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Introduction

Catalysts, often containing transition metals, are essential tools in chemical synthesis.^{1–3} Challenges in metal extraction, complex toxicity, and economic cost frustrate the long-term sustainability of their industrial application.^{4,5} Consequently, metal-free catalysts have been touted as environmentally friendly, economically viable, and less hazardous alternatives to metal-based catalysts.^{6–9} An emerging class of metal-free catalysts are bis(triphenylphosphine)iminium salts,^{10–12} thanks to their good solubility, stability at high temperatures and ease of handling.^{11,13}

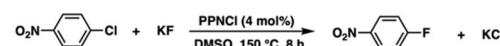
Bis(triphenylphosphine)iminium chloride (PPNCl) has been utilized in carbon dioxide (CO₂) valorisation^{14–18} to affect the coupling of CO₂ and epoxides to form cyclic carbonates as key reagents for the pharmaceutical and fine chemical industry.^{19–21} Wing *et al.* demonstrated that both the PPN⁺ and Cl[–] play important roles in the reaction mechanism.²² PPNCl has also been explored as a co-catalyst in the ring-open copolymerisation of CO₂ and epoxides to form polycarbonates.^{23,24} Showing catalyst versatility, PPNCl can also be utilized to facilitate the hydrogenation of CO₂ to yield higher alcohols,²⁵ and in difficult halogen-exchange reactions to yield

fluorinated aromatic compounds for pharmaceutical and agrochemical applications (Fig. 1a).¹¹

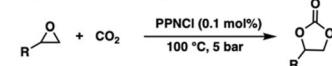
The material-intensive, multi-step synthesis of PPNCl means that catalyst recovery would be important, however, the recycling of PPNCl has thus far not been explored. In recent years,

(a) Previous work using PPNCl as catalyst

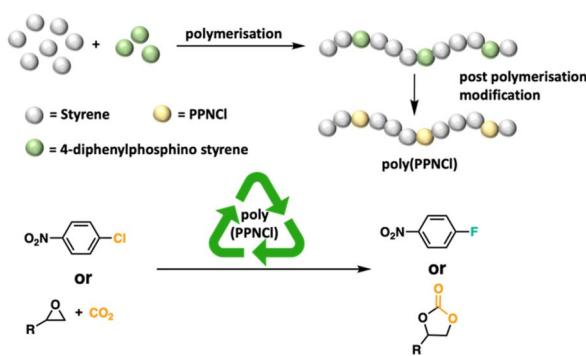
Halogen-exchange reaction



CO₂/epoxide coupling reaction



(b) This work



^aDepartment of Materials, School of Natural Sciences, The University of Manchester, Manchester, UK. E-mail: michael.shaver@manchester.ac.uk

^bSustainable Materials Innovation Hub, The University of Manchester, Royce Hub Building, Oxford Road, Manchester, UK

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Fig. 1 (a) Previous work using PPNCl as catalysts; (b) poly(PPNCl) as a recyclable catalyst for halogen exchange and CO₂/epoxide coupling reactions.

the recyclability of catalysts through incorporation into polymers has gained significant attention.^{26–29} Previous work in our group showed that polymer-supported catalysts featuring main-group elements including phosphorus, can be easily recovered and achieve comparable catalytic efficiencies to their small molecule counterparts.^{30–32}

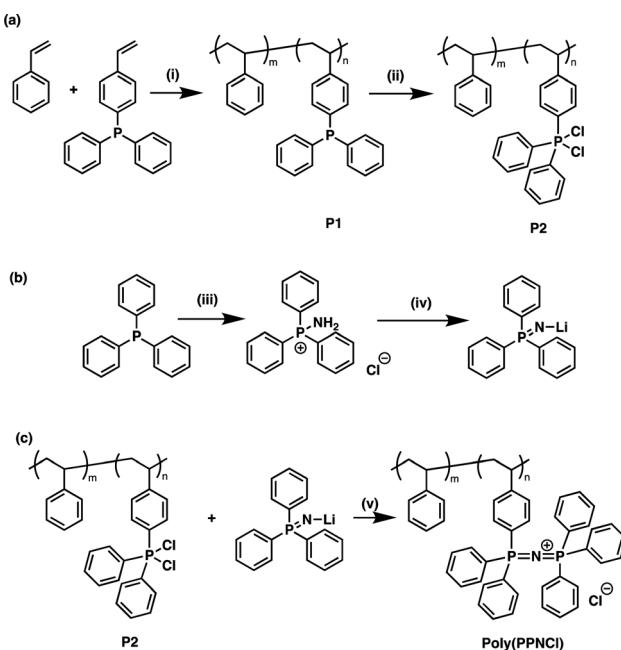
Developing a polymeric variant of PPNCl could generate a catalyst capable of maintaining high activity and new recyclability. In this work, we report for the first time, the preparation of macromolecular **poly(PPNCl)**. We demonstrate the catalytic reactivity of **poly(PPNCl)** in catalyzing both halogen-exchange and CO₂/epoxide coupling reactions. The catalyst is readily recovered through post-reaction precipitation and serves as an important step in non-metal catalyst recycling (Fig. 1b).

