Commissioned by the Federal Office for the Environment (FOEN)

Process for CO_2 Removal and Valorisation from Cement Flue Gas

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Contents

Imprint

Commissioned by: Federal Office for the Environment (FOEN), Air Pollution Control and Chemicals Division, CH-3003 Bern.

The FOEN is an agency of the Federal Department of the Environment, Transport, Energy and Communications (DETEC).

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FOEN support: Peter Bonsack

1 Abstract

Cement manufacturing accounts for a largeportion of global greenhouse gas (CO_2) emissions, changing the balance of life on earth and leading to global warming. Here, we developed a powerful catalytic method for the removal of CO_2 from gas streams, e.g. those generated during cement production,via a catalytic reaction between CO_2 and epoxides to afford useful cyclic carbonates. A continuous flow system employing a homogenous catalyst (tetrabutylammonium iodide, TBAI) and heterogenous catalyst (SiO_2) were shown to efficiently promote the reaction inhigh yield. The process was successfully applied to a range of epoxidesto generate a range ofcyclic carbonates in excellent yield. These products have wide range of applications, e.g. as 'green' polar aprotic solvents, additives in lithium-ion batteries, and feedstocks to produce functional polymers.In order to model real flue gas, common impurities including O_2, N_2, NO_2, CO and SO_2were evaluated and shown to not to have a negative impact on the reaction (although water was found to be detrimental).Modelling using ASPEN demonstrates the economicviability and sustainability of thecontinuous flow system.

2 General introduction tothe problem

CO_2 is a major greenhouse gas leading to global warming and its emission should be limited.[1]Global cement production accounts for about 1.4 Gt of CO_2 emissions per year,

corresponding to roughly 5.8% of global anthropogenic emission.[2] Cement flue gas contains 16% CO_2, which is far more than the average value of atmosphere of 0.04% (Fig. 1).[2-3]

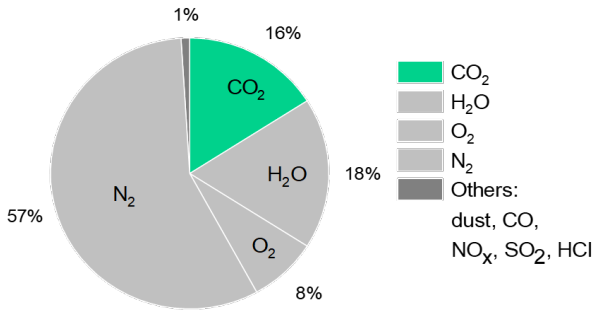

Figure 1. Characteristics of cement plant flue gas.[3]

CO_2 capture and utilization of the flue gas is considereda sustainable strategy to reduce the CO_2 emission.[4]At present, the vastmajority of carbon resources are based on crude oil, natural gas and coal, but CO_2 offers the possibility to create a renewable carbon economy and has become one of the most important industrial feedstocks due to its abundance,availability, nontoxicity and recyclability.

CO_2 as a source of single carbon atoms (termed C1 source) has received considerable interest over the last few decades, because it could potentially replace toxic C1 sources such as carbon monoxide, phosgene, etc.[4-5]In particular, incorporation of CO_2 into organic compounds and its transformation to value-added products has become an important topic in organic synthesis(Fig. 2).[5]However, activation and utilization of CO_2 is still problematic asthe carbon in CO_2 is in the most oxidized form, which is thermodynamically stable and also kinetically inert inmanyreactions.[6]Consequently, most strategies use highly reactive substrates and/or forcing reaction conditions to activate CO_2, limiting the application of such methods.

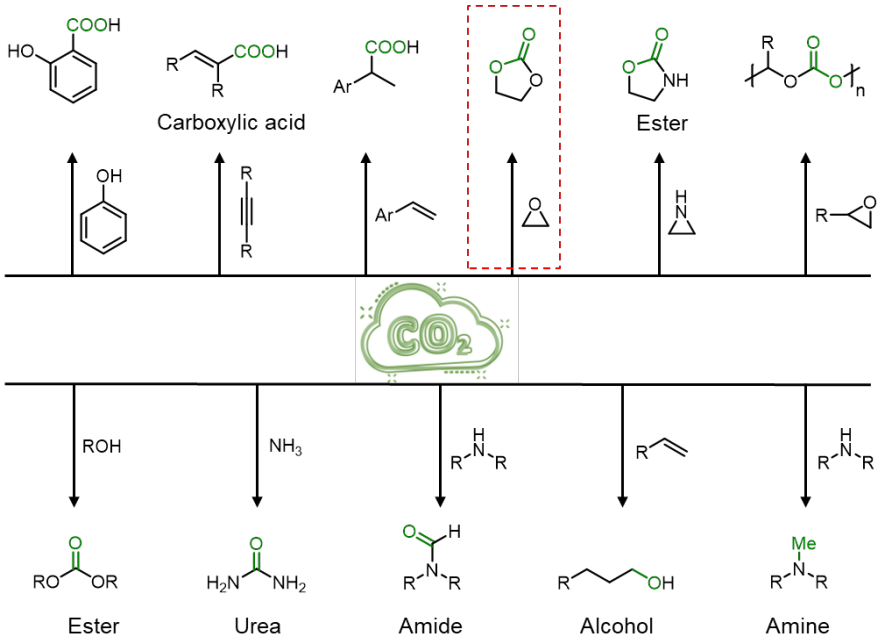

Figure 2. Applications of CO_2 in organic synthesis.

Moreover, all these reactions are performed in batch reactors, which is not suited to flue gas streams, and continuous flow methodologies would be advantageous,e.g. allowing reaction parameters to be monitored and optimized, resulting in reliable and reproducible processes.[7-9]Importantly, continuous flow systemsprovide veryefficient heat and mass transfer, acceleratingreaction rates,often leading to improved productivity with respect to batch systems.[10]However, switching chemical transformations from batch to continuous flow processestend to bedifficult (either reducing the product yield or in some cases is even considered impossible), primarily due to the limited interaction between the catalyst and substrates.

3 Solution

Cyclic carbonates have a continuously increasing market because of their extensive use as solvents, additives andas feedstocks used in the production of polymers, medicines and agricultural chemicals, etc.[11-14]Conventional synthesis of cyclic carbonates involves the reaction of diols with phosgene.[15] However, this reaction is not environment friendly due to the toxic and corrosive nature of phosgene. The formation of cyclic carbonates from epoxides and CO_2 involves fewer hazardous species, as it incorporates CO_2 as a C1 feedstock source instead of phosgene.The cycloaddition

reaction proceeds with 100% atom economy, i.e. there is no waste by-product, and thus constitutes one of the most efficient examples of artificial CO_2 fixation.

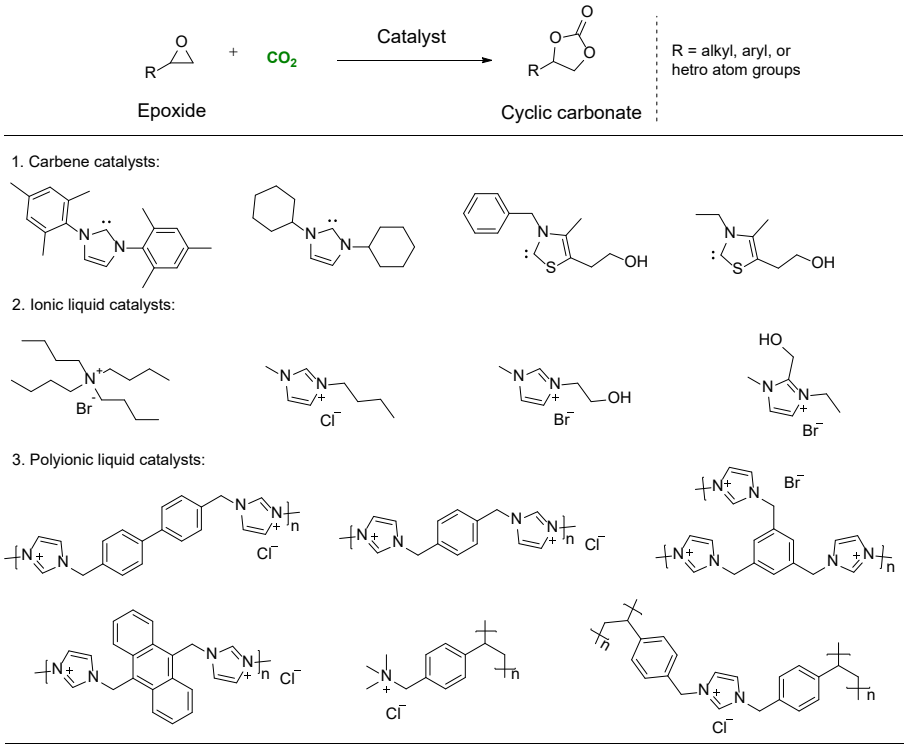

Figure 3. Fixation of CO_2 via cycloaddition with epoxides to produce cyclic carbonates and examples of catalysts used.

Ourgroup have developed powerful catalytic tools for the removal of CO_2 from gas streamsviacycloaddition with epoxides to form cyclic carbonates,[16-25]and carbene, ionic liquid and poly-ionic liquid catalysts have been intensely investigated (Fig. 3). These catalysts were developed using batch reaction conditions and in one case usinga continuous flow process, enabling continuous CO_2 removal from flue gas streams. Although the demand for cyclic carbonates does not correspond to the amount of CO_2 produced globally,the demand for cyclic carbonates has been increasing rapidly,[26-28] and could contribute towards CO_2 mitigation.

4 Specific goals and plan

1. Fixed-bed reactor design and construction. The feedstock (gas and epoxide) will be injected into a fixed-bed reactor packed with the catalyst. The flow rates (and thus also the residence times) will be controlled usinga pump (for the liquid epoxide) and mass flow meter (for the

gas). The product distribution will be monitored online (gas and liquid phase). Throughout the optimization process, flow-rates, reaction temperature and fixed-bed reactor pressure will be varied and the process parameters continuously monitored.

2. Catalyst design and optimization. Design and development of a highly activeand selective catalytic system for the conversion of CO_2 intocyclic carbonates under continuous-flow conditions is essential.[29] The most common catalyticsystems for this reaction have Lewisacid character, which activates the epoxide, and a Lewis base, which leads to ringopening of the epoxide. The Lewis acid is usually a metal complex or a hydrogen bond donor species and the Lewis base is usually a halide (Cl^-, Br^-, I^-). The two types of active sites can be included within a bifunctional singlecomponentcatalyst or in a binary system consisting oftwo separate components.
3. Determination of kinetic parameters. Once the reactor and catalytic system is operational, the kinetics of CO_2 extraction will be evaluated. To obtain the relevant kinetic parameters, a series of experiments will be conducted to study the reaction rate as a function of temperature, pressure and residence time in the reactor.
4. Development of a model for the process. The kinetic parameterswill be implemented into a model for the process, using ASPEN, and will lead to key feasibility data. Heat optimization and energy consumption of the plant will be calculated to estimated CapEx and OpExvalues.

5 Results

5.1 Continuous flow reactor design

Previously, we proposed a generalized catalytic cycle for the reaction of $CO_2$and epoxides to yield cyclic carbonates (Fig. 4), which facilitates catalyst design. In this cycle, an electrophile **a**coordinates to the epoxide to form epoxide adduct **b**. A nucleophile then attacks the coordinated epoxide at theβ-position to generate a ring-opened alkoxy intermediate **c**. Next, insertion of CO_2 into the metal–oxygen bond forms the carbonate intermediate **d**. Backbiting occurs with another inversion leading to ring closing and elimination toform the cyclic carbonate product. Thus, for the cycloaddition reaction, wither two catalysts, acting as nucleophile and electrophile separately,or one bifunctional catalyst which could act as both nucleophile and electrophile simultaneously, are required. The nucleophile should also be a good leavinggroup to facilitate opening of the epoxide

ring and ultimately allow cyclic carbonate formation. Similarly, to facilitate theCO_2 insertion step, the electrophile should formfavourable interactions that stabilizethe ring-opened epoxide**c**.

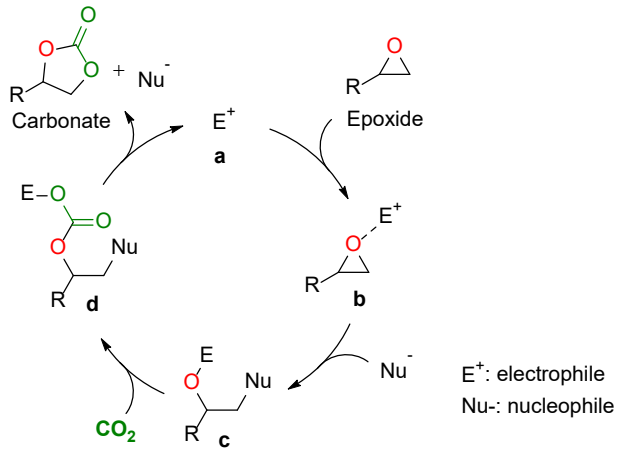

Figure 4. Mechanistic cyclefor the catalytic cycloaddition reaction between CO_2 and epoxides.

