A Brief Review on Industrial Alternatives for the Manufacturing of Glycerol Carbonate, a Green Chemical

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ABSTRACT: Glycerol carbonate is one the glycerol derivatives which attracts attention for industrial applications. This review compares strategies for its synthesis, and their analyses lead to the conclusion that (indirect) procedures starting from glycerol- and/or CO_2-derivatives are the most attractive. These are described and compared, taking criteria of industrial feasibility into account. As a result, the transesterification of dimethyl carbonate or ethylene carbonate with glycerol using uncalcined CaO as catalyst appears to be currently the most suitable industrial process. Finally, potential applications of glycerol carbonate as a multifunctional compound are exemplified.

INTRODUCTION

The increasing demand of biodiesel makes glycerol as a byproduct available in large quantities at decreasing prices. The search for new applications of glycerol as a platform chemical from which a broad spectrum of new valuable derivatives can be obtained is ongoing.[1] One of them is glycerol carbonate (GC) (4-hydroxymethyl-1,3-dioxolan-2-one, CAS #931-40-8) which has been incorporated to the portfolio of companies such as Huntsman[2] and Ube Industries Limited.[3] The increasing industrial attention for GC is based on its physical properties as well as on its reactivity. GC is a not flammable (fp > 204 °C), water-soluble, readily biodegradable, nontoxic, and viscous (85.4 mPa·s at 25 °C) liquid with a very low evaporation rate (bp 110−115 °C at 0.1 mmHg). On the other hand, GC has a high renewable content (the mass percentage of the molecule coming from renewable sources) ranging between 76%, if obtained from glycerol and another raw material apart from CO_2, and 100%, if manufactured directly from glycerol and CO_2. There is no R-phrase in its Material Safety Data Sheet.

All these features make GC a green chemical that can be used in a number of applications[4−9] such as the ones illustrated in Figure 1.

Regarding its reactivity, GC has an almost unique number of reactive sites: the three carbon atoms of the dioxolane ring and the pendant hydroxyl moiety. These reactive sites open numerous possibilities for using GC as a raw material for synthesizing chemical intermediates as well as polymers such as polyesters, polycarbonates, hyperbranched polyglycerols, polyurethanes, and non-isocyanate polyurethanes (NIPUs) with a lot of potential applications in manufacturing useful materials such as coatings, adhesives, foams, and lubricants. The use of glycerol carbonate in chemical synthesis will be discussed further in the Glycerol Carbonate As an Intermediate in Chemical Synthesis section.

As expected, the studies for developing synthetic procedures for obtaining GC have also grown in parallel to the increasing interest in GC applications. Consequently, the main aim of this

contribution is to review such procedures but focus specifically on those with potential industrial feasibility rather than in a comprehensive survey of all published methods for synthesizing GC.

SYNTHETIC STRATEGY

Whatever the selected synthetic strategy for industrial manufacturing of GC, it is obvious that it must meet some basic criteria to be industrially feasible, namely the following:

- C1: If catalytic, a cheap and easily separable and recyclable catalyst must be used.
- C2: Simple separation and purification methods
- C3: Avoiding or minimizing the use of solvents
- C4: High conversion and selectivity to facilitate accomplishment of criterion 2 and, together with criteria 2 and 5, to increase productivity and minimize capital investment
- C5: A low reaction time
- C6: Intrinsically safe (Therefore, both highly inflammable and toxic chemicals must be avoided.)

According to these criteria some synthetic methods will not be discussed herein.[10] On the other hand, from said criteria it is apparent that a synthetic direct strategy starting from glycerol and CO_2 (Scheme 1) seems to be the obvious choice because on one hand both are green chemicals commercially available at a low price, and on the other hand, the atom efficiency could be as high as 87%. However, attempts for synthesizing GC directly from glycerol and subcritical CO_2 carried out by Aresta et al. using $^nBu_2SnO$ and $^nBu_2Sn(OMe)_2$,[14] or CeO_2/Al_2O_3 and CeO_2/Nb_2O_5[15] as catalysts, have been unsuccessful due to poor CO_2 reactivity leading to a peak yield of 10% using tetra(ethylene glycol)dimethyl ether as solvent. Nevertheless, a more promising yield of 32% in milder conditions has been reported by George et al.[16] using $^nBu_2SnO$ as the catalyst and methanol as the solvent. However, their results have not been confirmed by Dibenedetto et al.[17] Earlier, Vieville et al[18] claimed the direct carbonation of glycerol in supercritical CO_2
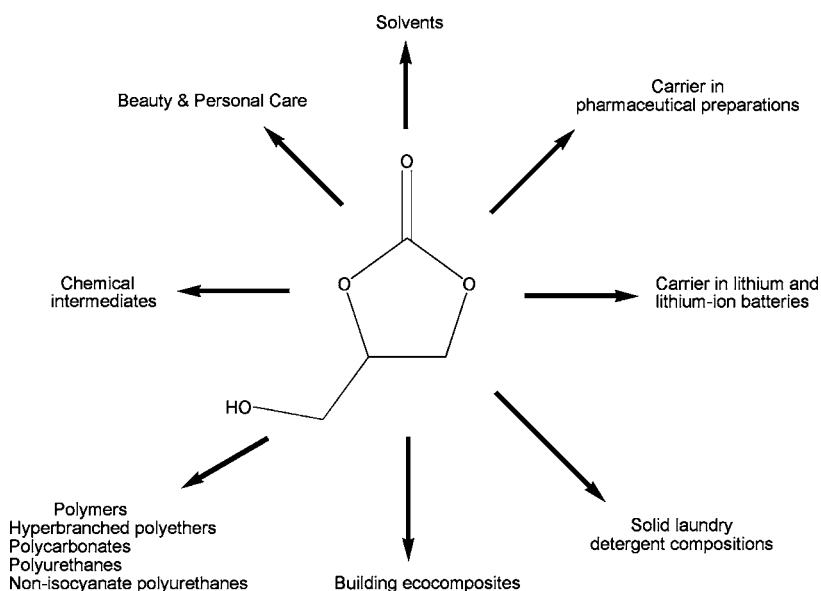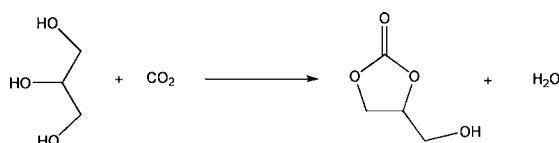
Figure 1. Applications of glycerol carbonate.