Results and discussion

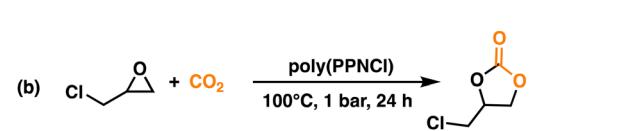
Synthesis of **poly(PPNCl)**

Macromolecular **poly(PPNCl)** was prepared through post-polymerisation modification of poly(styrene-*co*-diphenylphosphine styrene), **P1**, as shown in Scheme 1. **P1** was prepared by anionic co-polymerisation of styrene and *p*-(diphenylphosphino)styrene using *n*-butyllithium as the initiator in a methodology modified from our previous work on polymeric frustrated Lewis pairs.³⁰ The styrene co-monomer serves to provide inert spacers in the polymer chains, separating the active catalyst moieties, and improving solubility. The phosphorus groups incorporated into the polymer chains served as anchors for a modified small molecule synthesis.¹¹ As PPNCl is prepared by the reaction of

a dichlorinated phosphine (Ph₃PCl₂), accessible in near quantitative conversion, and a lithiated amino(triphenylphosphine) (Ph₃PNLi) that forms unavoidable side-products, it is essential to dichlorinate the polymer first. The reaction of **P1** with C₂Cl₆ generates **P2** with full conversion and high purity, as shown by NMR spectroscopy (Scheme 1a and Fig. S1†). A broad resonance at 63.2 ppm in the ³¹P NMR spectrum is comparable to the chemical shift for Ph₃PCl₂ (65.0 ppm).³³ Separately, amination of triphenylphosphine afforded amino(triphenyl)phosphonium chloride which was subsequently lithiated to afford lithium (triphenylphosphoranylidene)azanide (Scheme 1b). Finally, the targeted **poly(PPNCl)** was synthesised by the reaction between **P2** and lithium (triphenylphosphoranylidene)azanide (Scheme 1c). The obtained **poly(PPNCl)** was purified by dialysis to remove small molecule impurities. Analysis by ³¹P NMR spectroscopy (Fig. S1†) showed a single resonance at 20.7 ppm, confirming the full conversion of **P2** to the desired product. Diffusion order spectroscopy (DOSY) showed a single diffusion coefficient, confirming that styrene and PPNCl moieties were distributed within the same polymer chains (Fig. S3†). This synthetic protocol was modified to prepare catalysts with 5 and 10 mol% PPNCl moieties (**poly(PPNCl)-5** and **poly(PPNCl)-10** respectively; Table S1†). For further characterisation of **poly(PPNCl)**, thermogravimetry analysis (TGA) and differential scanning calorimetry (DSC) showed that **poly(PPNCl)-5** has a lower degradation temperature and glass transition temperature compared to **poly(PPNCl)-10** due to its lower PPNCl loading in the polymer chains (Fig. S4†). Importantly, the evident absorptions of Fourier-transform infrared spectroscopy (FTIR) in the region between 1100 and 1480 cm⁻¹ correspond to the vibration of P=N bonds according to the literature,³⁴ further supporting the formation of **poly(PPNCl)**.



Scheme 1 (a) Synthetic procedures of **P2** from phosphine-containing copolymer, $m:n = 95:5$ or $90:10$; (i) *n*-butyllithium, toluene, -78°C , 3 h; (ii) C₂Cl₆, THF, r.t., 3 h; (b) Synthesis of Ph₃PNLi from triphenylphosphine; (iii) hydroxylamine-*O*-sulfonic acid, methanol/DCM, r.t., 1 h; (iv) *n*-butyllithium, THF, initiated at -50°C , -15°C 2 h; (c) synthesis of **poly(PPNCl)** (v) THF, r.t., 3 h.