Regarding the reaction conditions, the influence of temperature on cyclic carbonate synthesis is difficult to predict. The reaction rate of the cycloaddition reaction generally increases with temperature due to an increase in catalyst activity at a higher temperature.[30] Moreover, increasing the temperature increases the gas diffusivity and decreases the viscosity of the reaction medium, both of which increase the gas-liquid mass transfer coefficient.[31] However, elevated temperaturesmay also accentuate side reactions such as isomerization and hydrolysis, leading to a significant decrease in product selectivity.[32-36]The effect of CO_2 pressure in various homogeneous and heterogeneous catalytic systems has been extensively studied, and increasing the CO_2 pressure results in an increase in reaction rate. Nevertheless, too high CO_2 pressure increases equipment costs and reduces the epoxide concentration,leading to a decrease in the reaction rate.[37-39]

According to our previous studies, we initially selected polymeric ionic liquid catalysts, (Fig. 5a), and tested their efficiency under batch conditions. Polymeric ionic liquid catalystsarebifunctional catalysts, which act as both electrophile and nucleophile.

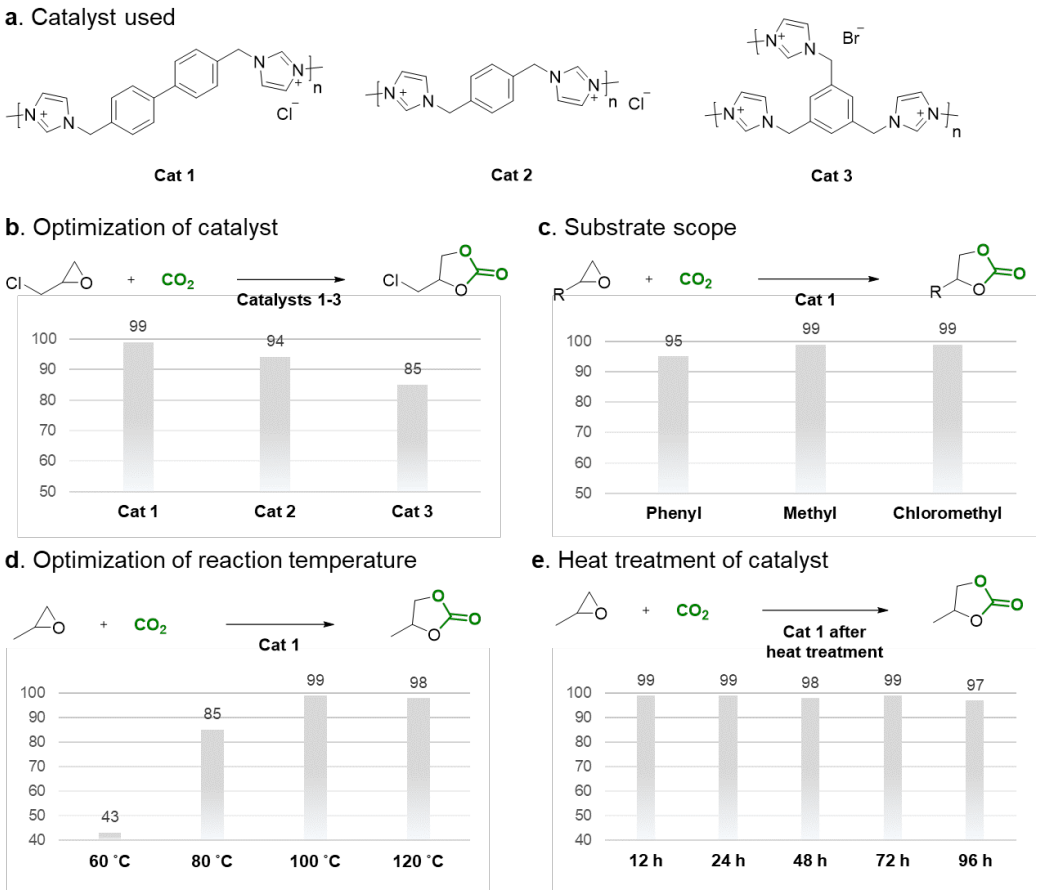

Figure 5. Optimization of the catalyst and reaction conditions in a batch reactor. (a) Polyimidazolium salt catalysts evaluated. (b) Catalytic activity tests. (c) Substrate scope evaluation. R = Phenyl, Methyl or Chloromethyl. (d) Reaction temperature tests. (e) Heat treatment of catalyst at 100 ºC.Yields were determined by gas chromatography and each reaction was repeated for 2-3 times and average yield is provided.

The biphenyl-based polyimidazolium catalyst (Cat 1) was found to be the most efficient catalyst (Fig. 5b). The substrate scope was also investigated. Alkyl propylene oxide and epichlorohydrin are both transformed to their corresponding cyclic carbonates in high yield (Fig.5c). Cycloaddition of CO_2 to propylene oxide was conducted at different reaction temperatures, with the highest conversion and yield achieved at 100 ºC (Fig.5d). In order to investigate thermal stability of Cat 1, heat treatment at 100 ºC was conducted before using Cat 1 in the cycloaddition reaction (Fig.5e). Cat 1 exhibits excellent thermal stability and was selected for further study in the fixed-bed reactor operating under continuous flow conditions.

A fixed-bed reactor was then constructed (Fig. 6) and evaluated. Propylene oxide (PO) and commercially available CO_2 gas wereused as substrates. The flow rates of liquid PO and $CO_2$was controlled via a liquid pump and CO_2 mass flow meter. After mixing, the CO_2 and POwere preheated and then passedinto the fix-bed reactor, containing Cat 1. After entering the cooling unit, the liquid product generated wasanalysed. The fixed-bed reactor with biphenyl based polyimidazolium catalyst (Cat 1) works well, but the catalytic efficiency is not satisfactory (liquid flow rate < 1 mL/h, conversion of PO < 10%, reaction temperature = 100ºC), which is not unusual when transferring a batch process to a continuous process.

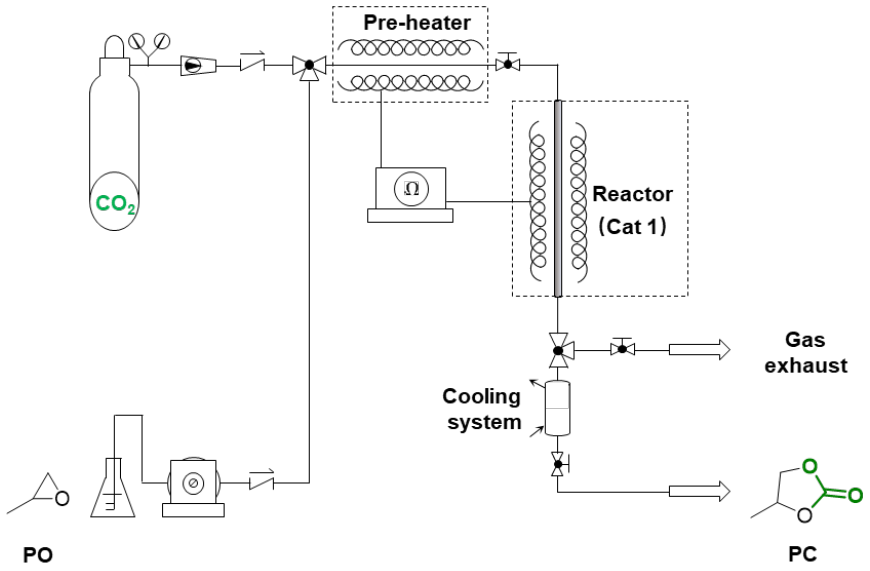

Figure 6. Schematicof the fixed-bed reactor system.

As mentioned above, compared to batch reactions, continuous flow processes provide a much lower retention time of substrate in the reactor, which requires a catalytic system with a short induction period and high turnover frequency. Hence, we hypothesized that a co-catalyst would be beneficial in a continuous flow process. Note that co-catalysts have been extensively studied in cyclic carbonatesynthesis.[40]Commonly used co-catalyst for this reaction are nucleophile additives such as quaternary ammonium and phosphoniumsalts.The role of co-catalyst during cyclic carbonate formation is to open the epoxide ring, the rate determining step.[41]Following screening studies (see below), wediscoveredthat usingtetrabutylammonium iodide (TBAI) as a co-catalyst allows commercially available silica (SiO_2) to be used as a highly efficient catalyst for the cyclic carbonatesynthesis (notably a metal-free, non-toxic and inexpensive system).Theeffect of the

amount of TBAI and SiO_2catalysts on the reaction between CO_2 and styrene oxide (SO) was initially studied in an autoclave batch reactor (Fig. 7). Reactions do not proceed in the absence of either the TBAI or SiO_2, and from the catalyst concentration studies, a synergetic effect between the two catalysts appears to be in operation. In the batch reaction, the SiO_2catalyst combined with the TBAI co-catalyst promotes the cycloaddition reaction to generated styrene carbonate (SC) in near stoichiometric yield (99%), even at room temperature.

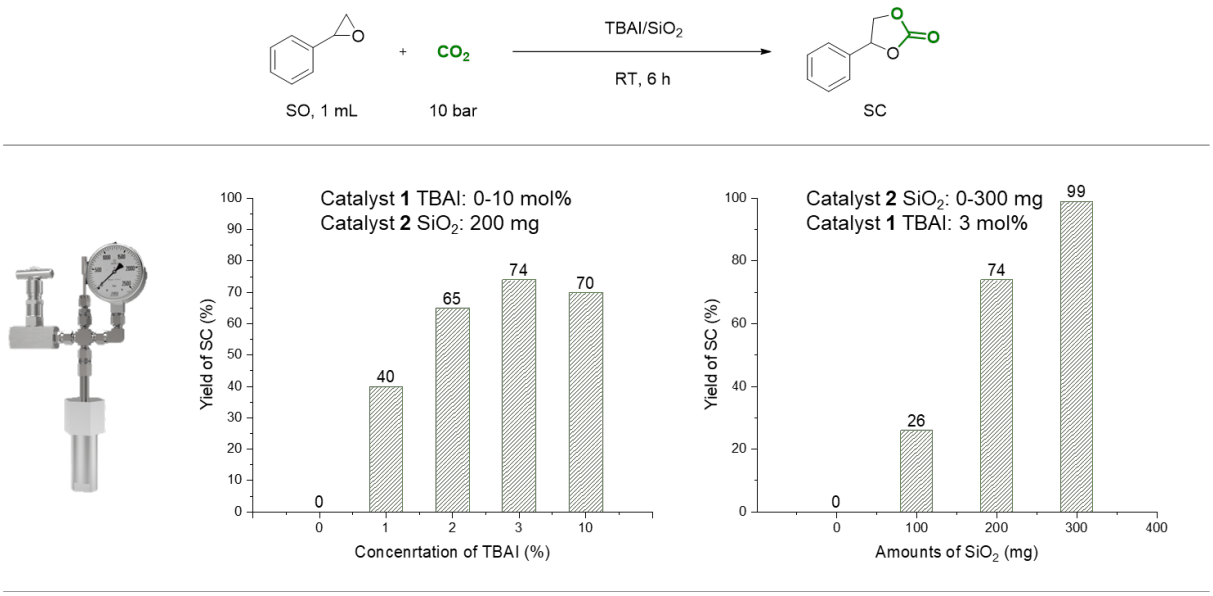

Figure 7. Cycloaddition of CO_2 to styrene oxide (SO) in a batch reactor. Reaction conditions: SO (1 mL), TBAI (0-10 mol%), SiO_2 (0-300 mg), room temperature (RT), 6 h.Yields were determined by gas chromatography and each reaction was repeated for 2-3 times and average yield is provided.

The heterogenous SiO_2 catalyst and homogeneous TBAI co-catalyst was then evaluated in a specially designed fix-bed reactor as shown in Fig. 8. In the continuous process the TBAI is dissolved in the substrate solution (SO). As the liquid flows through the fixed-bed reactor packed with SiO_2 it is mixed with the gas containing CO_2, promoting the reaction of CO_2 with SO to give the SC product in high yield.

