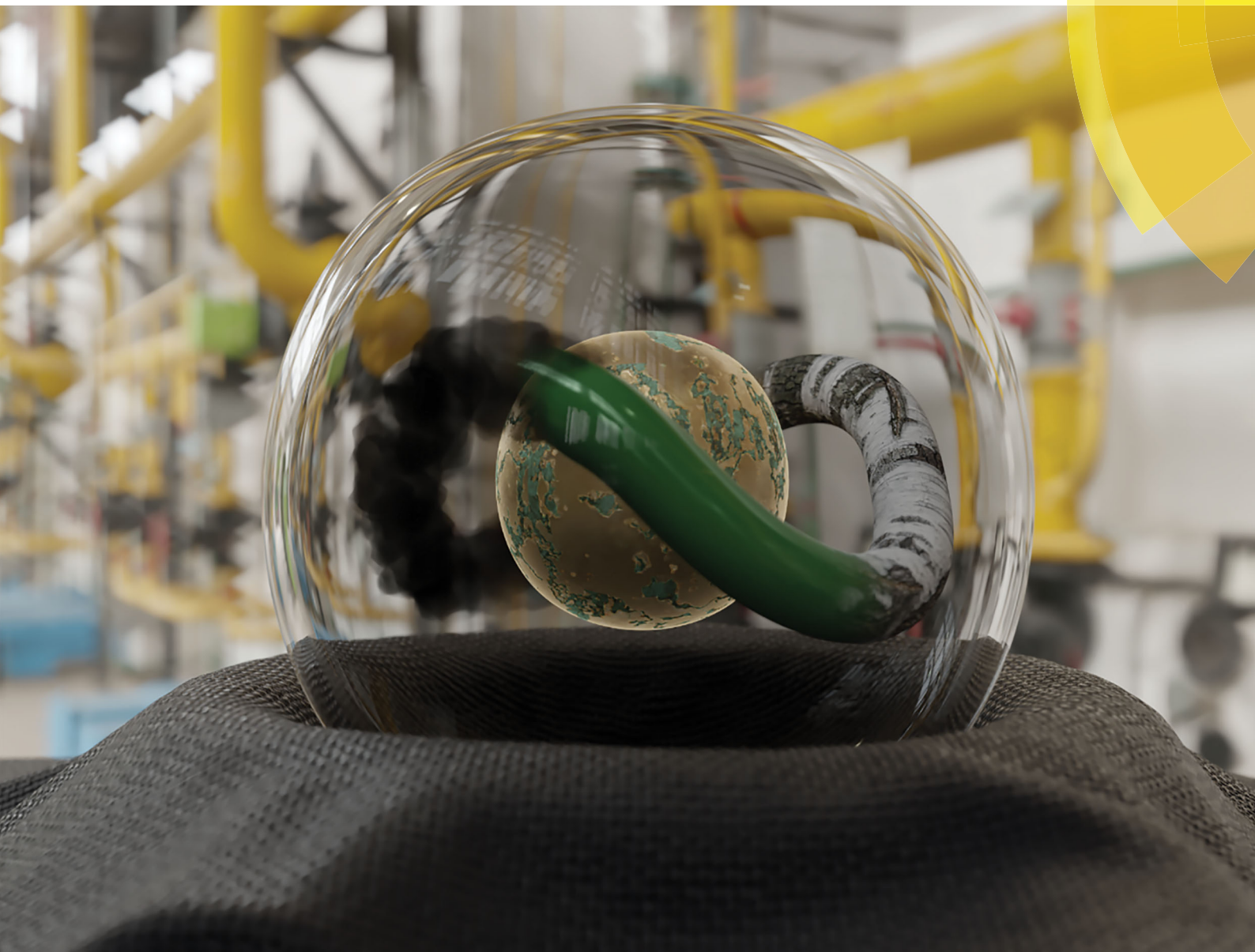


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catalytic synthesis of polycarbonates and non-isocyanate
polyhydroxyurethanes derived from cyclic carbonates*



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En route to CO₂-containing renewable materials: catalytic synthesis of polycarbonates and non-isocyanate polyhydroxyurethanes derived from cyclic carbonates

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Combining CO₂-chemistry with biomass conversion allows renewable polymeric materials including polycarbonates and polyhydroxyurethanes (PHUs) to be generated. The demand for robust materials with modular properties that can be prepared on an industrial scale is important and, to date, the most important polymeric materials are derived from petrochemicals. These materials inevitably result in CO₂ emissions, and therefore making robust materials from renewable sources will contribute to a more sustainable society. An attractive way to address this challenge is to combine biomass transformations with CO₂-fixation and material science. An identified target that combines all three aspects involves the preparation of PHUs (or non-isocyanate polyurethanes, NIPUs) via the polymerization of fully renewable cyclic carbonates derived from biomass and CO₂ with a diamine compound that can also be derived from biomass sources. In this review, we critically analyze the progress in catalyst development for the efficient transformation of epoxides and CO₂ to cyclic carbonates and polycarbonates. We also discuss the synthesis of PHUs from cyclic carbonates and diamines (not restricted to fully renewable compounds), including challenges in regiocontrol and biodegradability, as well as the role catalysts play in the synthesis of these polymers.

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Introduction

Today, most of society's chemicals, including chemical building blocks, fine chemicals, fuels and materials are derived from the petrochemical industry.¹ The intensive utilization of fossil

resources has strongly impacted on the modernization of our society and our quality of life. However, the exploitation of these resources has also led to an imbalance in the carbon cycle and other environmental problems.^{2,3} CO₂ is naturally involved in the carbon cycle, which balances the CO₂ in natural processes.⁴ The concentration of CO₂ in the atmosphere before the industrial revolution was around 280 ppm and reached 410 ppm in July 2018. Human emissions of CO₂ have stabilized

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over the last few years at *ca.* 34 GTons. CO₂ acts as a greenhouse gas, which results in the warming of the earth, with potential catastrophic consequences.⁵ Consequently, governments have recommended that the rate of emissions should be limited in order to contain global warming to 2 °C (decided in November 2015 at COP21 in Paris).⁶ To achieve this goal, emissions should be limited in all possible areas of activity including electricity generation, heating, transport, construction and chemical production. This prerequisite rationalizes the efforts that are made in clean energy storage and production,⁷ direct CO₂ reduction to fuels,⁸ *etc.* Moreover, post-combustion technologies that aim at sequestering CO₂ at the source of emission have emerged.^{9–11} These technologies are being implemented at the exhaust of power stations and rely, for example, on amine compounds that effectively form carbamate salts upon exposure to CO₂. Simultaneously, other technologies are emerging that aim to capture CO₂ directly from air, for example by relying on the affinity of atmospheric CO₂ with bases such as metal hydroxides or amines.^{12,13} The aforementioned technologies are meant to capture CO₂ and then release it in pure form so that it can be stored underground or under the oceans.¹⁴

It would be advantageous to benefit from the CO₂ that is emitted to generate value-added products, as is the case for the synthesis of urea, which is prepared from CO₂ on an industrial scale.^{15,16} A remarkable example of CO₂ valorization as a chemical reagent (or C1 source) involves the cycloaddition of CO₂ into epoxides (CCE reaction) to afford cyclic organic carbonates (COCs). This reaction was discovered in the early 1950s, has been industrialized,^{17,18} and requires a catalyst (see below).¹⁹ The production of the smallest COCs, propylene carbonate (PC) and ethylene carbonate (EC), is particularly important because of their diverse applications and low toxicity.^{17,18,20} They find applications in cosmetics, as solvents,²¹ and in batteries,²² and, importantly, they are biodegradable.²³ The reaction between epoxides and CO₂ is not restricted to the formation of the smallest COCs, and various terminal epoxides have been employed.^{24,25} Some of these epoxides can be derived from renewable sources such as cellulose, lignin, or vegetable oils and can subsequently be processed to polycarbonates (pC), polyurethanes (PUs) and polyhydroxyurethanes (PHUs).