Scheme 1. Direct synthesis of glycerol carbonate from glycerol and CO_2

Refs. 14,15: 5 MPa, 180°C, 15 h, tetra(ethylene glycol)dimethyl ether; catalysts: $^nBu_2SnO$, $^nBu_2Sn(OMe)_2$, CeO_2/Al_2O_3 or CeO_2/Nb_2O_5; yield ≤10%

Ref. 16: 3.5 MPa, MeOH, 80°C, 4 h, MeOH; catalyst: nBu_2SnO; yield 32%

employing zeolites and basic ion-exchange resins as catalysts reporting yields of 32%; however, their synthetic method cannot be considered as a direct carbonation but as a transesterification because they used ethylene carbonate in amounts as high as 63 mol % relative to glycerol. In fact, no GC was formed in the absence of ethylene carbonate either with or without basic catalysts.

Summarizing, GC direct synthesis from CO_2 and glycerol is currently a nonfeasible industrial reaction due to very low conversions because CO_2 is a highly stable molecule. Therefore, a substantial input of energy and very active catalysts are required for the conversion of CO_2.[17] Nevertheless, in a recent paper[19] Nguyen and Demirel make an economic analysis comparing the feasibility of a conventional biodiesel production plant and the possible next generation of a biodiesel–glycerol carbonate production plant in which the glycerol produced as byproduct in the biodiesel manufacturing is converted into GC by direct reaction with CO_2 according to the reaction conditions and results given by George et al.,[16] and they conclude that the novel integrated plant has a net present value of $13.21 million higher than the conventional biodiesel plant at the end of a 15-year project. Obviously, the study is theoretical and based on unconfirmed results and referring to the profitability of a biodiesel plant; however, it is a very interesting analysis showing that direct synthesis of GC from glycerol and CO_2 could be economically viable even at glycerol conversions (selectivity is

100%) as low as 32% provided that the current price of glycerol remains constant.

It is apparent from the above discussion that the industrial production of GC must be carried out through an indirect synthetic approach starting from more reactive and easily synthesizable derivatives of glycerol and CO_2, leading to the two basic combinations of raw materials discussed in this paper (Scheme 2): (a) glycerol is reacted with CO_2 derivatives such as ethylene carbonate (EC), dimethyl carbonate (DMC), or urea; and (b) glycerol derivatives like 3-chloro-1,2-propanediol (HAL, glycerol α-monochlorohydrin) or epichlorohydrin (EPI) are reacted with carbon dioxide or with alkaline carbonates or bicarbonates.[20]
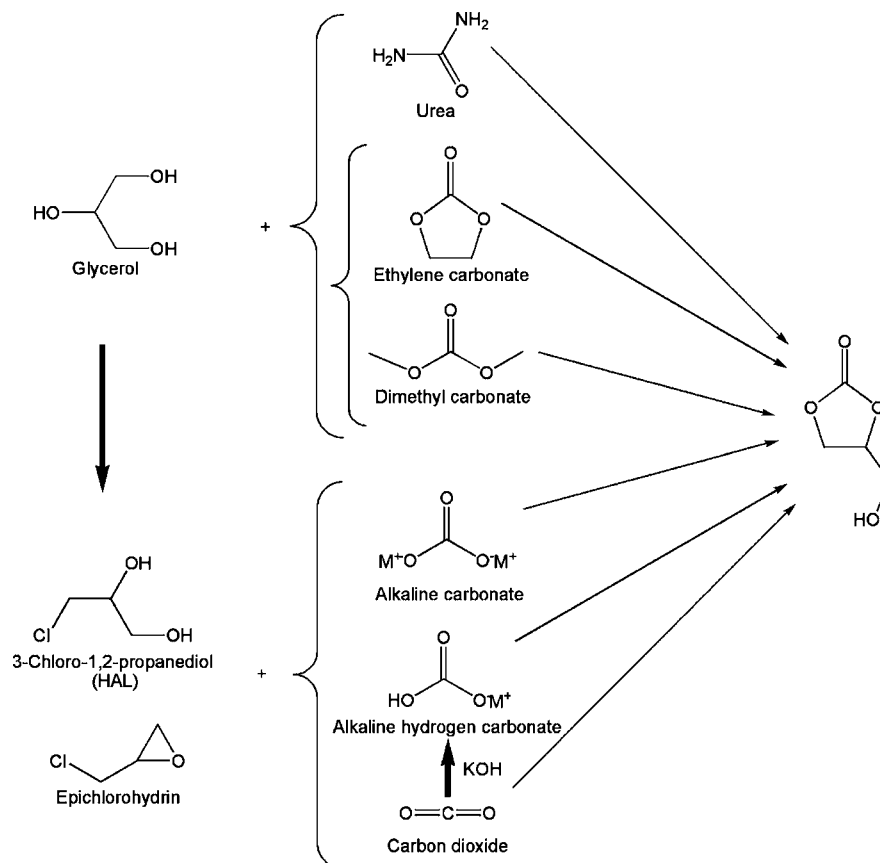
■ INDIRECT SYNTHETIC ROUTES