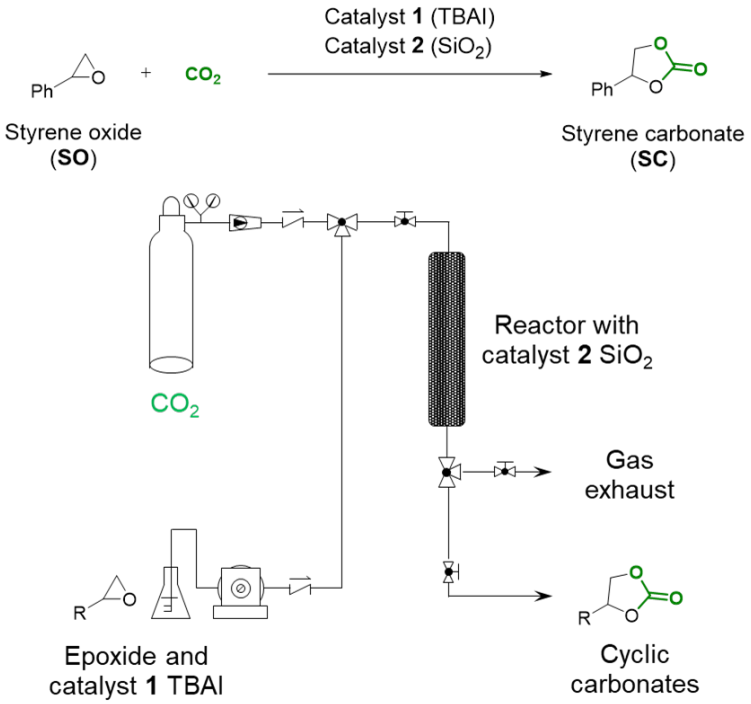

Figure 8. Reaction of styrene oxide (SO) and CO_2 to afford styrene carbonate (SC) (a valuable commodity chemical product) for direct CO_2 removal from gas streams (top). Outline of the fixed-bed reactor (bottom).

5.2 Parameter optimization

The type of heterogenous catalyst, concentration of the TBAI co-catalyst, reactor length, gas flow rate and reaction temperature, were further optimized asthey significantly influence the cycloaddition reaction (Fig. 9).The concentration of the TBAI catalyst in the SO substrate solution was found to be a simple way to regulate the yield of the SC product (Fig. 9a). Since the TBAI concentration also impacts on the viscosity of the solution, a 3 mol% concentration was found to be optimal. Several solid catalysts were evaluated including Al_2O_3 and molecular sieve, withSiO_2 providing the best performance (Fig. 9b). Notably, wet SiO_2 (commercially available product) gives a lower reaction yield of SC and water in the reaction system significantly reduces the reaction yield, see discussion below. As expected, the longer the reactor, the higher the yield of the product (Fig. 9c). The influence of the gas flow rate (Fig. 9d) and reaction temperature (Fig. 9e) were also optimized. At 25 ºC, the yield reached to 64%, but at 30 ºC, the reactor blocks due to the increased yield of SC (as the melting point of SC is ~50 ºC the product solidified when its concentration is too high). However,at a highertemperature of 40 ºC the SC product does not

precipitate in the reactor, and only solidifies after cooling. Thus, the yield of SC reached 81% at 40 ºC and 85 % at 50 ºC.

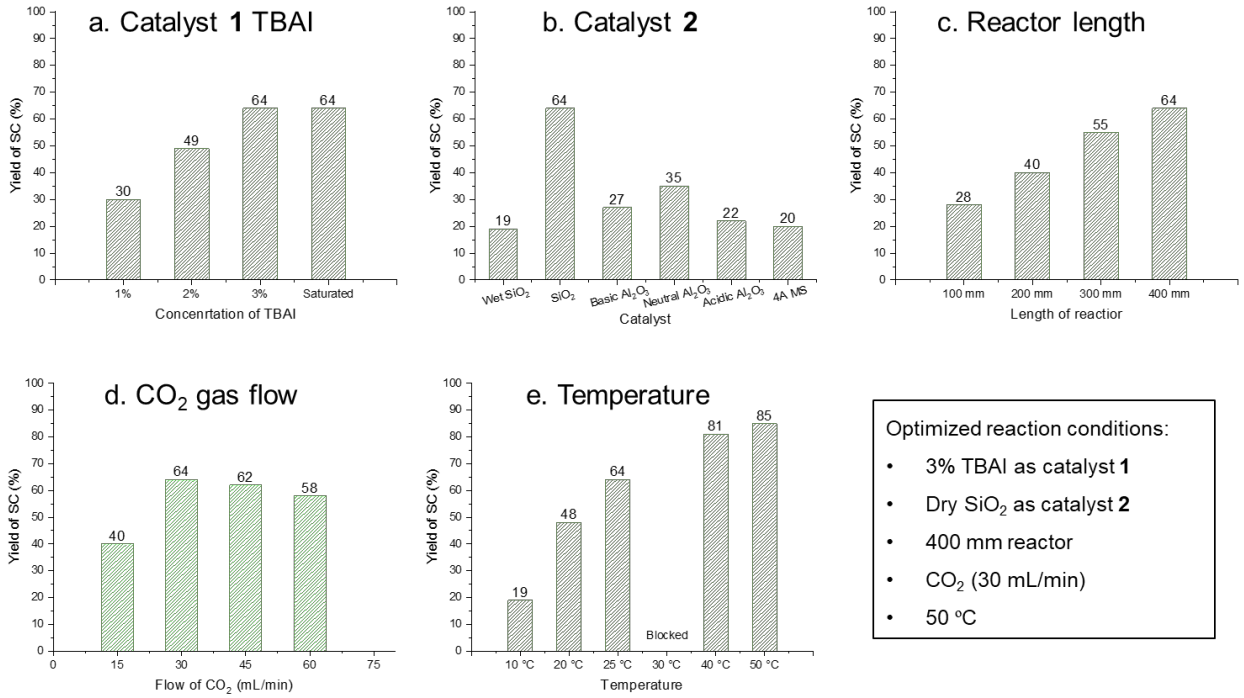

Figure 9. Reaction parameter optimization under continuous flow conditions. Reaction conditions: TBAI (1-3mol%), SiO_2 (10-40 g), SO (0.1 mL/min), CO_2 (15-60 mL/min), 10-50 °C.Yields were determined by gas chromatography and each reaction was repeated for 2-3 times and average yield is provided.

5.3 Substrate scope

The substrate scope was expanded to other alkyl epoxides with heteroatoms or unsaturated bonds (Fig. 10). Similar to thearomatic epoxide **1a**, alkyl epoxides with a chloride (**2a**), vinyl (**3a**) or methacrylate (**4a**) group also produce the corresponding cyclic carbonate, i.e.4-chloromethyl-dioxolan-2-one (**2b**), 4-((allyloxy)methyl)-1,3-dioxolan-2-one (**3b**), (2-oxo-1,3-dioxolane-4-yl)methyl methacrylate (**4b**) in high yield (78-85%).Styrene carbonate **1b** is widely used as an additive in lithium-ion traction batteries,[42]4-chloromethyl-dioxolan-2-one (**2b**) is low-toxicity coating remover,[43]4-((allyloxy)methyl)-1,3-dioxolan-2-one (**3b**) and (2-oxo-1,3-dioxolane-4-yl)methyl methacrylate (**4b**) are functional monomersused in the synthesis of polymers with high-end applications.[43-46]

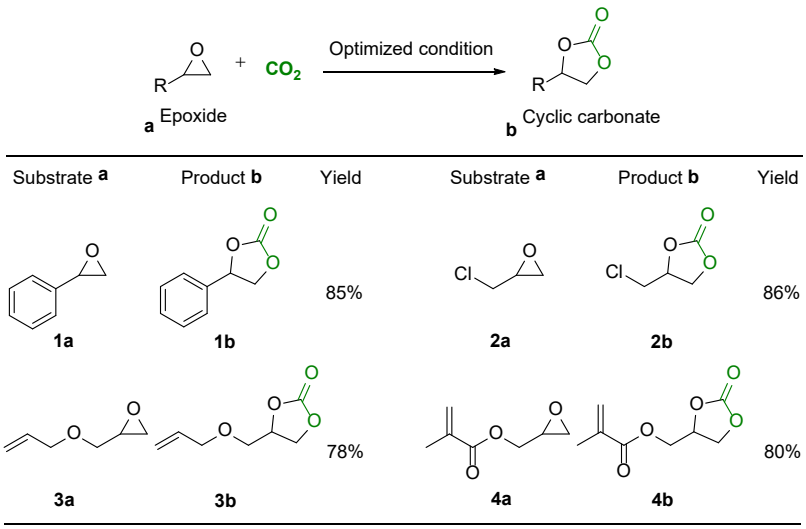

Figure 10. Substrate scope of the continuous flow system. Reaction conditions: TBAI (3 mol%), fix-bed reactor (400 mm ×10 mm), epoxide (0.1 mL/min), CO_2 (30 mL/min), 50 °C.Yields were determined by gas chromatography and each reaction was repeated for 2-3 times and average yield is provided.

5.4 Effect of gas impurities in cement flue gas

In addition to CO_2, the main gases in cement flue gases include O_2, N_2, H_2O and other relatively minor impurities including NO_2, CO and SO_2. Neither oxygen or nitrogen impact negatively on the reaction (see below), but water was found to be problematic. The evolution of the reaction yield over time in the flow reactor is summarized in Fig. 11.

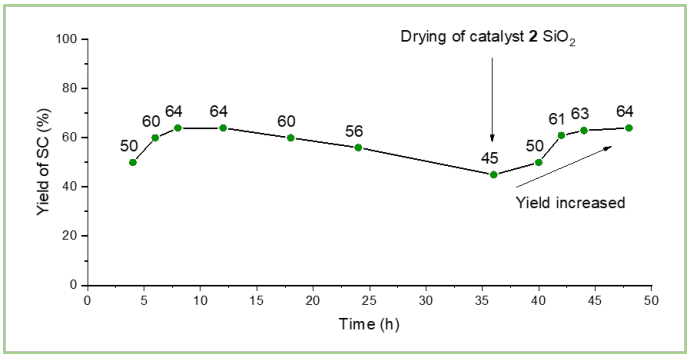

Figure 11. Evolution of the yield of SC to illustrate the effect of water on the reaction. Reaction conditions: TBAI (3 mol%), fix-bed reactor (400 mm ×10 mm), SO (0.1 mL/min), CO_2 (30 mL/min), 25 °C.

Under the optimized reaction conditions, the maximum yield is reached in ca. 8 hours. After this time the reaction yield of SC slowly decreases to 45% at 36 h. The decrease in yield may be attributed to the accumulation of water in the system during the reaction, which originates from moisture in the CO_2 stream. To confirm the detrimental impact of water, theSiO_2 catalyst was dried after 36 h and replaced in the reactor, with the SC product yield recovering.

Other minor impurities including CO and SO_2 have no observable negative impact on thecycloaddition reaction (Table 1, entries 1-2). NO_2 even slightly improves the product yield (Table 1, entry 3) and the reason for this improvement currently remains unknown. To model the real flue gas, CO_2 gas diluted with air was also tested. The yield of SO is 70%, with the lower yield attributed to the increased gas flow. These results demonstrate diluted CO_2 gas or CO_2 with impurities (with the exception of H_2O) can be used in the CO_2 and epoxide cycloaddition, confirming the potential application of the process to remove $CO_2$from cement flue gas.

Table 1. Effect of other gas impurities on the reaction of CO_2 with SO under continuous flow conditions.

Entry	CO_2 with additives	Yield of SC (%)	Effect
1[a]	10 ppm CO in CO_2	83	None
2[a]	2 ppm SO_2 in CO_2	80	None
3[a]	5 ppm NO_2 in CO_2	89	Yield slightly increases
4[b]	10% CO_2, 72% N_2, 18% O_2	70	None

Reaction conditions (**a**): CO_2 gas mixture (30 ml/min, based on pure CO_2), TBAI (3 mol%), SO (0.1 ml/min), 50ºC, reactor (40 cm × 1 cm). (**b**): CO_2 gas mixture (150 ml/min), TBAI (3 mol%), SO (0.05 ml/min),50ºC, reactor (40 cm × 1 cm). Limited by the current instrument, the flow of SO have to be decreased. Decreased yield may be attributed to the increased gas flow.