Scheme 2 (a) Halogen-exchange reaction from CNB to FNB; (b) coupling reaction of CO₂ with GC.



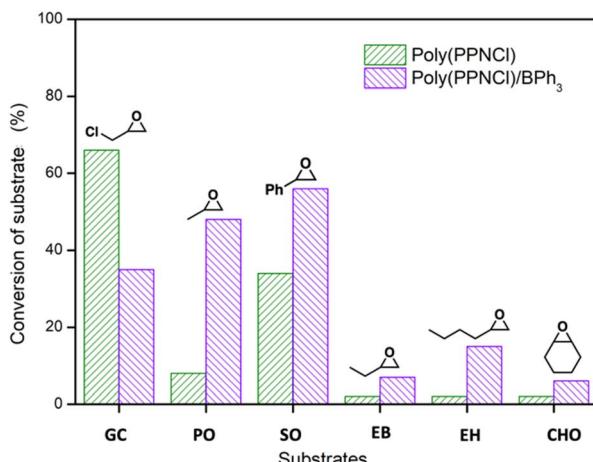


Fig. 2 CO_2 /epoxides coupling reaction to yield cyclic carbonates. Conversions calculated by ^1H NMR spectroscopy. Conversions for GC and PO were taken from the average value of three trials; the rest substrates were conducted once. Reactions were performed in a sealed ampoule on a 12.8 mmol scale at 0.1 mol% **Poly(PPNCl)** with or without 0.1 mol% BPh_3 (0.1 mol% as calculated from the number of expected active functional groups).

Poly(PPNCl)-5 was chosen as the preferred catalyst for the rest of this work.

Conversion of **CNB** with **Poly(PPNCl)-5** was systematically optimized (Table S2†). Minor increases in conversion by increasing the molar ratio of potassium fluoride (KF) added and when lower concentrations of catalyst were observed (2 mol%, 89%), further improving reaction sustainability. While the reaction worked in DMSO, MeOH and DMF, the optimal solvent was DMSO which correlated with enhanced catalyst solubility. **CNB** concentration is also important, with both lower (0.5, 1 M) and higher (3, 4 M) concentrations giving decreased conversions. High concentrations of **CNB** impact catalyst solubility in DMSO, reducing resultant reactivity.

With an optimized system in hand, we investigated whether this substrate scope could be expanded using **Poly(PPNCl)** as the catalyst. Electrophilic aromatic substitution is favoured by the inductive and resonance effects promoted by electron-withdrawing groups (EWGs); previously this reaction was only reported for nitro-substituted aromatics. Displacing the nitro group of **CNB** with other *para*-substituted EWGs or *meta*-substituted electron-donating groups (EDGs) (Fig. S6†) was challenging. Of the substrates tested, only 4-chlorobenzonitrile showed conversion by ^1H and ^{31}P NMR spectroscopy (Fig. S7†).

CO_2 and epoxide coupling reactions

The coupling of CO_2 and epoxides is an important reaction for CO_2 transformation, as the resultant cyclic carbonates are valuable intermediates for fuel additives,³⁶ polycarbonates,³⁷ and pharmaceuticals.³⁸ In previous reports, the PPNCl catalyst was usually paired with a Lewis acid co-catalyst such as triphenylborane (BPh_3) to enhance reactivity.^{39,40} The catalytic reactivity of **Poly(PPNCl)** for the insertion of CO_2 to epoxides in the absence of a solvent was investigated (Scheme 2b). Glycidyl chloride (GC) was selected as a model substrate, and the results

summarized in Table S3† under standard conditions of 1 bar CO_2 for 24 h with 0.1 mol% **Poly(PPNCl)-5**.

In the absence of **Poly(PPNCl)**, no conversion to chloropropene carbonate was observed. With 0.1 mol% (by catalyst moiety) **Poly(PPNCl)** without any borane co-catalyst, 66% conversion was achieved, increasing to 98% at 0.4 mol%. Conversions did not substantially change upon alteration of CO_2 pressure (1–5 bar) (Table S3,† entries 1 and 5–7), suggesting CO_2 is not involved in the rate-determining step. While the rate of epoxide activation is often enhanced through the addition of BPh_3 , the conversion of GC surprisingly decreased to 48% when the Lewis acid is added to the system (Table S3,† entry 9).³⁰ No reaction was observed when employing BPh_3 alone. We hypothesize that the coordination of BPh_3 to a key intermediate (**I** in Fig. S9†) would slow the rate of CO_2 insertion and therefore decrease reaction rates. As the reaction works without the addition of an air-sensitive Lewis acid, we explored milder conditions under an air atmosphere (Table S3,† entry 16). However, GC conversion remained unchanged compared to inert atmosphere (Table S3,† entry 2).