In PUs the monomers are linked one to another *via* a urethane functional group. Typically, these are formed by reacting an isocyanate with a diol (or alternatively a diamine or an aminol) and have a rich history since their development in the 1930s.²⁶ The market for these compounds is enormous,^{27,28} and currently all the precursors are derived from petrochemical sources. Moreover, the isocyanate group is moisture sensitive,²⁹ and isocyanates are notoriously toxic with, for example, the release of methyl isocyanate being responsible for the Bhopal catastrophe in India.³⁰ Therefore, finding alternatives to existing routes is ongoing, and routes involving bio-based or partially bio-based PUs/PHUs are under investigations.^{31–35} Efforts to discover novel materials that are derived from biomass sources and that display properties comparable to those of existing materials is important *en route* towards a more sustainable chemical industry and society.

In this review, we will present the state of catalyst research for the preparation of cyclic organic carbonates (COCs) and their corresponding polycarbonates. In addition, the synthesis of PHUs from COCs and diamines will be described and compared to the well-established PU synthesis. Throughout this review, the focus is directed to the available catalytic tools, the renewable aspects of the reaction and the biodegradability of the materials.

Role of catalysis in CO₂-containing COCs and pCs

COC synthesis

Prior to discussing the synthesis of COCs from bio-based epoxides some general remarks on the catalyzed CO₂-epoxide coupling (CCE) reaction are provided. The CCE reaction proceeds according to Fig. 1 and represents a successful application of CO₂ chemistry.³⁶ As mentioned above, the reaction has been intensively investigated, and numerous efficient catalysts have been developed and described.^{37–40} For example, ionic liquids (ILs) have been identified as potent catalysts for this reaction that operate under mild, solvent-free conditions. Typical examples involve simple ammonium salts such as *N*-tetrabutylammonium bromide/iodide (Fig. 1, catalyst 1) or 1-butyl-3-methylimidazolium chloride (Fig. 1, catalyst 3). Similarly, alkali metal salts combined with a polar aprotic solvent have also been used (Fig. 1, catalyst 5).^{19,41–43}



Paul J. Dyson

Paul Dyson joined the Swiss Federal Institute of Technology in Lausanne (Ecole Polytechnique Fédérale de Lausanne, EPFL) in 2002. He grew up in the UK, completing his doctoral thesis at the University of Edinburgh. Prior to his appointment at the EPFL he held appointments at Imperial College of Science, Technology and Medicine and the University of York as a Royal Society University Research Fellow.

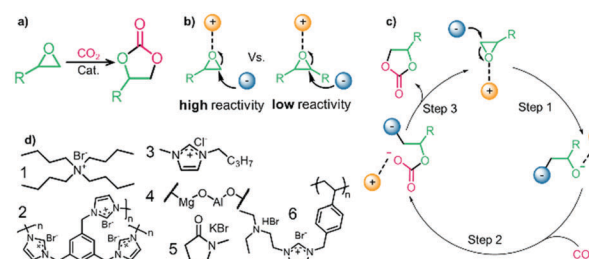


Fig. 1 (a) General CCE reaction. (b) Key mechanistic step for IL catalyzed CCE reaction. (c) Mechanism for IL-catalyzed reaction. (d) Selected catalysts.



For processing purposes, heterogeneous versions of the catalysts have been developed, such as imidazolium-based polymers used in place of ILs (see Fig. 1, catalysts 2 and 6).^{44–47} It should be noted that while the reaction is considered “green”, little emphasis has been put on the sustainability of the catalyst itself. In this context, it has been shown that ILs are not necessarily biodegradable and that their synthesis poses problems.^{48–50} ILs often require dichloromethane, tetrahydrofuran (THF) or diethyl ether during synthesis, all of which are towards the bottom of the solvent sustainability scale.⁵¹ Note, ILs based on naturally occurring cations can potentially be obtained from renewable sources.⁵² In contrast to organocatalysts, metal composites are not derived from petrochemical resources even if their extraction can produce a significant amount of waste. These catalysts are based on available materials and can, to some extent, be considered green (Fig. 1, catalyst 4).^{52,53} Advances in the catalysts and the mechanism of the reaction have been reviewed several times in recent years.^{54–56} The CCE reaction is often considered a reaction that requires harsh conditions to proceed, but recent studies have shown that simple and cheap catalysts convert epoxides into cyclic carbonates under atmospheric pressure of CO₂ at temperatures well below 100 °C.⁵⁷ Notably, a study from 1993 demonstrated that the reaction takes place at atmospheric pressure.⁵⁸ The mechanism of the transformation proposed for IL and organic salt catalysts proceeds *via* ring opening of the epoxide (Fig. 1, step 1) by the anion of the salt, followed by insertion of CO₂ into the alkoxide (Fig. 1, step 2). Finally, the product is formed *via* a ring-closing step (Fig. 1, step 3).⁵⁹ The mechanism and the rate determining step can vary according to the nature of the catalyst.⁶⁰

The reactivity of epoxides with CO₂ is dependent upon the structure of the epoxide with the typical reactivity of different epoxides depicted in Fig. 2. Epichlorohydrin (ECH) is among the most reactive epoxides for the CCE reaction (converted to (chloromethyl)ethylene carbonate, which will be referred to as epichlorohydrin carbonate, EpC) and can be converted at 50 °C under 1 atm of CO₂ using a simple homogeneous IL catalyst.⁵⁷ It should be noted that ECH can be prepared from glycerol, a renewable chemical obtained during biodiesel production (*via* the Epicerol[®] process).⁶¹ Despite the renewable aspect of ECH, it is very toxic and must be handled with care, and this may hinder industrial development.⁶²

Complete solubility/miscibility of the salt catalyst in the reaction solution is crucial for high activity, a feature that is frequently overlooked in organic-salt catalyzed reactions (ILs are not necessarily soluble in the epoxide under solvent-free conditions, and can therefore be considered as heterogeneous catalysts

rather than homogeneous). Furthermore, propylene oxide (PO) and ethylene oxide (EO) are somewhat inconvenient to use on a laboratory scale due to their low boiling points, thus necessitating the use of pressure reactors and, consequently, they are not exclusively used as model substrates, despite their high industrial importance. The utilization of internal epoxides such as cyclohexene oxide (CyO) or limonene oxide (LO) requires harsher reaction conditions because of the lower reactivity of the tertiary carbon compared to secondary carbons in terminal epoxides (steric hindrance). Notably, both internal and terminal epoxides can be derived from renewable sources.⁶³