5.5 Modelling

In order to investigate the kinetics and economic viability of the reaction process, the experimental data wasimplemented into a model using ASPENto analyze crucial parameters of the reaction process. A process model for the production of SC from SO and CO_2 was developed in Aspen Plus. SO and CO_2react to form SC in the presence of SiO_2 (solid catalyst) and TBAI (co-catalyst). Ethyl

acetate is used to recover and recycle TBAI. In the Aspen Plus database, SO, $CO_2$and ethyl acetate are available. SCwas defined with properties estimated using the UNIFAC group contribution method, and TBAI was modelled as an inert solid.[47]In addition, the Peng-Robinson thermodynamic model was used to simulate the process flowsheet.[22]

The production process (Fig. 12) was designed for a production rate of 101.4 kmol/h. SO is mixed with TBAI (3 wt.%) and then reacts with CO_2at 3 bar and 25 ºC in a fixed-bed reactor. The volumetric flow ratio for the $CO_2$and SO is set to 225, resulting in a SC yield of 58%. Subsequently, the reaction products enter a flash tank, where unconverted $CO_2$is recovered and recycled back to the reactor inlet and mixed with fresh CO_2. Theco-catalyst, TBAI, which remains in the liquid stream, is recovered by precipitation in ethyl acetate, to be recycled with theSO flow at the reactor inlet. A distillation column is used to separate ethyl acetate from the SC and unreactedSO. The recovered ethyl acetate is mixed with make-up ethyl acetate. Finally, SC and SO are separatedmaking use of their boiling point difference in a flash tank. The recovered SO is mixed with fresh SO, and the SC product is obtained with 98% purity, when cooled to ambient temperature. The production process has several compressors, pumps and heaters/coolers. In order to control the impurities, the process has several purge streams, and an overall product loss of 5% has been assumed. The process consumes 103 kmol/h SO, 101.6 kmol/h $CO_2$and 6.8 kg/h TBAI.

The total installed cost of a plant is 5.68 million $ (Aspen Economic Analyzer). And the minimum selling price of SC is 38.43 $/kg.From the company Toronto Research Chemicals, the price of SC is over 10’000 times than SO. Thus, our simulation results showan economic viability of the CO_2removal process established. Many other cyclic carbonates could be prepared via this process and in nearly all cases the price significantly exceeds that of the epoxide precursor. Hence, the price of cyclic carbonate products obtained by this process is competitive to those prepared by the usual methods. Since the cyclic carbonates prepared by this method also contain one renewable carbon atom derived from CO_2 (and some epoxide substrates are derived from biomass which would lead to entirely renewable cyclic carbonates), there would also be incentives to purchase cyclic carbonates prepared in this manner.

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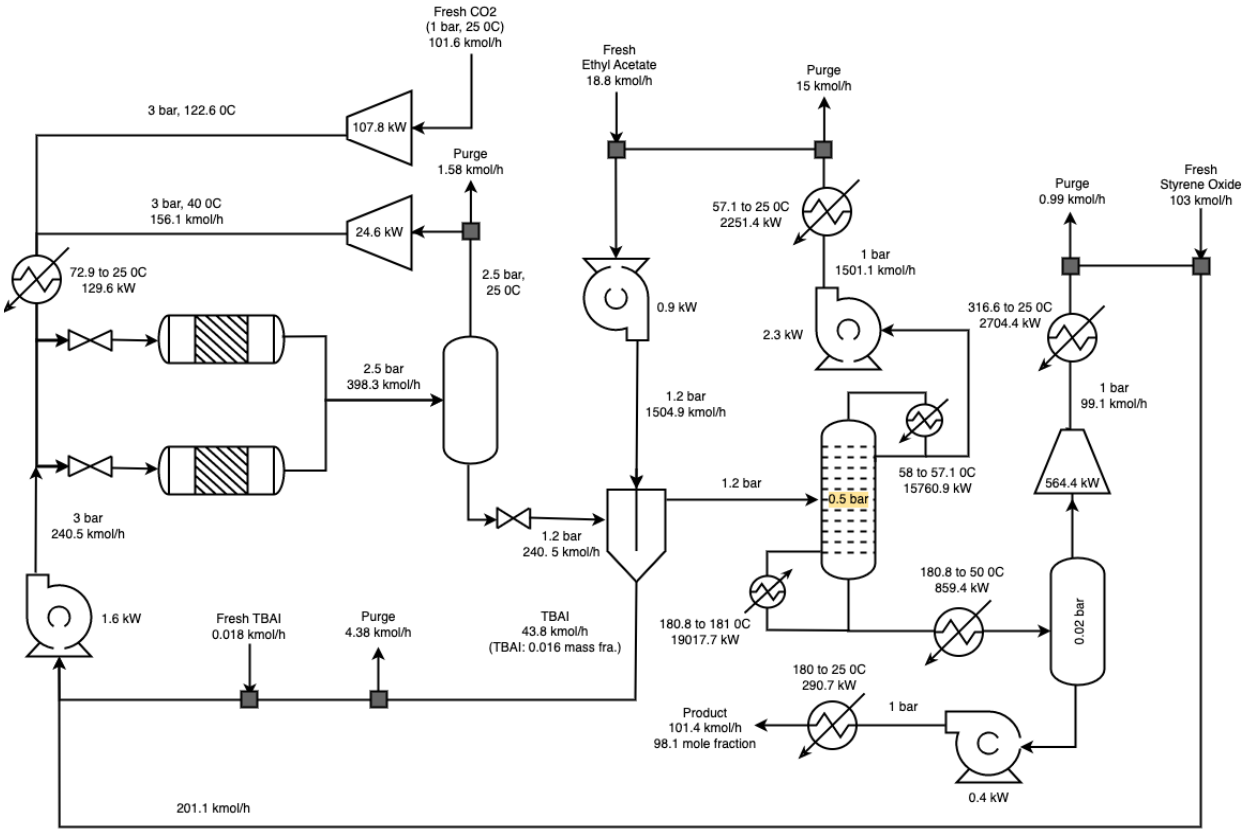

Figure 12. Process flow diagram for styrene carbonate production using SO and CO_2.

6 Future work

The process should be patented and a demonstrator reactor constructed. Following optimization of the demonstrator, real cement flue gas should be studied and the economic viability of the process based on data from the demonstrator determined. The size of the demonstrator must also be defined, which will depend on future investment.

7 Financial

Funding support from FOEN and Cemsuisse was used for personal costs. One postdoc has been hired for the duration (two years) of the project. Other staff at EPFL (technician, PhD student, postdoc, senior scientist and admin) have been dedicated part of their time to this project. Furthermore, EPFL has contributed with costs of consumables and equipment.

8 Acknowledgements

We thank Dr. Antoine P. Van Muyden and Dr. Xutao Hu for help constructing the fixed-bed reactor. We also thank Dr. Shivom Sharma, Ms. Jones Marie Jane Francine and Prof. Maréchal François for the process modeling and help preparing this report. We thank Mr. Xunhui Wang for the contribution to the reaction mechanism study. We thank Cemsuisse and Federal Office of the Environment for financial support. We thank Mrs. Jacqueline Morard for administrative support.

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10 Supplementary information

10.1 Abbreviations and designations

TBAI, tetra-n-butylammonium iodide

TBAB, tetra-n-butylammonium bromide

C1, single carbon

Cat 1, catalyst 1

HPLC, high-performance liquid chromatography

GC-EI-MS, gas chromatography - electron ionization - mass spectrometry

SO, styrene oxide

SC, styrene carbonate, 4-phenyl-1,3-dioxolan-2-one

PO, propylene oxide

PC, propylene carbonate, 4-methyl-1,3-dioxolan-2-one

CapEx, capital expenditures

OpEx, operating expenses

RT, room temperature

1a, SO, styrene oxide,2-phenyloxirane

2a, epichlorohydrin, 2-(chloromethyl)oxirane, chloropropylene oxide

3a, glycidyl vinyl ether

4a, glycidyl methacrylate, 2,3-epoxypropyl methacrylate

1b, styrene carbonate, 4-phenyl-1,3-dioxolan-2-one

2b, 4-chloromethyl-dioxolan-2-one

3b, 4-((allyloxy)methyl)-1,3-dioxolan-2-one

4b, (2-oxo-1,3-dioxolane-4-yl)methyl methacrylate

10.2 Materials

Epoxide substrates**1-4a**, propylene oxide, solventsand other organic compounds were purchased from Sigma-Aldrich. Silica gel was purchased fromSiliCycle Inc. CO_2 gas or CO_2 gas mixtures were purchased from Carbagas AG. Fittings,valves, regulators and tubing for the reactor

construction were purchased from Swagelok Company. REAXUS HPLC reciprocating pump (LS-class) was purchased from IGZ Instruments AG. Gas mass flowmeter (EL-FLOW® Prestige) was purchased fromBronkhorst (Switzerland) AG.

10.3 Typical method of CO_2 and epoxide cycloaddition reaction

Liquid substrate was prepared by dissolving TBAI (3 mol%) catalyst in epoxide and filtered to remove the impurities. Fix-bed reactor (10 × 400 mm) was filled with 8.7 g silica gel (Before use, commercially available silica gel was dried at 150 ºC for 24 h to remove H_2O). Liquid (0.1-0.5 mL/min) and gas (130 mol%) flow were mixed together and passed fix-bed reactor. Liquid and gas products were collected and analyzed per hour. Yield was determined by GC (error range ~5%) and reactions were repeated at least twice and up to 10 times to ensure reproducibility. Pure cyclic carbonates were isolated by Column Chromatography.

10.4 TBAI recovery

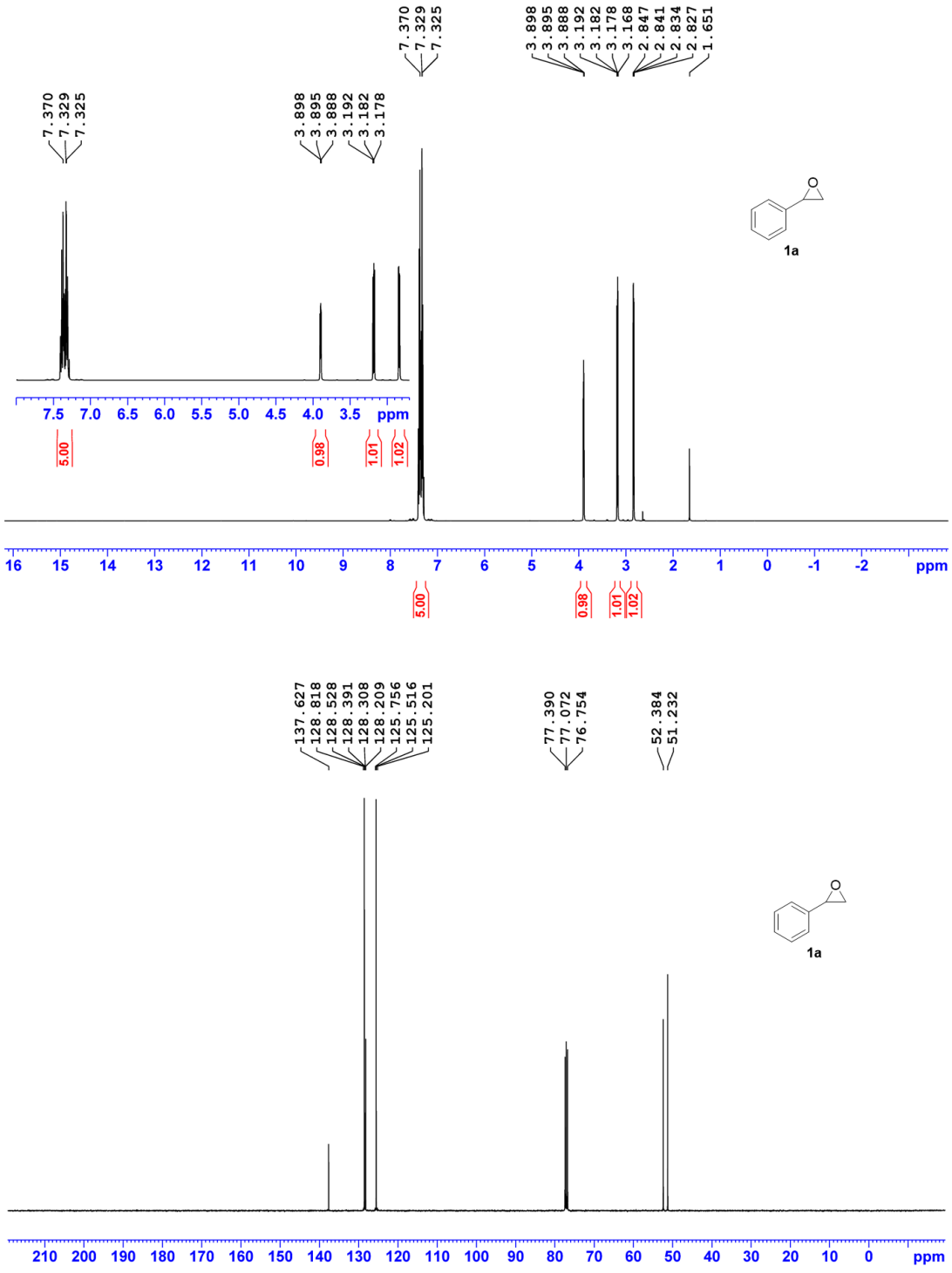
Mixture products containing TBAI solution (1 mL) were diluted with ethyl acetate (EA, 10 mL). Recovered TBAIprecipitated and was dried in an oven (100 ºC, overnight). The weight of recovered TBAI was recorded.

