (400 MHz) and ³¹P (161 MHz) or a Bruker AV300 spectrometer for ¹H (300 MHz) and ³¹P (122 MHz). ¹H NMR spectra were referenced using residual solvent resonances. GPC was performed using an Agilent 1260 Infinity GPC-SEC instrument with a 1 mL min⁻¹ flow rate at 35 °C with a THF eluent using a PLgel 5 µm MIXED-D 300 × 7.5 mm column. Mass spectrometry was performed using a Bruker MicrOTOF Electrospray Time-Of-Flight Mass Spectrometer coupled to an Agilent High Performance Liquid Chromatography unit. Compound 1, 2-(benzoxyl)-1,3-di-tert-butyl-2,3-dihydro-1H-1,3,2-diazaphosp-hene, was synthesised according to a literature procedure, as was 2-bromo-1,3-di-tert-butyl-2,3-dihydro-1H-1,3,2-diazaphosphole, as was 2-bromo-1,3-di-tert-butyl-2,3-dihydro-1H-1,3,2-diazaphosphole.
Compound 3, N,N′-di-tert-butylethene-1,2-diamine was synthesised via modified literature conditions using methanol.[17]

Synthetic Procedures and Characterisation

2-(hydroxy)-1,3-di-tert-butyl-2,3-di-hydro-1H-1,3,2-diazaphosphole-2, 2. Potassium hydroxide (829 mg, 14.8 mmol) was dried in vacuo and transferred into a Schlenk flask containing 2-bromo-1,3-di-tert-butyl-2,3-di-hydro-1H-1,3,2-diazaphosphole (2.75 g, 9.85 mmol) followed by ~40 mL of toluene. The resulting beige suspension was sonicated for 5 minutes before being left to stir overnight. The resulting white suspension was filtered, producing a colourless solution. The solvent was removed in vacuo. The resulting colourless solution was methanolised and filtered before removing the solvent in vacuo.

General Procedure for Degradation of Polymers

PLA (50 mg), 2 (5 mg, 0.02 mmol) or 3 (5 mg, 0.03 mmol) and methanol (158 mg, 200 μL, 4.49 mmol) were added to a J. Young’s NMR tube with 500 μL of d₆-toluene. Initial 'H NMR spectroscopic analysis performed. The reaction was then heated to 80°C inside the NMR machine, an 'H NMR spectrum collected and then collected again every hour for 70 hours in the case of the reaction with 2, or every 10 minutes for 8 hours for the reaction with 3.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

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