Table 1 compiles reaction conditions for selected CO₂-epoxide cycloadditions, including examples of homogeneous and heterogeneous salt catalyzed reactions (Table 1, entries 1, 2, 4 and 5), as well as a Mg-Al-oxide catalyst (Table 1, entry 3). The table compiles one simple organic salt (Table 1, entry 1), one heterogeneous salt (entry 2), and three examples of H-bond donor salts (entries 4–6). The example of inorganic catalyst (entry 3) is included as a reminder that many classes of catalysts have been developed over the past decades. Direct comparison between catalysts is hampered by the absence of benchmark experimental reaction conditions. Typical reaction conditions for propylene oxide conversion require pressures of 5–10 atm at temperatures ranging from room temperature to 100 °C (Table 1, entry 3). When other epoxides are employed, the reaction can conveniently be conducted at atmospheric pressure at temperatures ranging from 25 °C to 100 °C (Table 1, entries 1, 2, 4 and 5). The difficulty to compare different catalysts has been identified previously and benchmark conditions have been proposed,^{57,64} as it is difficult to assess the extent of progress that has been made between the catalysts reported between 1999 (Table 1, entry 3) and 2018 (Table 1, entries 4 and 5). Nonetheless, it appears that the most promising systems in terms of catalytic efficiency are composed of an onium salt combined with an external H-bond donor, allowing the reaction to proceed at room temperature under atmospheric pressure (Table 1, entry 6).^{57,64,65} It should be noted that the catalysts for COC synthesis presented above are most often not oxygen sensitive and the reaction does not require anhydrous conditions and water can even accelerate the reaction rates of certain IL catalysts.⁶⁶ Epoxides possess a stereogenic center and hence stereoselective reactions are possible using chiral catalysts that afford optically pure COCs,^{67–69} although optically pure COCs may also be obtained from the catalytic chiral resolution of racemic epoxides.⁷⁰

pC synthesis

Catalysts have also been developed that convert epoxides and CO₂ directly into pCs. The mechanistic pathway of the reaction differs and, for the direct polymerization, a metal catalyst is usually required (see Fig. 3 for representative examples).⁷⁴ The main epoxides that are converted into pCs are PO, CyO and LO and lately efforts have been devoted to the development of tailored epoxides for the reaction.⁷⁵ Co-polymerization of PO with CO₂ leads to polypropylene carbonate (pPC), a polymer that finds applications in ceramics (as a binder), in adhesives and as a propellant.^{76,77} Polymerization of CyO with CO₂ leads

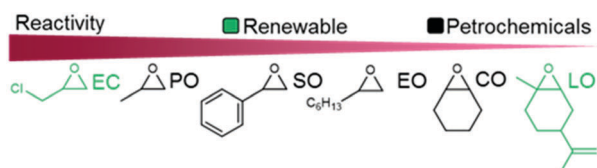
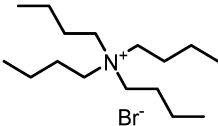
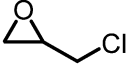
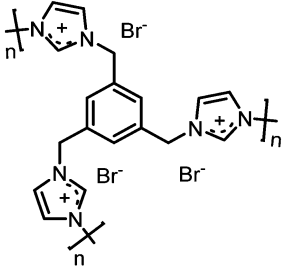
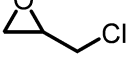
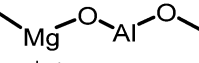

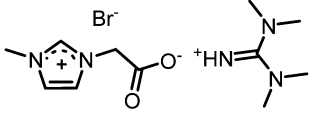
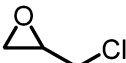
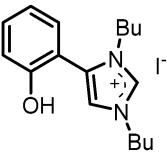
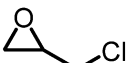
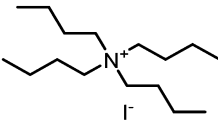



Fig. 2 Epoxides derived from non-renewable and renewable sources and their relative reactivity for COC synthesis.



Table 1 Selected reaction conditions and yields for COC synthesis catalyzed by organic salts and Mg-Al oxide

| Entry | Catalyst | Epoxide | Reaction parameters | Yield [%] | Ref. year |
|-------|--|---|--|-----------|-----------|
| 1 |  homogeneous |  | 1 atm, 60 °C, 22 h, 2 mol%, 30 g epoxide | 78 | 42, 2002 |
| 2 |  heterogeneous |  | 1 atm, 100 °C, 24 h, 5 mol%, 76 mg epoxide | 99 | 44, 2017 |
| 3 |  heterogeneous |  | 5 atm, 100 °C, 24 h, 0.5 g cat, 0.232 g epoxide | 88 | 53, 1999 |
| 4 |  homogeneous |  | 1 atm, 30 °C, 12 h, 25 mol%, 0.185 g epoxide | 84 | 71, 2018 |
| 5 |  homogeneous |  | 10 atm, 80 °C, 1 h, 0.75 mol% cat., 148 mg epoxide | 99 | 72, 2018 |
| 6 |  homogeneous |  | 1 atm, 25 °C, 20 h, 8 mol% cat., 348 mg epoxide | 86 | 73, 2016 |

to polycyclohexene carbonate (pCyC). The pC prepared from LO and CO₂ is a viable bio-based polymer candidate for industrial applications since the resulting polymer displays excellent properties including high thermal resistance, hardness and transparency as well as having a low polydispersity index (PDI < 1.2) and high molecular weight (108.6 kDa).⁷⁸ Moreover, in contrast to many other polymers (polyethylene for example), pCs are often biodegradable, a major advantage as plastic waste is heavily polluting the environment.^{79–82}

As discussed above, the CCE reaction to prepare COCs is most efficient with terminal epoxides, and mechanistic studies show that internal epoxides (CyO for example) result in a more controlled polymerization reaction than terminal epoxides and decreases the selectivity towards COCs.⁷⁴ Furthermore, the use of CyO (or LO) facilitates co-polymerization while avoiding the formation of unwanted polyethers (pEs) derived from the epoxide.^{83–85}

While pEs are unwanted in the context of pC synthesis, these polymers are also valuable in their own right and are obtained from the polymerization of epoxides in the absence of CO₂. For instance, polypropylene oxide (pPO) is used as a component in PU synthesis.⁸⁶ Efforts to produce isospecific polymers by catalytic routes are ongoing.⁸⁷ Interestingly, the catalysts employed in the synthesis of pC and pE tend to be structurally related. For example, mono- and bimetallic cobalt salen complexes have been employed as effective catalysts to transform PO into pPO.^{88,89} Bimetallic Cr-based catalysts afford isospecific polyethers containing alcohol end-groups,⁹⁰ and the resulting polymers are semi-crystalline and display average molecular weights (M_n) in the range 2–15 kDa. Active catalysts for the co-polymerization of CO₂ and epoxides are typically metal-based and may contain ionic sites directly attached to the ligands.^{91,92} Alternatively, when no ionic part is present in the metal-catalyst, a co-catalyst