10.5 SiO_2 recovery

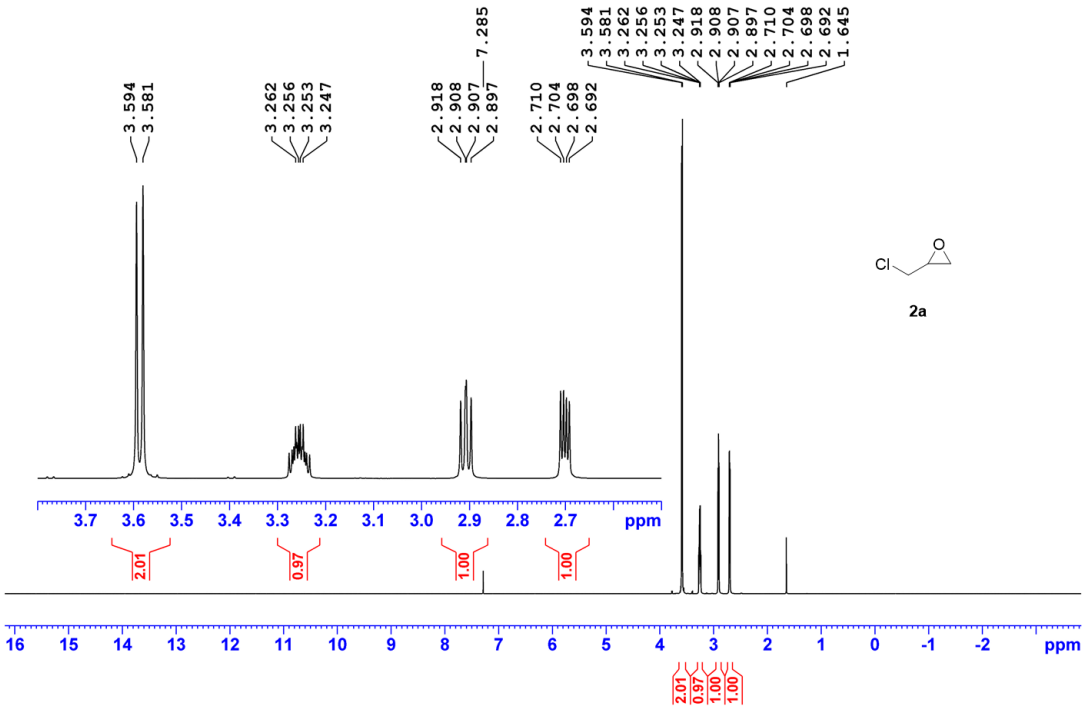
After reaction, the CO_2 gas flow was closed and the fix-bed reactor was washed with acetone (30 mL, 1 mL/min). Recovered SiO_2 was collected by drying in oven (100 ºC, overnight).