The kinetics of the GC/ CO_2 coupling reaction catalysed by **Poly(PPNCl)** was explored (Table S3,† entries 10–15). Conversion of GC increased from 3 h to 48 h, indicating a long-lived catalyst (Fig. S11a†) and first-order kinetics for $[\text{GC}]$ (Fig. S11b†). A catalytic mechanism for the GC/**Poly(PPNCl)** system is proposed (Scheme S1†). Switching the substrate to propylene oxide (PO) showed remarkably different results: PO conversion was very low (9%) when using **Poly(PPNCl)-5** while the introduction of a BPh_3 co-catalyst increased conversion to 48% (Table S4†). This reversion of the trends observed for PO suggests a significant change in the mechanism proposed in Scheme S2.† Increased reaction time resulted in a higher conversion (61%) suggesting catalyst death is not the reason for reduced yields. The effect of CO_2 pressure on PO conversion gave no significant change in conversion (1–5 bar). PO conversion was enhanced to 71% by increasing catalyst loading to

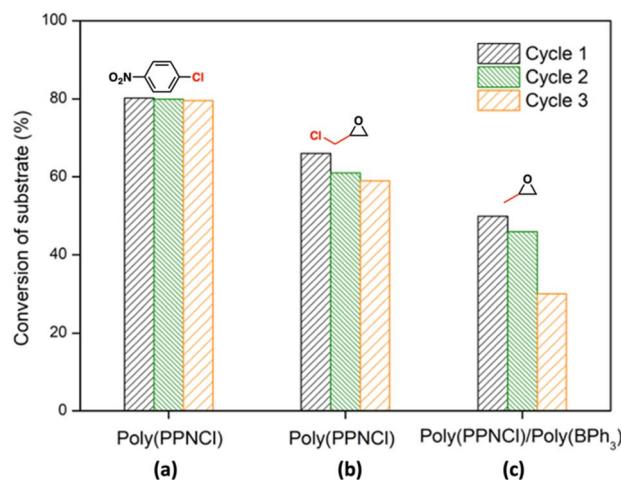
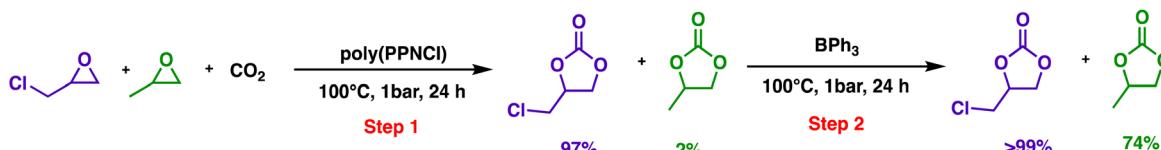


Fig. 3 Reaction conversions over three cycles (a) halogen-exchange, (b) CO_2 /GC coupling, and (c) CO_2 /PO coupling reactions. Conversions calculated by ^1H NMR spectroscopy. Conversions for recycled **Poly(PPNCl)** were obtained from an average value of two trials.



Scheme 3 The selective one-pot, two-step reaction of epoxide conversion to cyclic carbonates. General conditions: the feed ratio of GC : PO : poly(PPNCl) : BPh₃ is 1000 : 1000 : 4 : 4.

0.2 mol%. The efficacy of the borane system also allowed us to test the poly(Lewis acid) variant previously developed in our group.³⁰ Poly(BPh₃), a co-polymer of styrene and 4-styryl-diphenylborane, gave conversations comparable to poly(PPNCl)/BPh₃ system, demonstrating that both PPNCl and BPh₃ can be switched to recyclable polymeric systems while maintaining catalytic reactivity (Table S4,[†] entry 10).