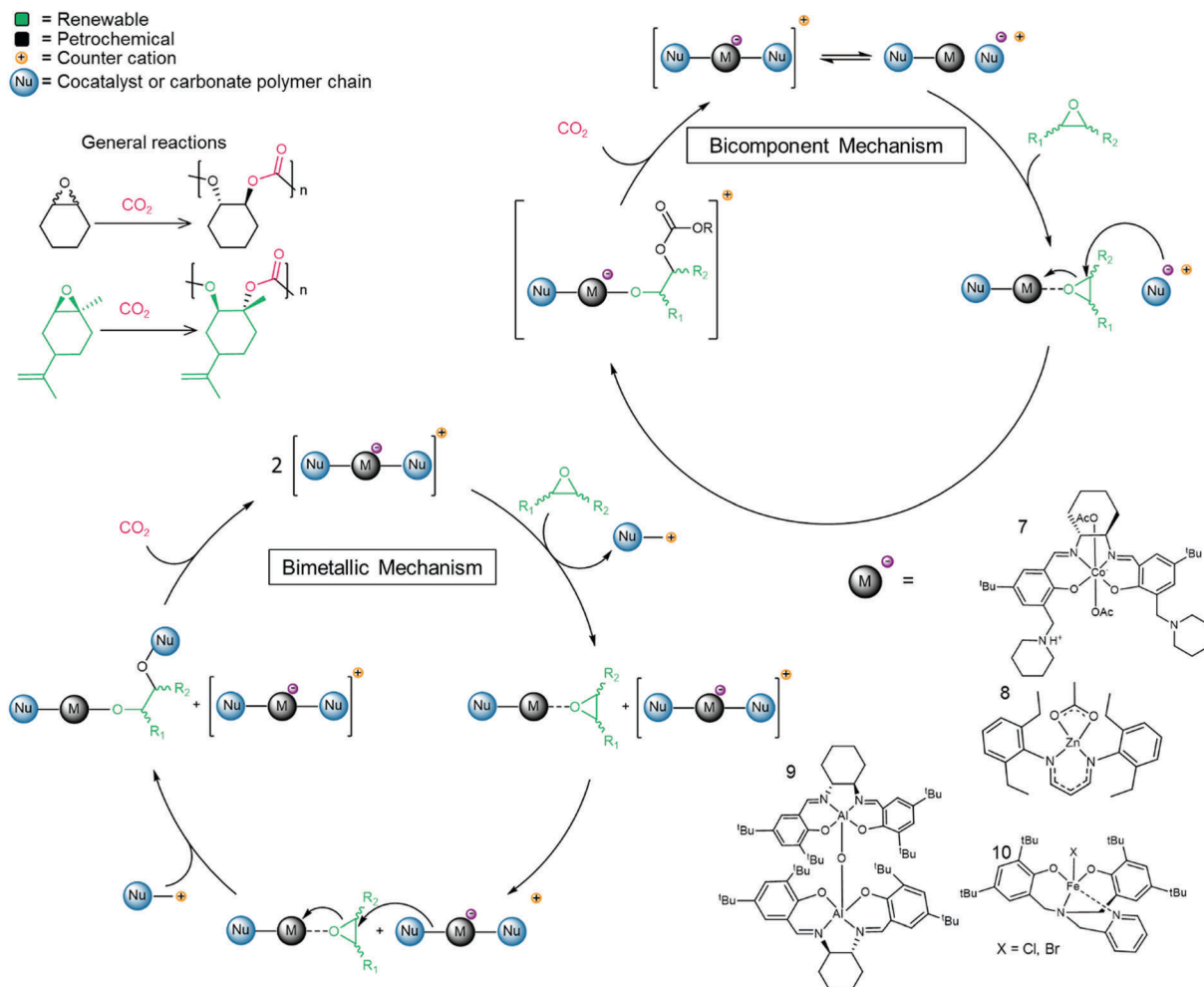


Fig. 3 Co-polymerization of epoxides and CO₂ to afford pCs, representative catalysts and the generally accepted bicomponent and bimetallic catalytic cycles.^{64,74,78,97,98}

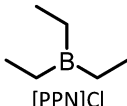

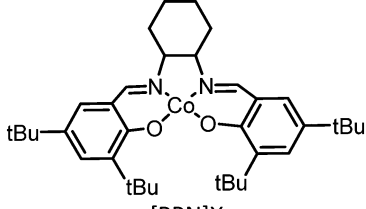

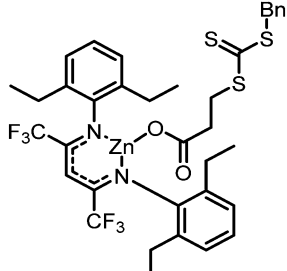
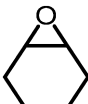
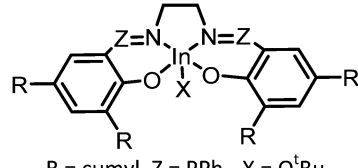
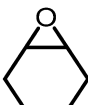
is required to promote the reaction, typically TBAB or PPNCl or other salts that are commonly used in COC synthesis (see examples in Table 2). Several metal complexes have been successfully applied for this reaction including Co,^{74,93} Zn,⁹⁴ Al⁶⁴ and Cr,^{95,96} and examples of Fe⁹⁷ and In⁹⁸ complexes have also been reported (see Fig. 3, structures 7–10 as examples).⁹⁹ The reaction proceeds *via* either a bicomponent or bimetallic pathway, and this typically depends on the catalyst and reaction parameters.^{100,101} In this context, evidence for a monometallic pathway has been provided for an In catalyst (see Fig. 3 for general catalytic cycle).⁹⁸ Recently, an example of a metal-free, salt catalyst has been reported for the polymerization reaction, which is of interest towards the development of a sustainable, metal-free process.¹⁰²

The increasing importance of CO₂-epoxide derived pCs has also led to their application in other types of polymerization reactions. For example, living reversible addition-fragmentation chain transfer (RAFT) has been applied to the reaction, which leads to polymers with very narrow PDIs (<1.11). RAFT polymerization has been achieved using a β -diiminate Zn catalyst (see Fig. 4, the structure is structurally related to that of catalyst

8 in Fig. 3).⁹⁴ Living polymerization methods also allow more complex block co-polymers to be prepared. In this respect, CO₂-epoxide ring-opening copolymerization (ROCOP) has been combined with RAFT polymerization of vinyl monomers.¹⁰³ Achieving controlled polymerization and block co-polymerization could, in turn, lead to polymers with superior properties, since pure pCs based on PC or limonene carbonate suffer from low rigidity and brittleness, respectively.⁷⁹ Furan-containing monomers have been prepared and converted into their corresponding pC. This is particularly relevant in terms of sustainability because the furan ring is present in 5-hydroxymethylfurfural (5-HMF), a platform chemical obtained from cellulose (see Fig. 9, right).¹⁰⁴ A useful feature of furan rings is that they react *via* well-established Diels-Alder (DA) chemistry (see Fig. 4 for an example), which enables post-polymerization functionalization.^{104–106} In the example given in Fig. 4 (top), the polymer is reacted with 10 equivalents of maleimide for 48 h at 60 °C (maleimides may be obtained from renewable resources). A retro-DA reaction proceeds at 100 °C and restores the furan-containing polymer. Interestingly, if the polymer contains both an olefin and a furan ring, reversible cross-linking of the polymer can be achieved using the DA reaction.¹⁰⁷



Table 2 Selected reaction conditions and yields for CO₂-epoxide copolymerization

| Entry | Catalyst | Epoxide | Reaction parameters | Remarks | Ref, year |
|-------|---|--|-------------------------------------|---|-----------|
| 1 |  [PPN]Cl |  | 10 atm, 60 °C, 10 h, THF solvent | Yield = 35%, M_n = 37 kDa, PDI = 1.1 | 102, 2016 |
| 2 |  [PPN]X X = dinitrophenolate |  | 15 atm, 22 °C, 2 h | TON = 802 ± 26, M_n = 27 kDa, oxidant = FcPF ₆ | 113, 2016 |
| 3 |  |  | 30 atm, 50 °C, 3 h, 1 mL toluene | M_n = 28.6 kDa polymer, PDI = 1.11, T_g = 112 °C, block-polymer achieved with addition of <i>N</i> -isopropylacrylamide | 94, 2018 |
| 4 |  R = cumyl, Z = PPh ₂ , X = O ^t Bu |  | 1 atm, 80 °C, 23 h, 0.1 mol% | > 99% carbonate linkage, TON = 350, M_n = 3400 Da | 98, 2018 |

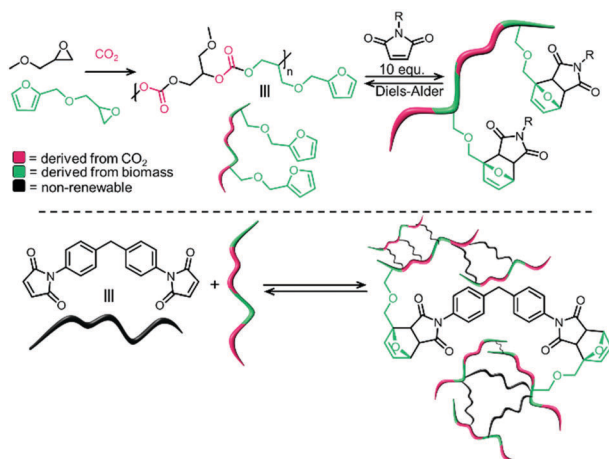


Fig. 4 Schematic representation of post-polymerization functionalization of furan-containing pC using the DA reaction.