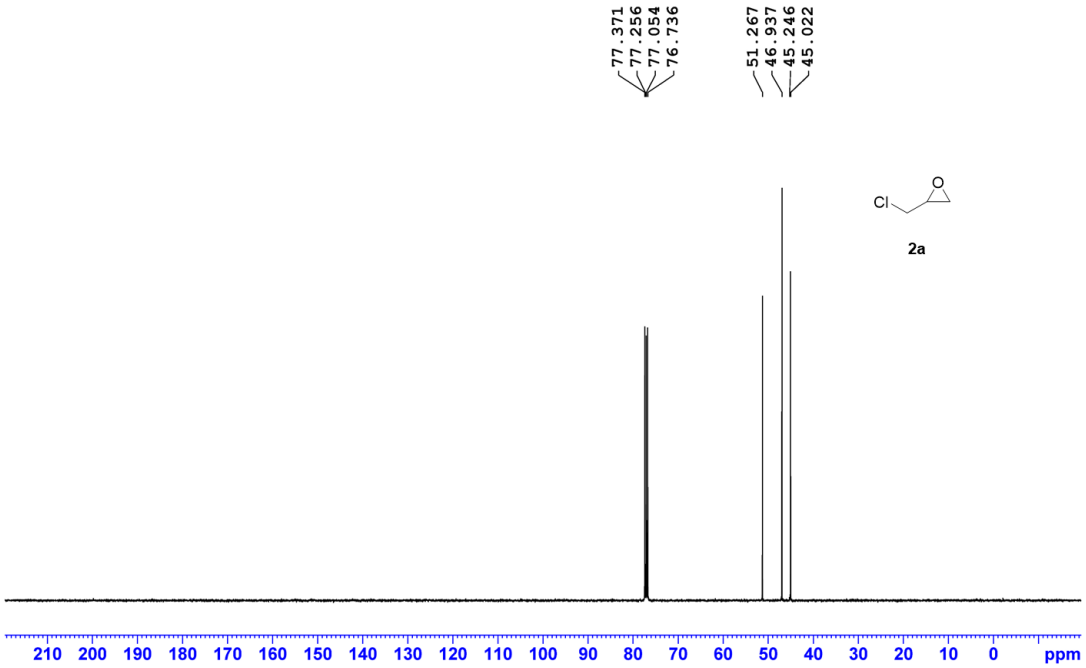
10.6 NMR spectra of the substrates

1a, styrene oxide

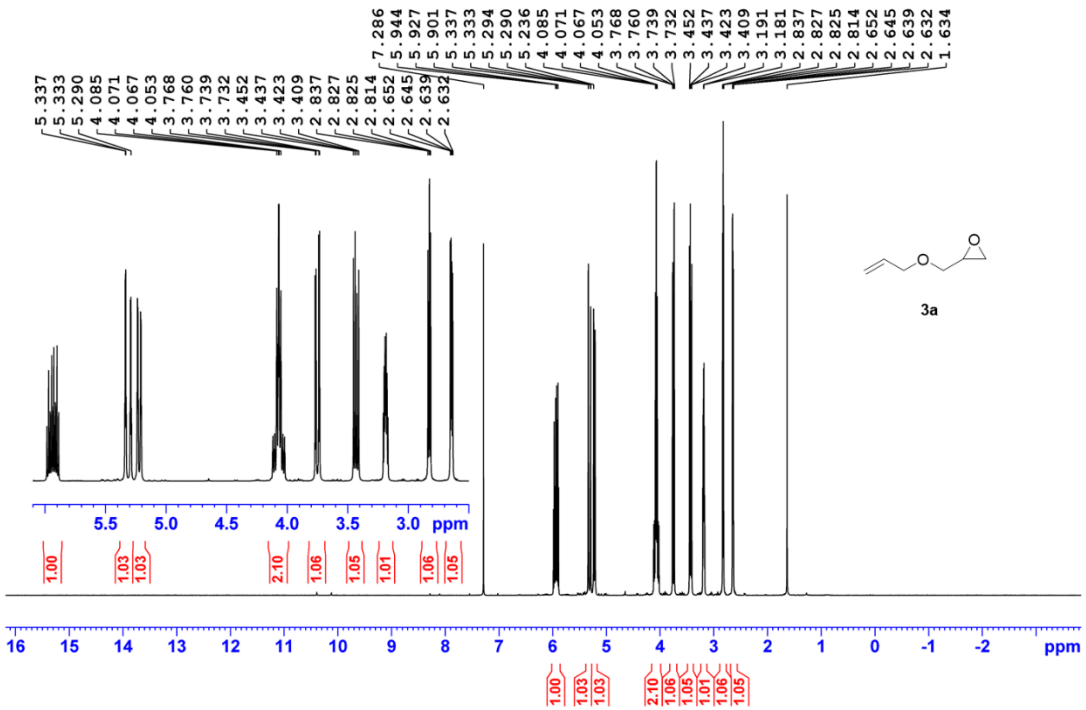


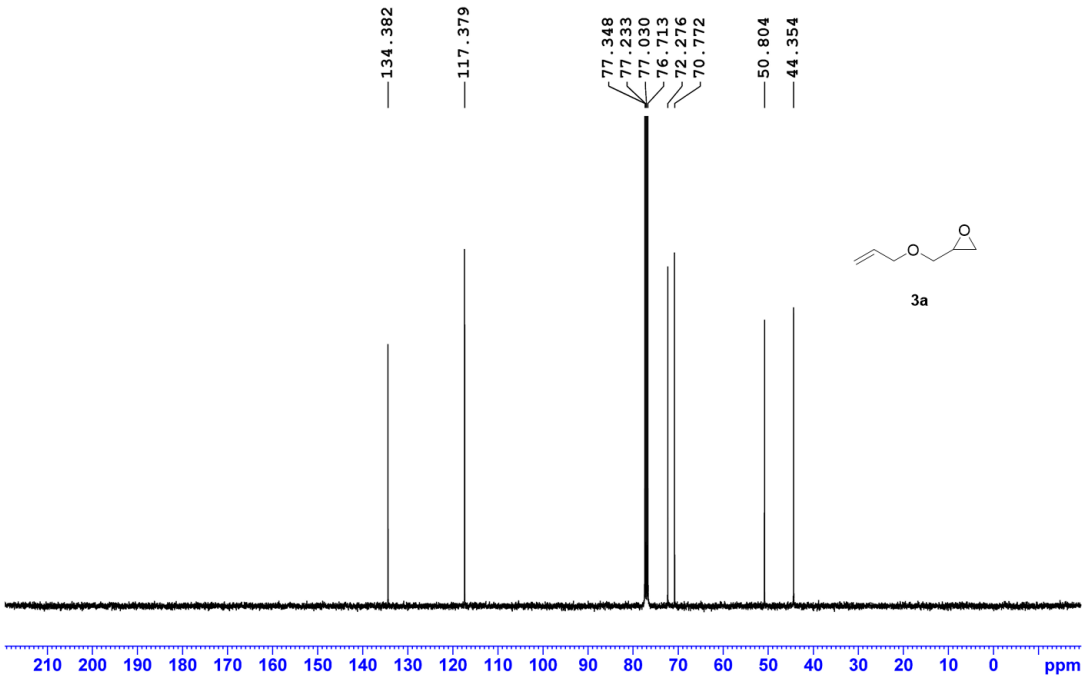
2a, epichlorohydrin



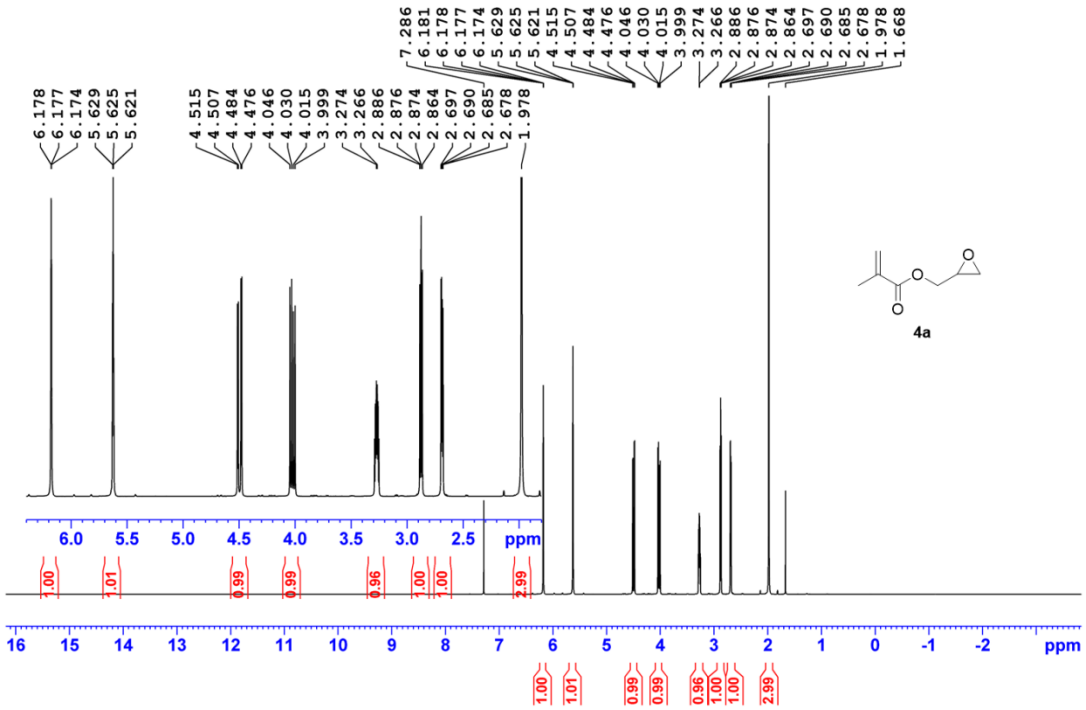


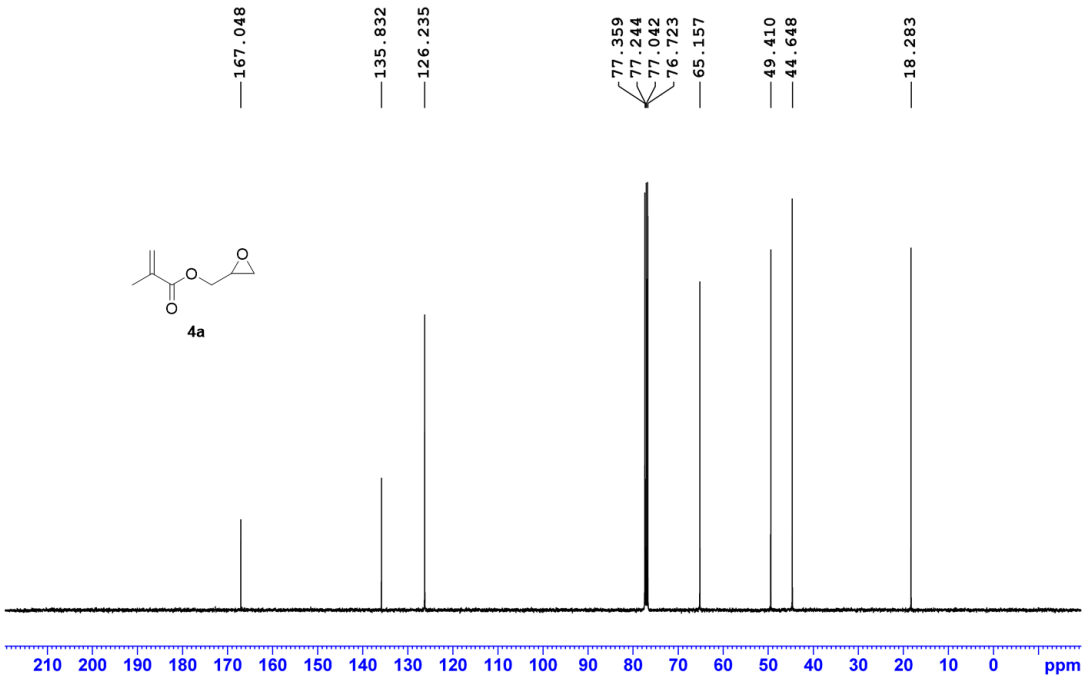
3a, glycidyl vinyl ether





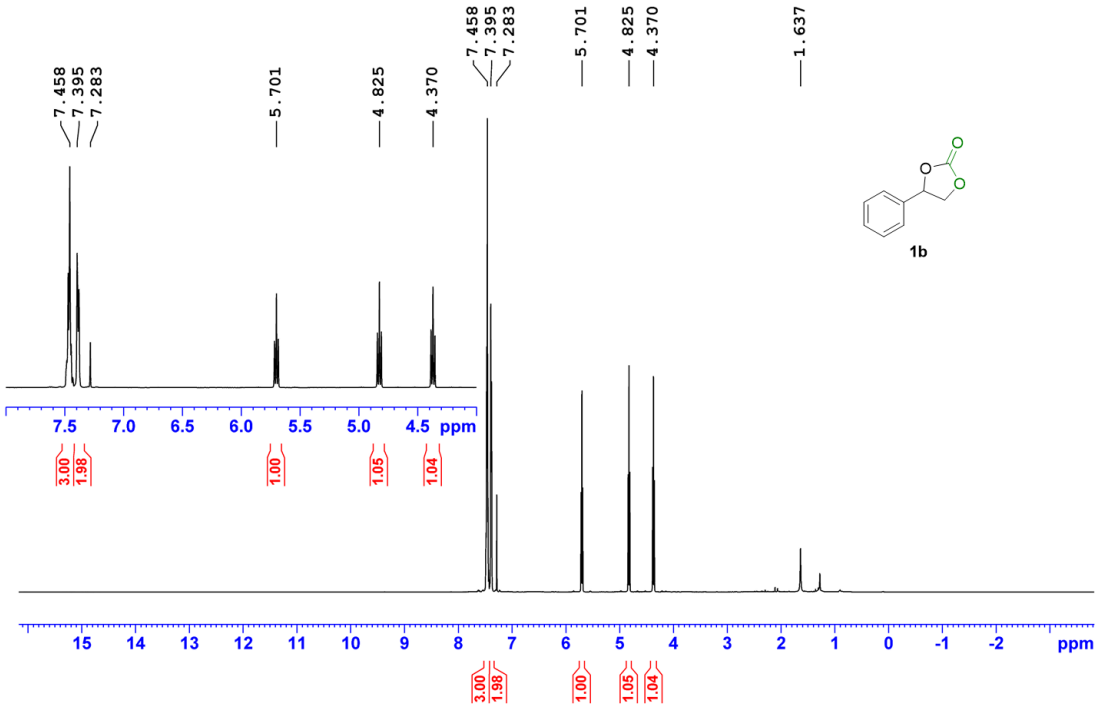
4a, glycidyl methacrylate

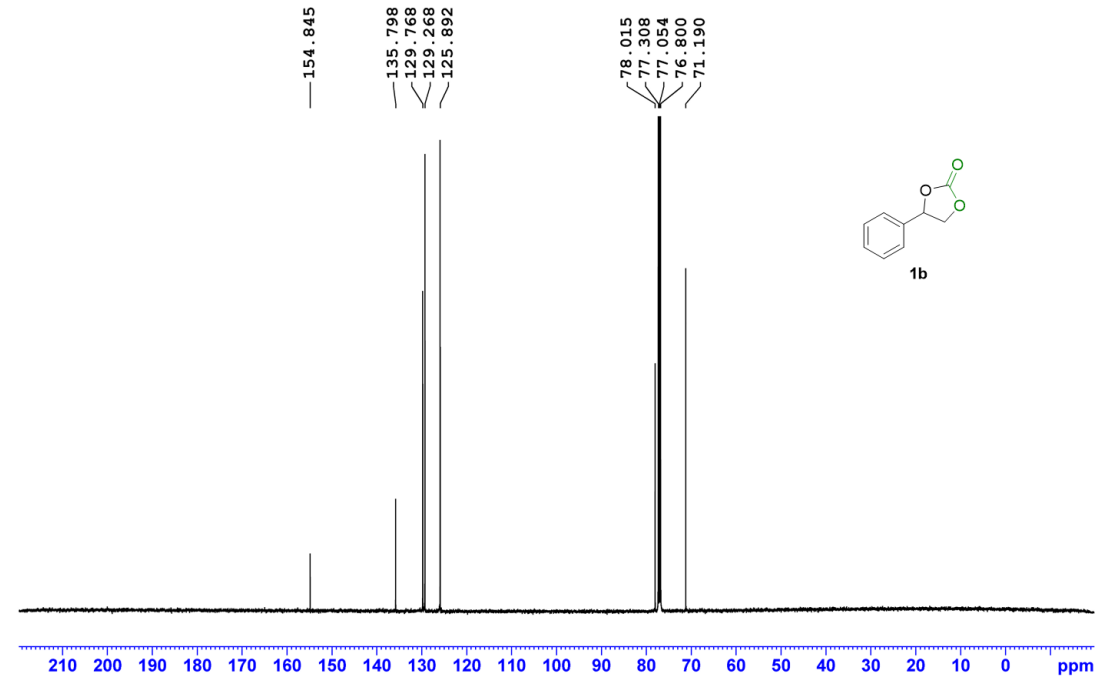




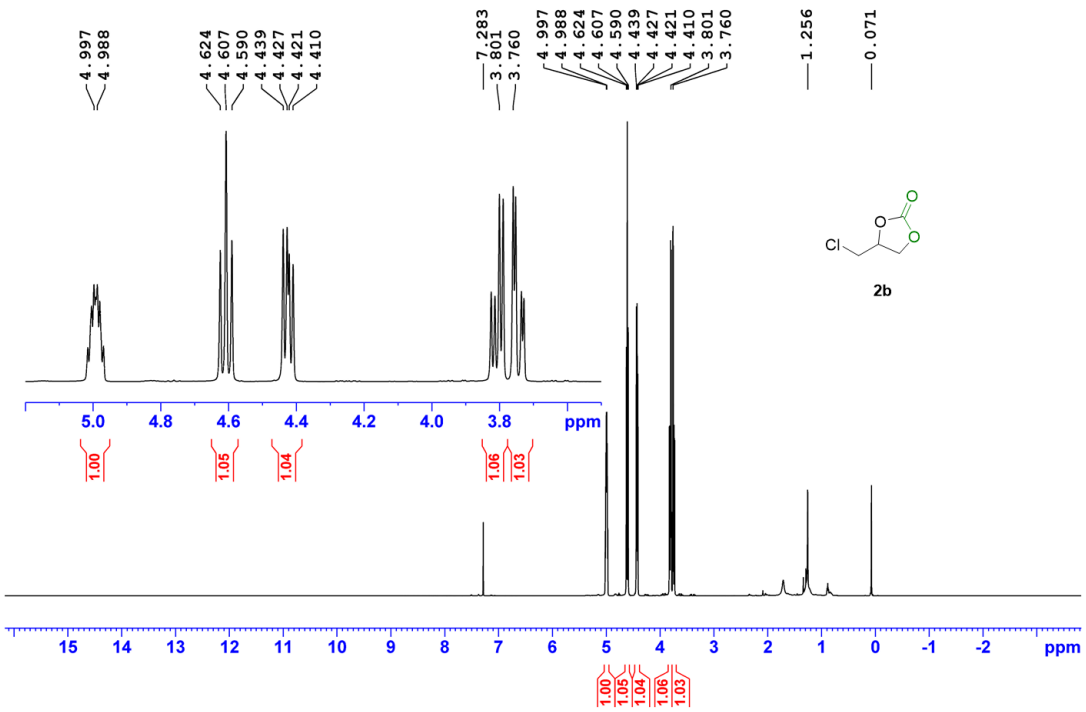