Further expanding the substrate scope delineated two clear classes, evaluated by the overall catalytic reactivity of poly(PPNCl) *versus* poly(PPNCl)/BPh₃ under conditions that avoided reaching full conversion in order to probe structure/activity relationships (Fig. 2). Only the most reactive substrate, GC, favoured poly(PPNCl) as a lone catalyst and outperformed all other tested epoxides (66%). Styrene oxide achieved the second highest conversion (34%) using only poly(PPNCl), supporting the theory that the electron-withdrawing nature of the substituents is key to ensuring reactivity. Interestingly, whilst the poly(PPNCl)/BPh₃ binary system resulted in a lower conversion of GC than for poly(PPNCl) alone, this trend was reversed for all other substrates screened. As the most reactive substrate, GC can be activated by both poly(PPN⁺) and BPh₃, the two catalytic mechanisms may compete with each other to stall catalytic turnover. The sterically hindered cyclohexene oxide had the lowest conversion, attributed to its high steric hindrance preventing associative ring-opening.

Importantly, the selectivity of cyclic carbonates is 100% in nearly every case. Under no reaction conditions is polycarbonate and polyether generated in the presence of poly(PPNCl) alone. The good leaving group abilities of both poly(PPN⁺) and Cl⁻ in the ring-closure step to form chloropropene carbonate likely facilitate this selectivity. For the GC/poly(PPNCl)/BPh₃ system, a secondary product was observed (¹H NMR: 4.7 ppm, Fig. S17 and S18[†]), identified as the carbonate anion adduct of BPh₃ following ring opening by Cl⁻. This suggests that chlorine may attack the more substituted carbon to form an off-cycle product.

Finally, the catalytic selectivity and kinetic switch can be used in one-pot stepwise catalytic transformations. GC and PO could be sequentially converted into their cyclic carbonates as shown in Scheme 3. The epoxide mixture was first treated with poly(PPNCl) to yield chloropropene carbonate and propylene carbonate conversions of 97% and 2% respectively. The addition of BPh₃ to the reaction led to the conversion of the unreacted PO (74%), evidencing this epoxide selectivity.

Catalyst recycling

Polymer-supported catalysts are important additions to sustainable catalyst development as their ready isolation allows for recyclability.³¹ We sought to explore the catalytic

performance of both poly(PPNCl) and poly(PPNCl)/poly(BPh₃) after repeated recovery of the polymer-supported catalysts from crude products (Fig. 3). Poly(PPNCl) can be recovered easily from the product by precipitation from *n*-hexane and dried before reuse in subsequent reactions.

In the halogen-exchange reaction, the addition of *n*-hexane precipitated poly(PPNCl)-5 which was recovered from the crude product by filtration and dried under vacuum prior to weighing between each cycle. Catalytic performance was well-maintained over three reuse cycles (1st cycle: 80%; 2nd: 79%; 3rd: 77%), demonstrating excellent recyclability. For CO₂/epoxide coupling, precipitation of the catalyst or catalysts from the crude chloropropene carbonate (poly(PPNCl)-5) and propylene carbonate (poly(PPNCl)-5/poly(BPh₃)) reactions was conducted in the reaction vessel. The catalytic reactivity of poly(PPNCl) drops slightly over three reaction cycles of GC/CO₂ coupling (1st cycle: 67%; 2nd: 61%; 3rd: 59%). A more precipitous decrease in substrate conversion is observed in the poly(PPNCl)/poly(BPh₃) binary catalyst system (1st cycle: 50%; 2nd: 46%; 3rd: 30%) likely due to the mass loss and partial deactivation of air-sensitive poly(BPh₃) during catalyst recovery.

Conclusions

In summary, we report the synthesis of poly(PPNCl) using post-polymerisation modification. Poly(PPNCl) can achieve high conversion at a low feeding ratio in the halogen-exchange reaction of chloroarenes to fluoroarenes, matching catalytic efficiency to the unrecoverable small molecule analogue, PPNCl. In CO₂/epoxides coupling, the selective formation of cyclic carbonates is catalysed by two mechanisms. Depending on epoxide reactivity, either air-stable poly(PPNCl) can be used on its own or with the addition of BPh₃ or poly(BPh₃) as a co-catalyst. The robust poly(PPNCl) can be recovered by simple precipitation and reused in further reactions, with both halogen-exchange and CO₂ coupling of reactive epoxides displaying excellent recyclability. The recovery and reuse of this key metal-free catalyst is an essential step to support sustainable chemical syntheses.

Data availability

The data supporting this article have been included as part of the ESI.[†]

Author contributions

Ziwei Xu and Meng Wang: investigation, methodology and manuscript writing. Michael P. Shaver: conceptualisation,



manuscript writing – review and editing, supervision and funding acquisition.

Conflicts of interest

There are no conflicts to declare.

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