Another reversible cross-linking strategy is to react the furan containing polymer with a bis-maleimide (Fig. 4, bottom).^{106,108} In the example shown, however, only 50% of the native polymer could be recovered following the retro-DA reaction. Moreover, the reaction requires a large excess of the dienophile when no catalyst is employed (10 eq. for the example in Fig. 4, top).¹⁰⁹

Table 2 compiles the reaction conditions required by selected catalysts to copolymerize CO₂ and epoxides. As for COC synthesis discussed above, no straightforward analysis is possible due to the vastly different reaction conditions employed. However, salen ligands are privileged ligands for the copolymerization reaction (Table 2, entries 2 and 4, as well as catalysts 7 and 9, Fig. 3). In most cases, an ionic/basic co-catalyst is required, and in some cases is covalently linked to the ligand (for example in catalyst 7, Fig. 3). Typically, the co-polymerization reaction is conducted at low temperatures and pressures (<100 °C, <30 atm, Table 2, entries 1–4). The resulting polymers often display a high M_n (for example 27 kDa, Table 2, entry 2) and narrow PDIs (<1.2). Notably, the Zn catalyst depicted in Table 2, entry 3, affords high M_n (28.6 kDa) homodispersed polymers (PDI = 1.11) at 50 °C and a moderate CO₂ pressure (30 atm). The examples discussed above were presented without taking into account that the polymerization leads to two different stereoisomeric products as the epoxide starting material possesses a chiral center. Advantageously, catalysts have been developed that lead to a single, highly crystalline isotactic product. Producing isotactic polymers confers different properties to a material compared to a material displaying low or no tacticity, and highlights the crucial role of the catalysis in the polymerization reaction.^{110,111} Obtaining fully regio- and



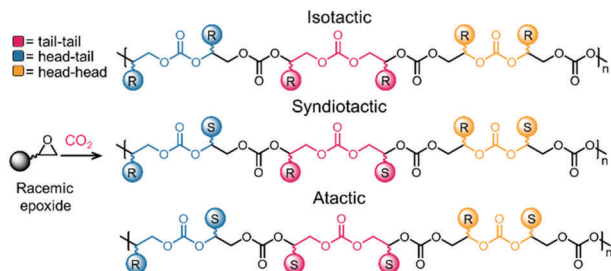


Fig. 5 Example of stereoselective control during pC synthesis. Top: All-*R* stereocenter. Middle: Alternating *R*-*S* stereocenters. Bottom: Random *R*-*S* distribution.¹¹¹

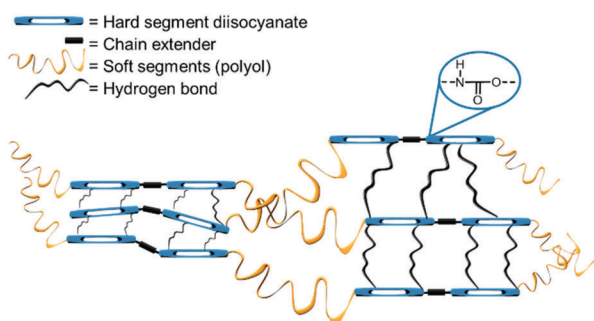
stereo-controlled polymers usually also leads to higher glass transition temperatures.⁹² A generic example of isotactic polycarbonate is shown in Fig. 5. Control over the stereoselectivity requires an appropriate catalyst, although the substituents on the epoxide can play a role as well. For instance, using a Co(III) catalyst, it has been shown that an electron withdrawing group on the epoxide can lead to highly isotactic polymers, allowing semi-crystalline and crystalline polymers to be obtained.¹¹²

PHU synthesis from COCs and diamines

Definition of PUs and conventional synthesis methods

As mentioned in the Introduction, the definition of PUs is not restricted to polymers containing only urethane linkages. Rather, many classes of polymers are referred to as PUs because they contain urethane groups. Block polymers containing polyethers, polyesters or silicone polymers, in addition to PU segments, may be classified as PUs.¹¹⁴ Consequently, PUs have a large number of applications. PUs typically contain both rigid and flexible parts, and it is this combination that confers their thermoplastic properties (see Fig. 6).^{115,116} The chemistry of PUs has been intensively studied and numerous reviews and books describe the properties and applications of PUs.^{26,115,117–119} Similarly to PUs, PHU elastomers comprising rigid and flexible segments can be conveniently obtained from the COC-diamine route described below.¹²⁰

The most common route to prepare PUs is *via* the reaction of isocyanates with diols (Fig. 7).¹²¹ The isocyanate functional



Alternating hard segment & soft segment structure

Fig. 6 Schematic structure of a typical PU.¹¹⁹

group is water sensitive and the reaction between isocyanate and water leads to the release of CO₂. For processing of PUs into foam-like structures, water is added intentionally to the process,¹²² but this method requires using an excess of isocyanate and may be less economically viable than other methods.¹²³ The addition of water leads to a decrease in the density of the polymer, which is an important parameter for foams. PUs are routinely prepared on an industrial scale, and the materials find applications as sponges, in foams for car seats, in mattresses, and even in medicine.^{79,123} Fig. 7 shows selected monomers (isocyanates, diols and diamines) and catalysts that are routinely employed in the synthesis of PUs.²⁶ In general, N-containing bases are used as catalysts (*e.g.* DABCO, BDMAEE, *etc.*, see Fig. 7).¹²⁴ Notably, the reaction produces a single product and, unlike pC synthesis, a chiral catalyst is not needed for the reaction.

PHU synthesis from COCs and diamines and their applications

In contrast to PUs, PHUs (also referred to as “non-isocyanate polyurethanes”, NIPUs) prepared from COCs and diamines have been less well investigated, but several excellent contributions demonstrate their high potential.^{125–129} Similar to PUs, PHUs derived from COCs and diamines have been prepared by combining different COCs and amine precursors, some examples of which are illustrated in Fig. 7.¹³⁰ Examples of COCs employed include bisphenol A diglycidyl ether carbonate (BPAC) and diglycerol dicarbonate (DGC); the former is not derived from biomass sources but has been used routinely in pC packaging for decades. Unfortunately, BPA is harmful (it is being banned in food packaging), and alternatives are being investigated,^{131,132} for example DGC, a presumably less toxic molecule that can be derived from (renewable) glycerol.¹³³

Any diol can be reacted with ECH to generate bis(epoxides) that can be converted to the corresponding COCs.¹³⁴ The diols can be derived from biomass sources (for example cellulose or

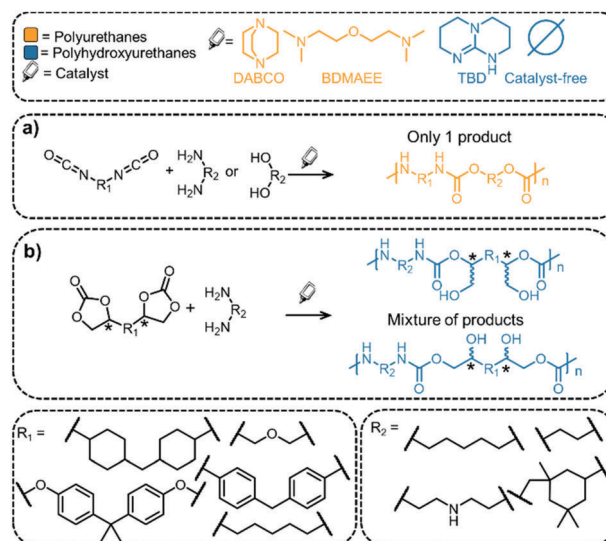


Fig. 7 Synthesis of PUs and PHUs and selected functional groups and catalysts that have been used.