10.7 NMR spectra of the products

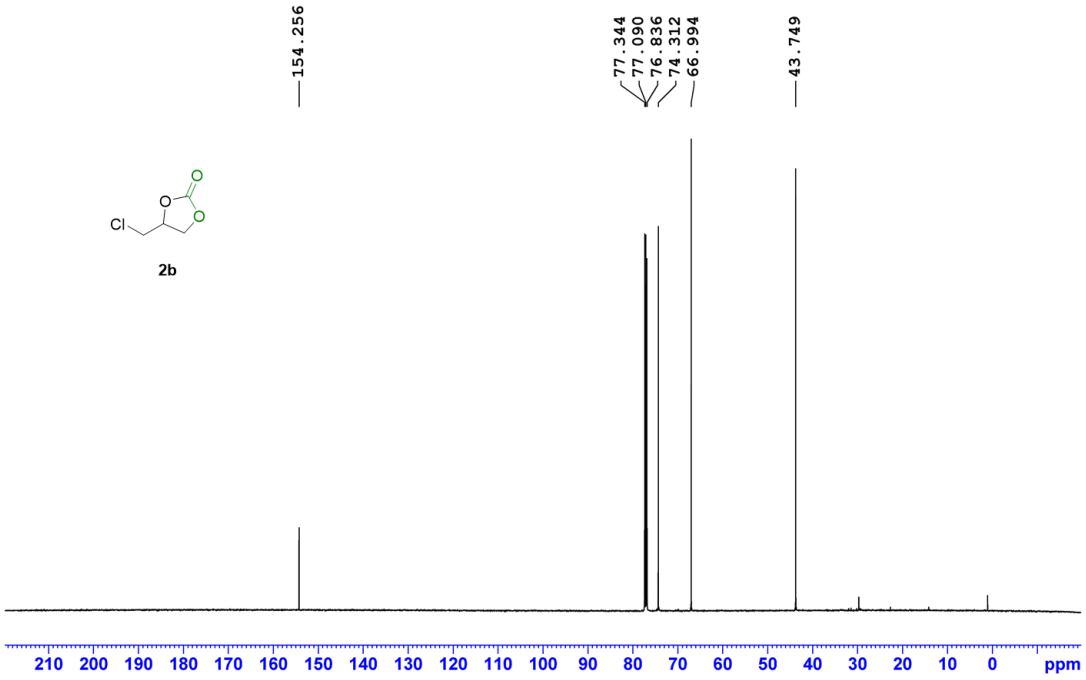
1b, 4-phenyl-1,3-dioxolan-2-one



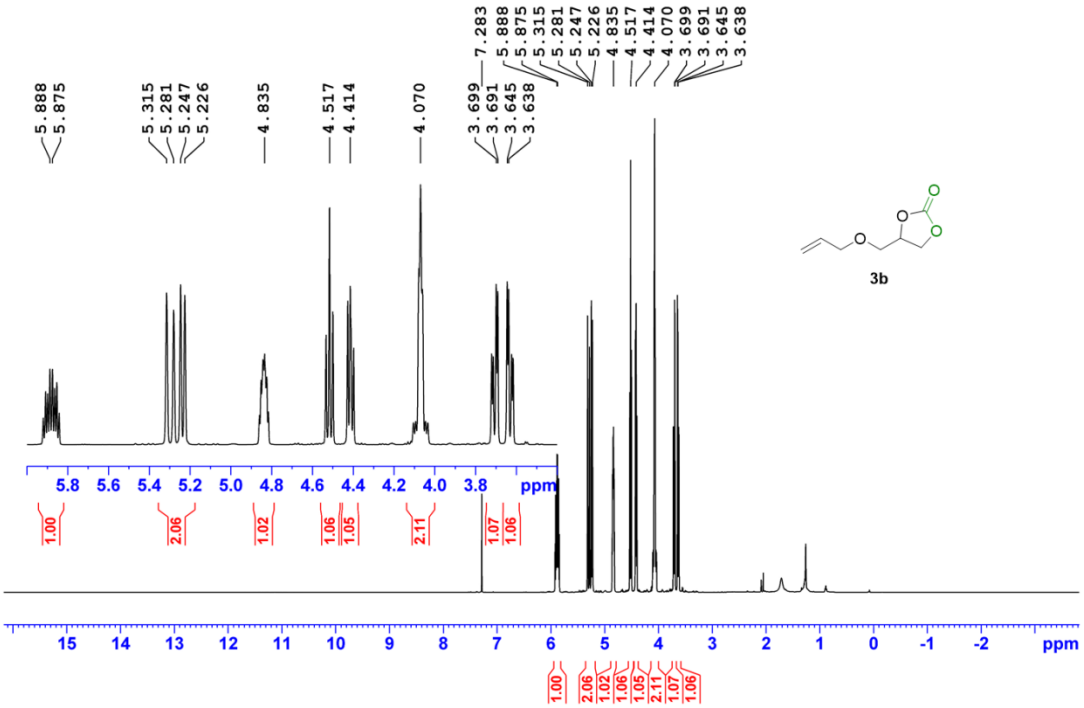


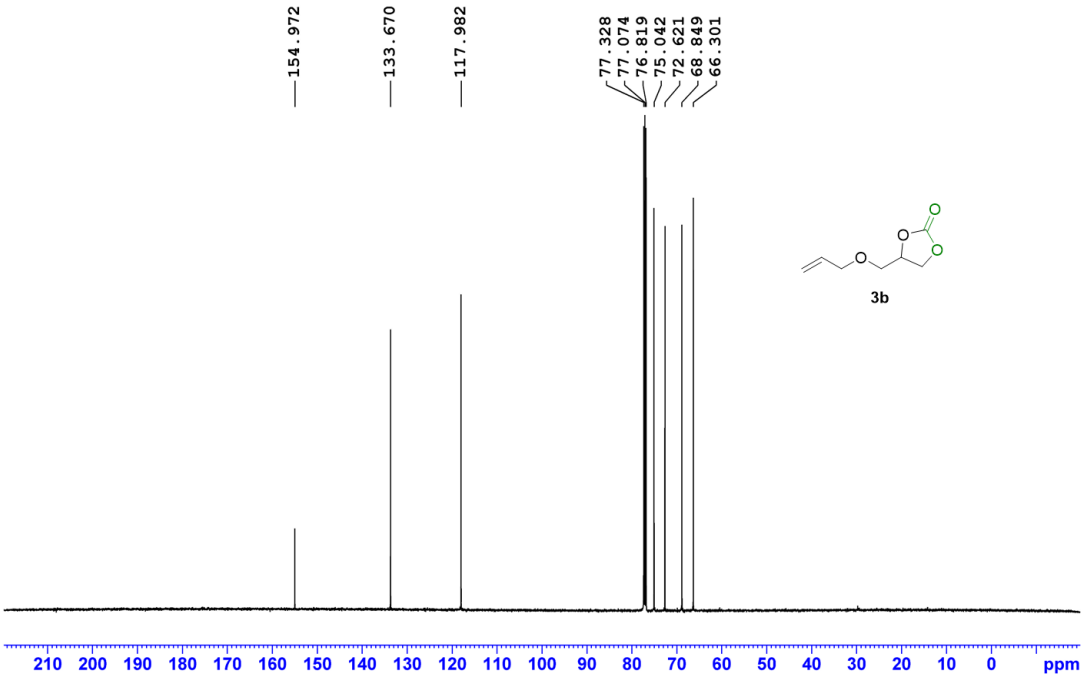
2b, 4-(chloromethyl)-1,3-dioxolan-2-one



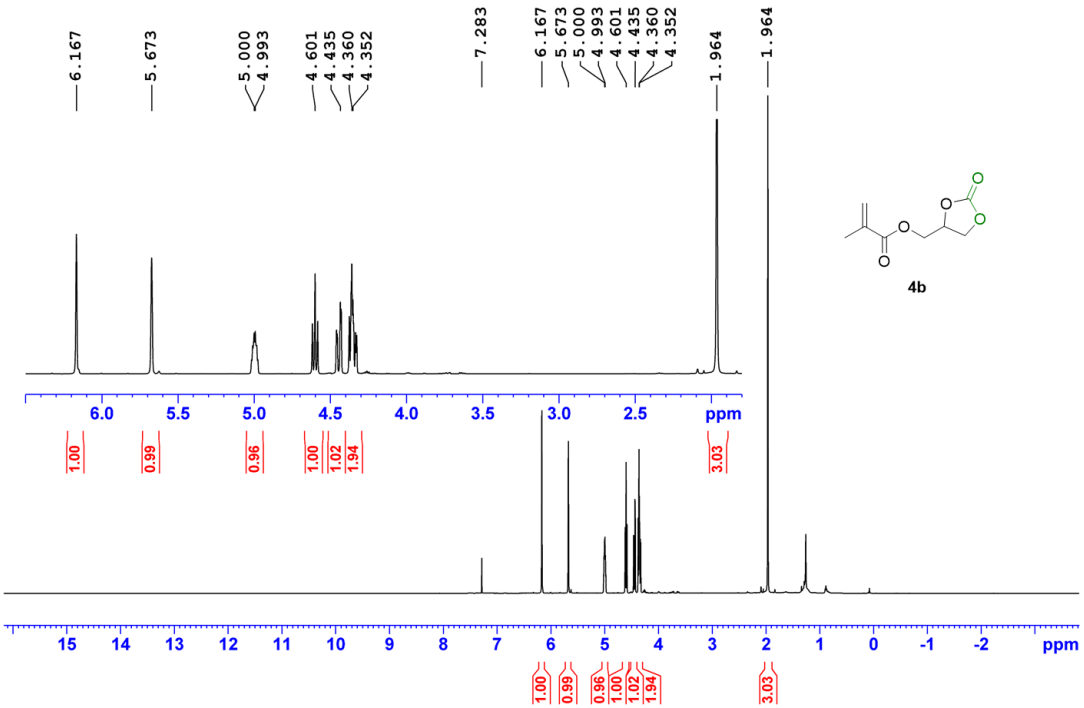


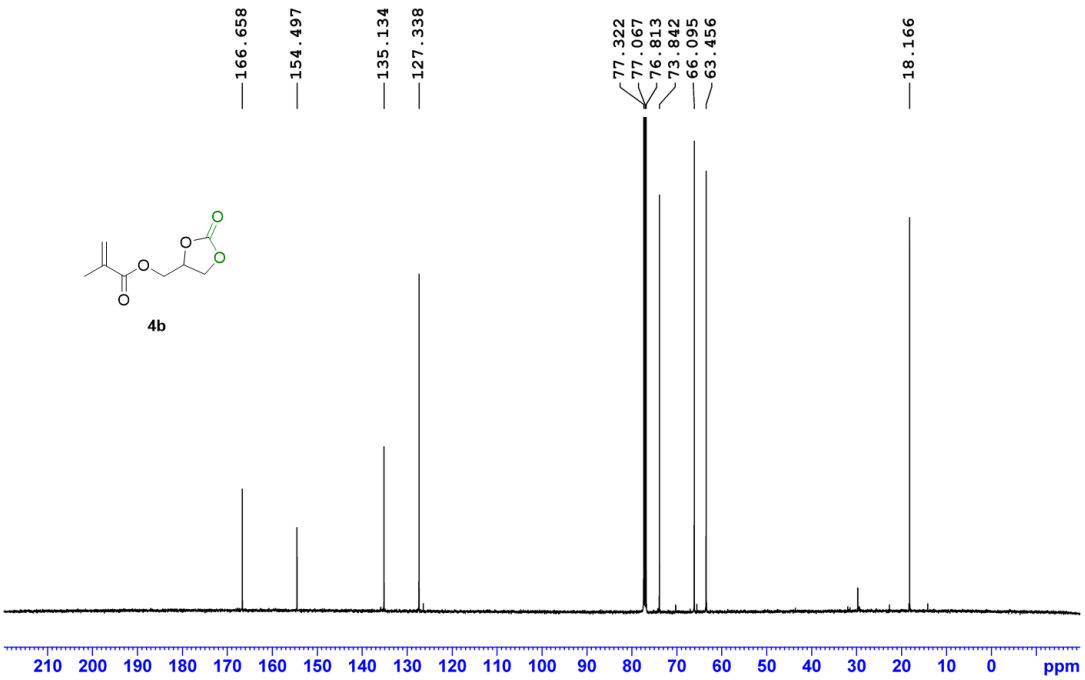
3b, 4-((allyloxy)methyl)-1,3-dioxolan-2-one





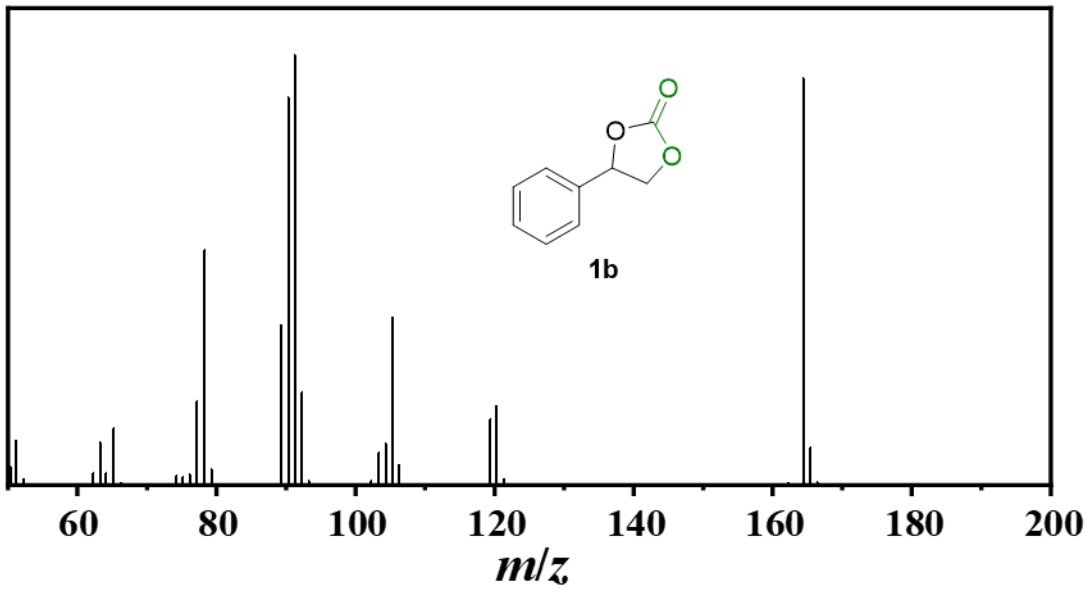
4b, (2-oxo-1,3-dioxolan-4-yl)methyl methacrylate