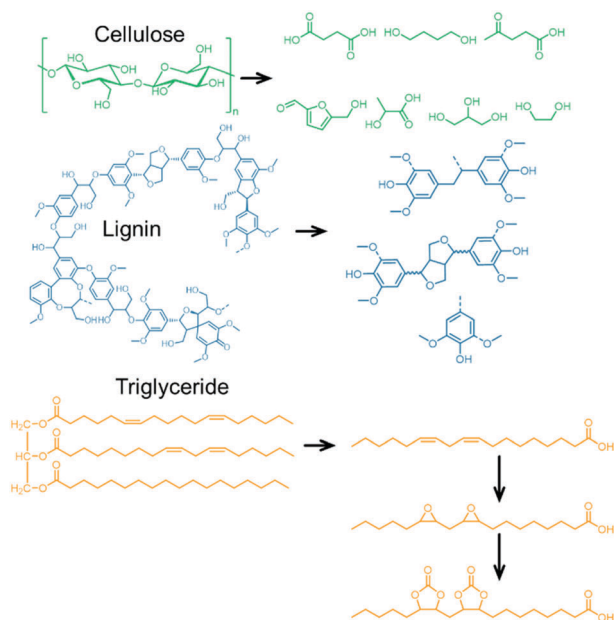


Fig. 8 Examples of alcohols/diols derived from cellulose and lignin (top, middle) after hydrogenation/hydrogenolysis reaction. Example of a carbonated vegetable oil (linoleic acid, bottom) obtained from a natural triglyceride.

lignin, see Fig. 8 for examples).^{135–137} Biomass conversion can lead to a variety of functional groups including acids, ketones, and others (alcohols, amines).¹³⁸ Acids and ketones can be converted to alcohols by hydrogenation, and subsequently to COCs using ECH and the CCE reaction presented above. Note that acids or ketones obtained from biomass can also be used as platform chemicals for other polymeric products, such as poly lactic acid (pLA, one of the most important bio-based polymer that is biodegradable) or poly γ -valerolactone (pGVL).¹³⁹ Diols can be obtained from lignin containing biomass sources by catalytic reductive fractionation with hydrogen and typically employ supported metal catalyst (Pd, Ni, Ru, Rh). Fig. 8 contains examples of structures of diols that may be obtained from biomass sources.^{140,141}

1,2-Diols obtained from carbohydrate sources are converted to COCs using the highly toxic phosgene route or dimethyl carbonate (transesterification reaction).¹⁴² Notably, 1,2-diols can also be converted to COCs using CO₂ as the C1 source, although this reaction is hindered by the release of water as a by-product (thermodynamic limitation, the reverse reaction is employed to generate EG from EC and water),^{143,144} which leads to moderate yields and significant amounts of waste because of the water capture strategies (utilization of alkyl halides as dehydrating agents, for example). COCs can also be obtained from vegetable oils or fatty acids because they contain olefin bonds. The olefins are first epoxidized and further transformed into their corresponding COC (see Fig. 8, bottom).¹²² These oil-based COCs can then be converted to a PHU by reaction with a suitable amine.^{145,146} This strategy is attractive because of the availability of the vegetable oil starting material and the properties of the resulting material that can be used as coatings and thermal insulators, *etc.*^{122,147}

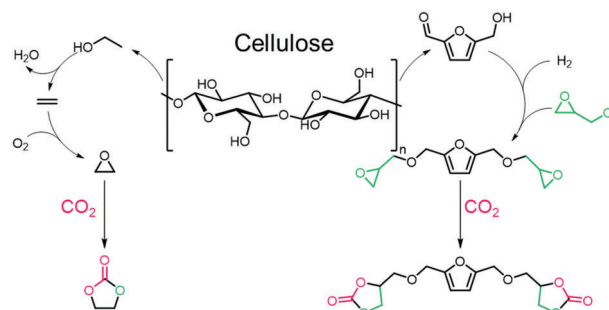


Fig. 9 Preparation of renewable EC (left) and 5-HMF derived bis(carbonate) (right) from cellulose.

The dehydration of ethanol (obtained from cellulosic feed-stock) yields ethylene, which can be oxidized to afford ethylene oxide,¹⁴⁸ a substrate in the CCE reaction. Sugar-based polymers have attracted attention due to the availability of non-edible cellulosic feedstocks (which can be broken down into sugars), and examples of the polymerization of glucose and related compounds have been reviewed elsewhere.^{149,150} The hydrolysis/dehydration of cellulose leads to carbohydrates that can be further converted into 5-hydroxymethylfurfural (5-HMF, see Fig. 9, right),¹⁵¹ that can be transformed into a bis-epoxide and subsequently converted into a bis(carbonate).^{72,152,153} To make the material fully renewable, the coupling partner to the COC must also be derived from renewable sources.¹⁵⁴ The formation of bio-based diamines is also possible from lignin derivatives when ammonia is added into the reaction mixture as a reagent.^{155,156} Currently, ammonia is generated from the Haber-Bosch (HB) process, but efforts to produce more sustainable ammonia are underway.¹⁵⁷ The synthesis of ammonia (Haber-Bosch) is energy-intensive and, therefore, the biopolymers chitin and chitosan are being investigated as alternative sources of nitrogen containing compounds. Chitin is the second most abundant biomass source after cellulose.^{154,158} Efforts to prepare bio-based amines from chitin have been reviewed previously.^{155,159} Fig. 10 shows a generic strategy to obtain COCs and diamines from biomass sources and catalysts that have been employed in the synthesis of PHUs.

An example of a renewable PHU is depicted in Fig. 11, bottom, where the diamine is derived from the 5-HMF platform (furfural) by reaction with NH₃ and the COC is derived from lignin.¹³⁵ The polymer obtained from the compounds depicted in Fig. 11 is prepared in the molten phase, in the absence of a catalyst at 160 °C, and has a molecular weight of 5.3 kDa and a high PDI of 3.2. The polymer exhibits a glass transition temperature of 73 °C and decomposes at 267 °C, comparable to that of a bisphenol A polymer prepared under the same conditions ($T_g = 79$ °C and $T_d = 276$ °C). PHUs obtained from isosorbides and Jeffamine (a polyetheramine based on propylene oxide/ethylene oxide) display properties suitable for coatings (low glass transition temperature of –8 to 59 °C).¹⁶⁰ PHU vitrimers (polymers networks whose cross-links undergo associative exchange at elevated temperatures) have been prepared from COCs and diamines that possess similar mechanical properties to PU



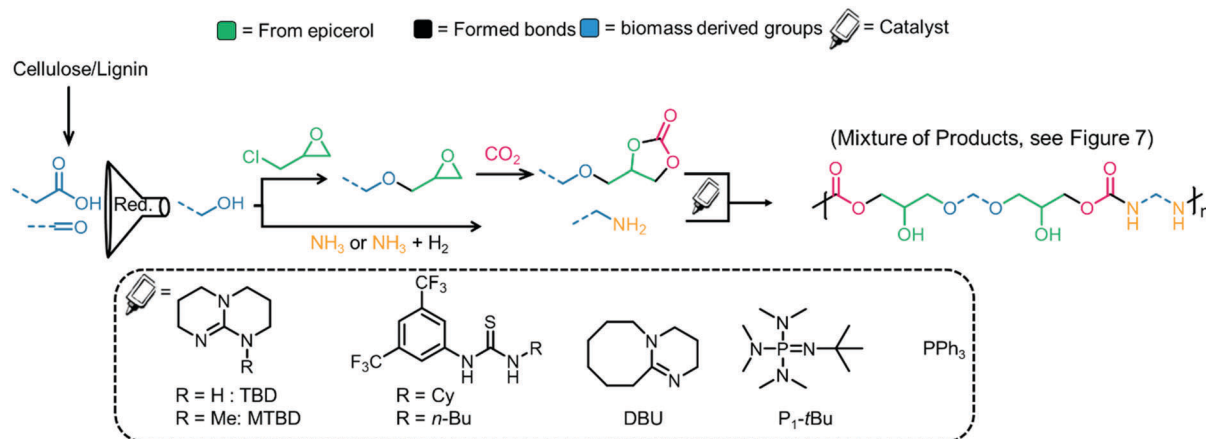


Fig. 10 Generic strategy for the preparation of renewable PHUs from biomass sources and catalysts that have been used for PHU synthesis. The product is the result of the reaction between a bis-carbonate and a diamine. Only one side is presented for clarity.^{135,162,163}

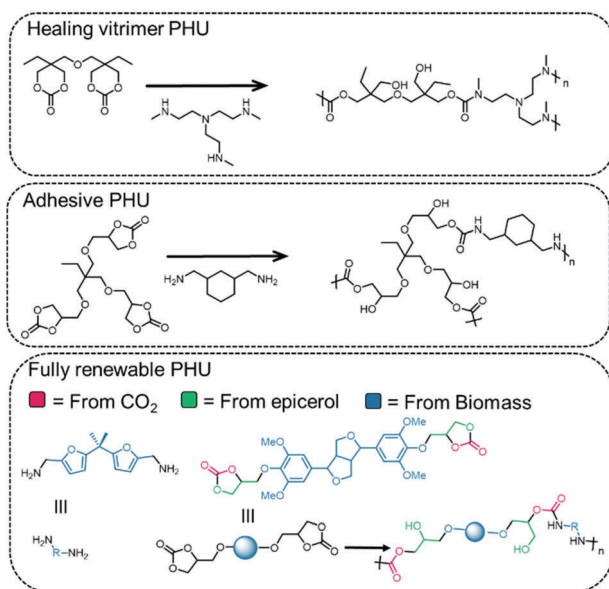


Fig. 11 Examples of PHUs and their applications.

thermosets, but with enhanced reshaping and repair properties by compression molding (Fig. 11, top).¹²⁹ The PHUs prepared from trimethylolpropane tris-carbonate (TMPTC) and commercial diamines such as 1,3-cyclohexanebis(methylamine) (CBMA) are used as adhesives and effectively bind to wood, aluminum and glass supports (Fig. 11, middle).¹⁶¹

Challenges in regiocontrol of PHUs

The structural difference between PUs and PHUs (*i.e.* one pendant alcohol group) confers very different properties to the polymers (more extensive H-bonding in the latter usually leads to higher glass transition temperatures, for example).¹⁶⁴ It should be noted that it is difficult to control the regioselectivity during PHU synthesis and that often several different polymers (that differ in their regioselectivity or stereoselectivity) are formed (see Fig. 7).¹⁶⁵ Chiral centers are also present in

COCs and in the polymeric materials derived from them and a lack of stereocontrol leads to poorly defined polymers, which explains why PHUs are generally amorphous.¹²⁷ PHUs typically have low molecular weights, which is attributed to the many side reactions that can occur during their synthesis, especially at higher temperatures. However, the presence of a pendant hydroxyl group in PHUs enables post-polymerization modifications.^{166,167} The side reactions that hinder high polymerization degrees of PHUs include the formation of ureas¹⁶⁸ and oxazolidinones,²⁰ (see Fig. 12 for representative side-reaction pathways that can occur in catalyzed and non-catalyzed reactions).¹²⁷ At the same time, it is the relatively high reactivity of the urethane C–O bond that renders these polymers biodegradable.^{114,169} Foaming of PHUs is also problematic, since no gas is released during the synthesis (addition of water to isocyanate-based PUs forms CO₂ – the foaming agent) which makes processing more challenging.¹²² Nevertheless, foaming strategies for non-isocyanate PUs have been proposed, using, for example, poly(methylhydrogenosiloxane) as a blowing agent.^{170,171}

The catalysts used to prepare PHUs comprise a few N-bases, metal salts and thiourea compounds (see Fig. 10, examples include TBD and DABCO).^{162,165,172–174} While catalysts accelerate the reaction they currently do not solve the regioselectivity issues. Moreover, it was shown that if the catalyst is highly basic (for example TBD), then the selectivity can decrease and the reaction can lead to the formation of urea or COC functional groups rather than urethane linkages (see Fig. 12, bottom, for the mechanism of the TBD-catalyzed transformation).¹⁷⁵

Strategies that lead to regioregular polymers are being investigated. It appears that one promising approach to obtain such polymers is to use/design suitable monomers. For example, using COCs and amines with bulky substituents leads to regioregular polymers when TBD is employed as a catalyst.¹⁷⁶ Furthermore, when α -alkylidenes are used as the starting materials, regioregular PHUs are obtained (Fig. 13, top).¹⁷⁷ Note that if two equivalents of EC is reacted with a diamine, then it is possible to avoid the pendant hydroxyl group and hence the regioselectivity issues. The resulting product is a diurethane diol that can be



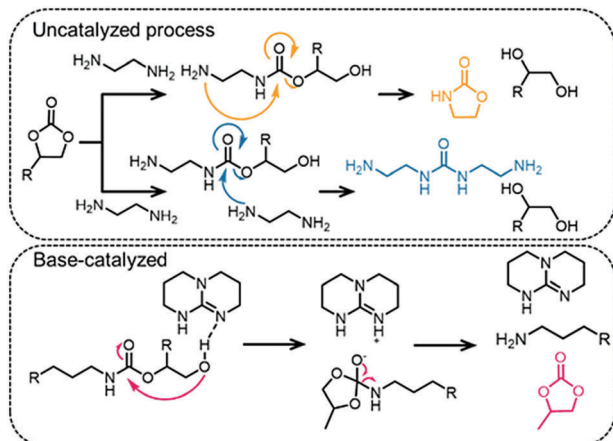


Fig. 12 Unwanted side-reactions that take place during PHU synthesis from COCs and ethylenediamine.

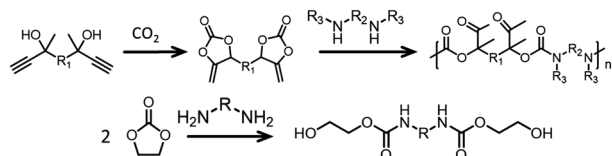


Fig. 13 Example of regioregular poly(oxourethane) (top) and diurethane diol (bottom).¹⁷⁷

transformed into polyesters–polyurethanes (Fig. 13, bottom).¹⁷⁸ Recently, *trans*-carbamates were obtained by taking advantage of existing tools for pC synthesis (see above). Incorporating an amine into an epoxide:CO₂:catalyst mixture leads to *trans*-carbamate products in the presence of chiral aluminum or cobalt catalysts (Fig. 14).^{179,180} Presumably, this strategy could open a way to controlled polymerization by reacting the epoxide:CO₂ mixture with diamines.