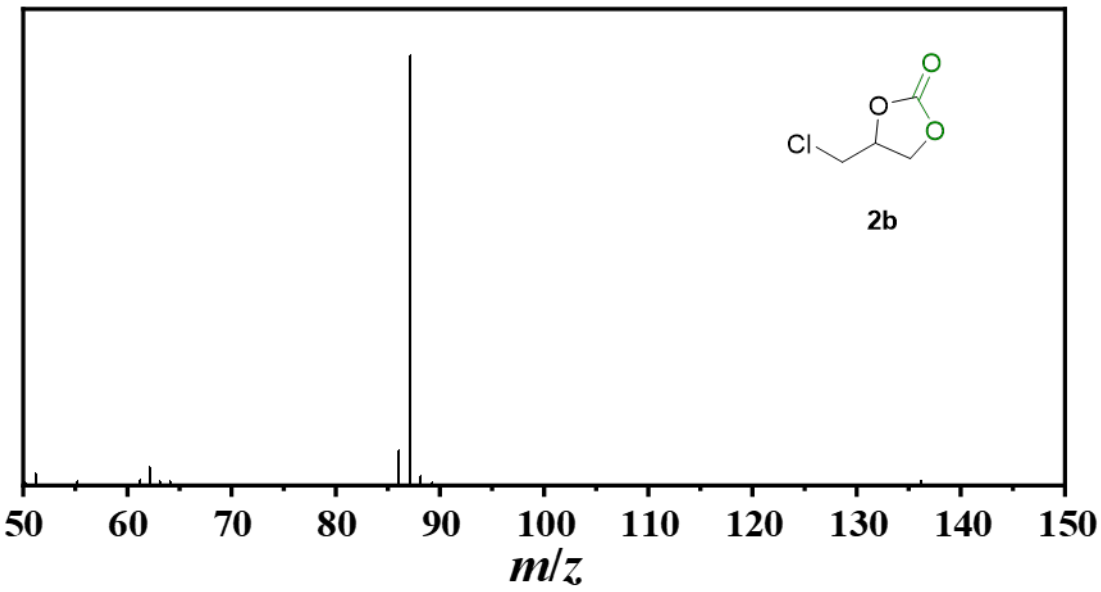


10.8 Mass spectra of the products

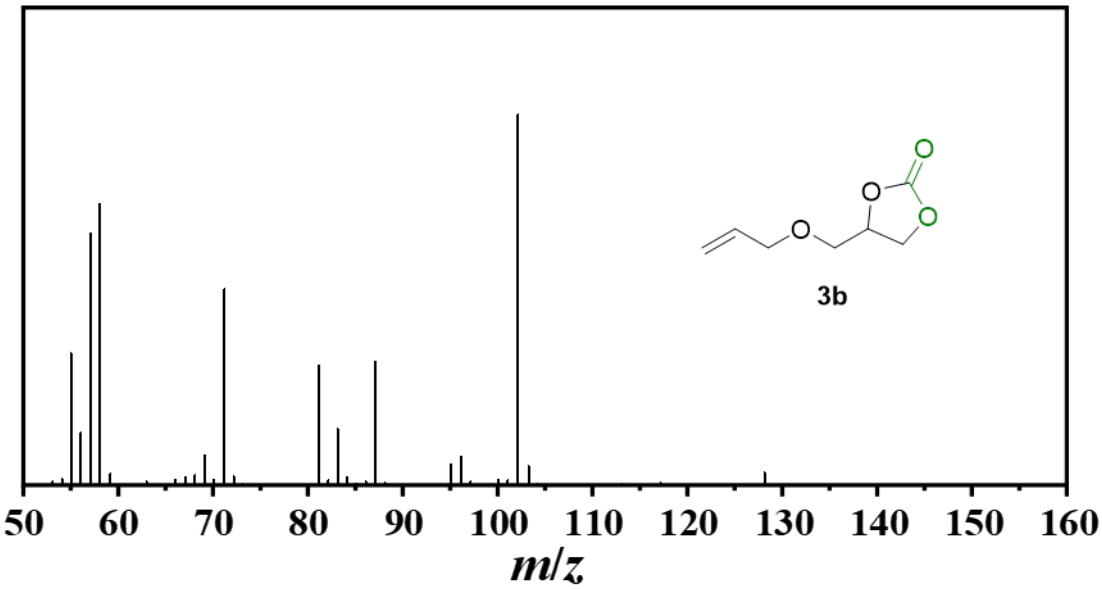
1b, 4-phenyl-1,3-dioxolan-2-one



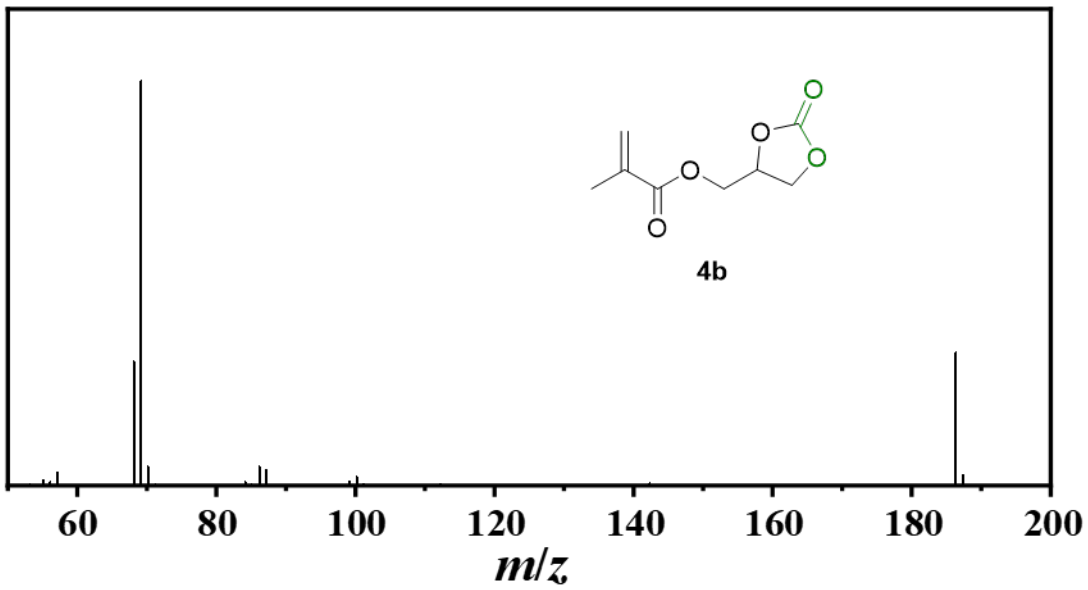
2b, 4-(chloromethyl)-1,3-dioxolan-2-one



3b, 4-((allyloxy)methyl)-1,3-dioxolan-2-one

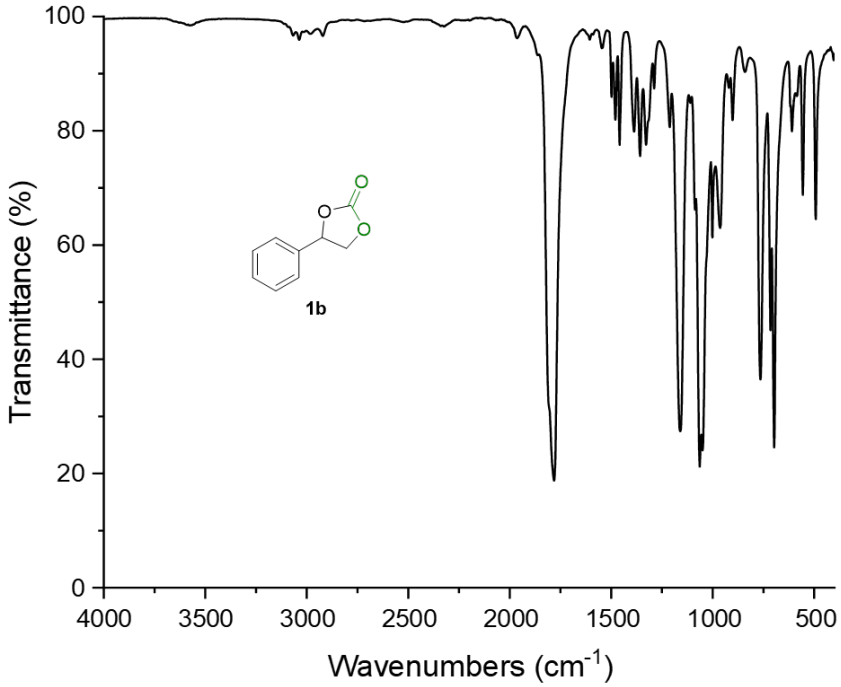


4b, (2-oxo-1,3-dioxolan-4-yl)methyl methacrylate

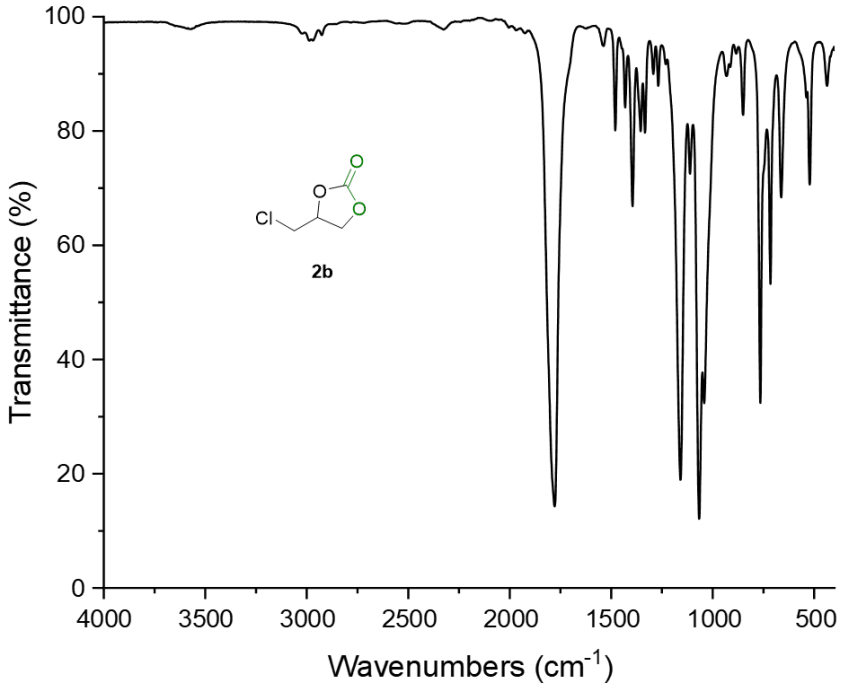


10.9 FT-IR spectra of the products

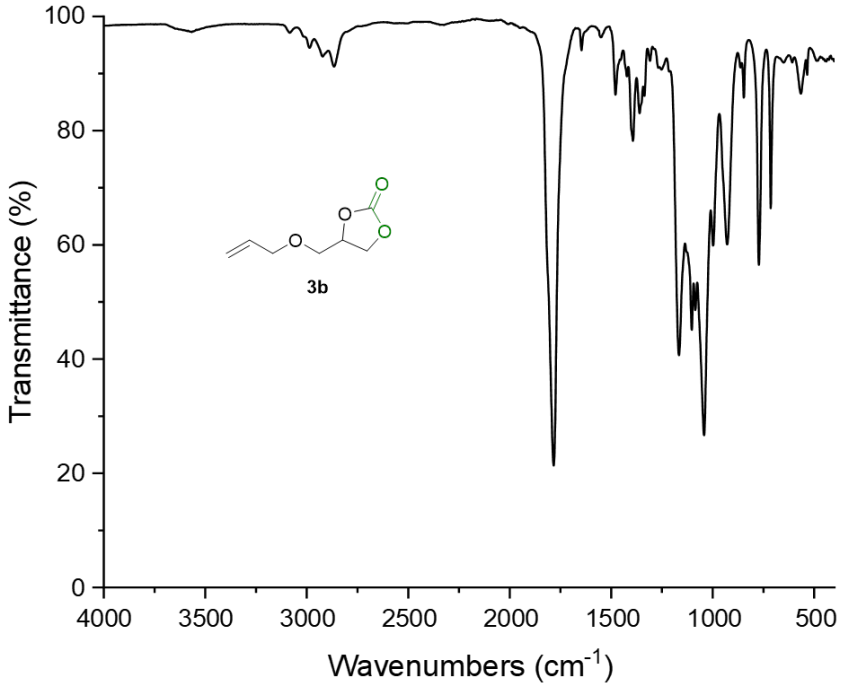
1b, 4-phenyl-1,3-dioxolan-2-one



2b, 4-(chloromethyl)-1,3-dioxolan-2-one



3b, 4-((allyloxy)methyl)-1,3-dioxolan-2-one



4b, (2-oxo-1,3-dioxolan-4-yl)methyl methacrylate