Biodegradation of the polymers/polymer end-of-life

It is not only important that future polymers are based on renewable sources, but that they do not pose long-term environmental problems. Therefore, designing tomorrow's materials will require a better understanding of (bio)degradation pathways and how to ensure polymers degrade within reasonable time scales and do not release toxic by-products into the environment. Biodegradation requires chemical bonds to be cleaved by enzymes (present in microorganisms). Other degradation pathways such as oxidation, hydrolysis or irradiation are often considered as biodegradation, even if these pathways do not require enzymes/microorganisms.⁸⁰ The behavior and degradation of polymers under physiological conditions, for example, has been extensively studied in the context of implants.^{181–183} Biodegradation often relies on a depolymerization step followed by a mineralization step. The first step converts the polymer into its monomer, and in the second step digestion of the monomer into (ideally) CO₂ and water, takes place.¹⁸⁴ Biodegradation is often limited as polymers cannot be readily accessed by the enzyme capable of cleaving the

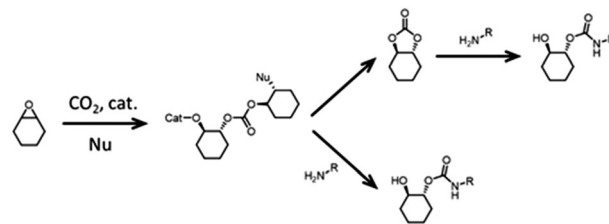


Fig. 14 Trapping of a *trans*-carbamate product via a pC intermediate.

polymer bonds. Hence, polymers are required that can penetrate within the active site of enzymes. For instance, not all pCs are necessarily biodegradable and care must be taken when referring to pCs as biodegradable. In this respect, the pC based on bisphenol A is not readily degradable and persists in the environment.⁸⁰

Fig. 15 depicts a conceptual representation of enzymatic biodegradation. Biodegradation pathways are complex and a simple change in the polymeric structure can lead to major changes in the decomposition pathway. For example, polyethylene glycols (PEGs) and polypropylene glycols (PPGs) decompose *via* different routes.¹⁸⁵

The mechanism of biodegradation of PUs has been studied and several pathways are possible including oxidative biodegradation. If the PU contains polyesters or polyureas, then esterases or ureases are able to cleave the bonds and degrade the polymer. The prerequisite is that the polymer can reach the active site of the enzyme.¹⁸⁶ In fact, including PUs in the structure of functional materials represents a strategy to increase the degradability of polymers that would otherwise not degrade. This strategy is employed in the preparation of biodegradable conducting polymers for biomedical applications.^{187,188} Notably, even if the materials are bio-derived, there is no guarantee that the resulting polymer will be degradable (for example if the material is highly cross-linked and hydrophobic).¹⁸⁹ Thermal degradation pathways of the polymers can result in the release of toxic chemicals. The decomposition products from the thermal degradation of a PHU is depicted in Fig. 16.¹⁹⁰ The main reactions

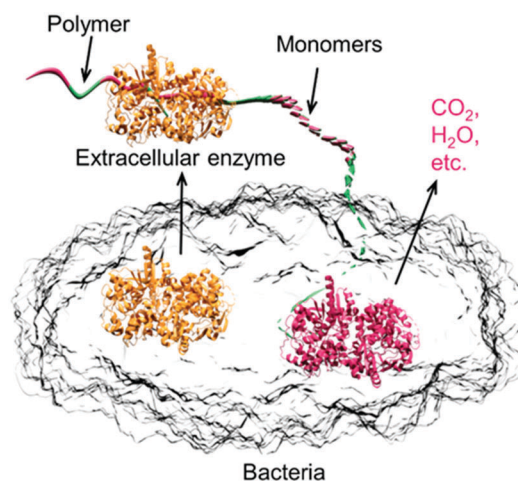


Fig. 15 Representation of enzyme catalyzed polymer degradation.⁸⁰



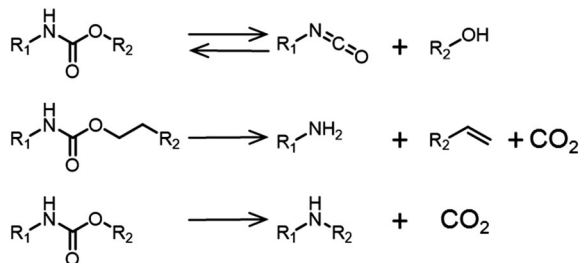


Fig. 16 Decomposition pathways of urethane linkages at 200–300 °C.¹⁹⁰

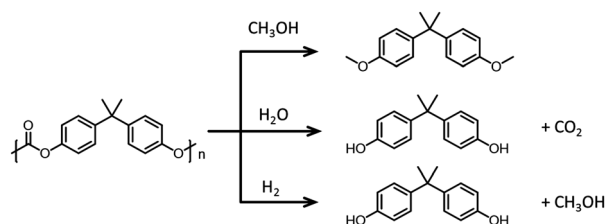


Fig. 17 Chemical depolymerization of bisphenol A carbonate. Top: Methanolysis. Middle: Hydrolysis. Bottom: Hydrogenolysis.

include the reversible depolymerization reaction of the urethane bond to form an isocyanate and an alcohol. CO₂ is also liberated upon degradation of the polymer, as well as amines and olefins.

Chemically converting polymers into their monomers in order to reuse the monomers is an attractive recycling concept. This approach has been extensively studied for polyesters and pCs, where the polymeric linkages (esters or carbonates) can be disrupted by hydrolysis,¹⁹¹ alcoholysis,¹⁹² glycolysis¹⁹³ or hydrogenolysis (see Fig. 17 that illustrates the chemical pathways for bisphenol carbonate depolymerization).¹⁹⁴ Currently, it is more cost-effective to dispose of the waste and generate new polymers from petrochemicals than to recycle and reuse existing materials.¹⁹⁵

Current limitations, future perspectives and conclusions

The preparation of COCs has been extensively studied due to the wide range of uses of liquid COCs such as PC and EC. COCs are also used as reactive precursors to PUs and PCs. Terminal epoxides react smoothly in the presence of easily accessed catalysts and does not require elevated CO₂ pressures, high temperatures or prolonged reaction times. Indeed, the reaction can be conducted under diluted, continuous-flow reaction conditions at atmospheric pressure.^{196,197} Hence, thermally robust catalysts that are resistant to water, oxygen, and industrial contaminants such as H₂S are sought after.

Suitable terminal epoxides can be derived from waste biomass sources. Importantly, for the process to be sustainable the use of waste (inedible) biomass is essential rather than using biomass from crops specifically grown to produce a chemical (non-food) product.

The reaction between COCs and diamines (or aminols/diols) leads to PHUs (or pCs), and it seems likely that bio-derived

PHUs will find large-scale applications in the future. Although PHUs are prepared from COCs and diamines in the absence of a catalyst, discovering catalysts that enable a higher degree of regio- and stereo-control should afford polymers with more homogeneous properties and will accelerate the utilization of renewable PHUs at an industrial level.

The catalysts described herein are derived from petrochemicals. The catalysts are not used in the same quantities as the chemicals they are used to produce, but if the preparation of renewable materials must become fully sustainable, the development of renewable catalysts becomes relevant. In this respect, catalysts based on lecithin,^{198,199} chitosan²⁰⁰ or animal-based wool have been used for COC synthesis¹⁰⁰ and natural catalysts/supports are being exploited in other applications.^{201,202}

Finally, a thorough life-cycle analysis (LCA) of the obtained polymers is required to assess the sustainability of the process. For example, CO₂-containing materials do not necessarily decrease the net amount of CO₂ since energy is required for their transformations.²⁰³ Further, at the “end-of-life”, the polymers will typically be converted into CO₂ again, as mentioned in the section on biodegradation. An extensive review on the LCA of CO₂-derived chemicals has been published very recently and these types of analysis are extremely relevant to pursue the quest of catalytically produced sustainable materials.²⁰⁴

Conflicts of interest

There are no conflicts to declare.

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