Carbamoylation/Carbonation of Glycerol with Urea. In this reaction, glycerol is reacted with urea in equimolar amounts at 130−150 °C in the presence of a catalyst and usually under vacuum to shift the thermodynamic equilibrium by removing continuously the ammonia formed, although the ammonia displacement by continuously flowing nitrogen at ambient pressure is also described. Typical reaction conditions together with usual conversions and yields relative to glycerol are given in Scheme 3.
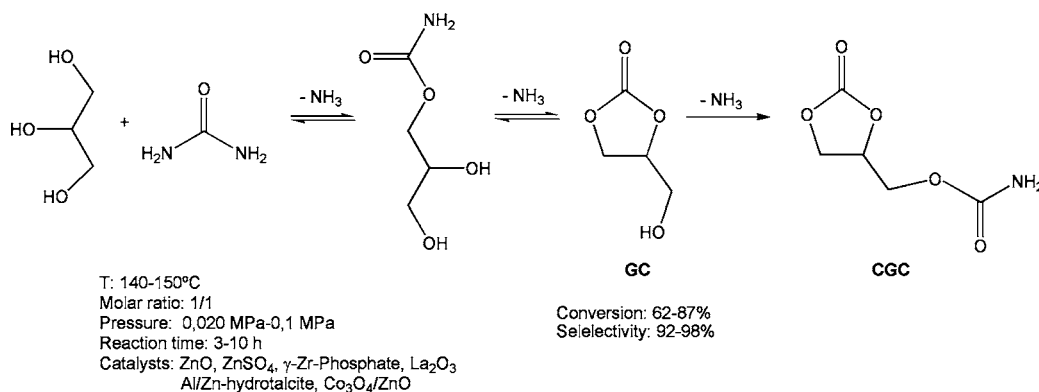
As depicted, the formation of GC proceeds in two consecutive steps.[24] As shown by Calvino-Casilda et al.[24b] with the use of real-time attenuated total reflection FTIR spectroscopy the first step is fast, whereas the second one is relatively slow. Reaction conditions must be carefully selected to avoid a decrease in selectivity by reaction between glycerol carbonate and urea, leading to the carbamate of glycerol carbonate (CGC).[25] Reaction proceeds thermally but with yields lower than 30%.[24a] Therefore, catalysts are needed.

Initially, the reaction was carried out using ZnO and ZnSO4 as catalysts[26] with a conversion of 83% and a selectivity of 100%. However, these catalysts have a major drawback in that they are soluble in the reaction mixture or are pulverized upon stirring, which makes their recovery difficult (criterion 1 for industrial feasibility is not accomplished) as well as the separation of GC (criterion 2). Consequently, in the last years researchers

Scheme 2. Indirect synthetic strategy: raw material combinations

Scheme 3. Synthesis of GC by carbamoylation/carbonylation of glycerol with urea

T: 140-150°C
Molar ratio: 1/1
Pressure: 0,020 MPa-0,1 MPa
Reaction time: 3-10 h
Catalysts: ZnO, ZnSO$_4$, γ-Zr-Phosphate, La$_2$O$_3$
Al/Zn-hydrotalcite, Co$_3$O$_4$/ZnO

Conversion: 62-87%
Selelectivity: 92-98%

working in this route have focused their efforts on developing heterogeneous catalysts able of keeping their structure under the reaction conditions. Thus, catalysts such as γ-Zr-Phosphate,[24a,27] Co$_3$O$_4$/ZnO,[24b] Al/Zn-hydrotalcite,[28] La$_2$O$_3$,[29] and gold-based catalysts[25] have been employed successfully. However, as far as we know, only Dubois and Aresta[27] describe the full process, i.e. including the separation and isolation of glycerol carbonate, key steps for considering the industrial feasibility of any chemical process. A simplified flow diagram of it showing experimental conditions and yield is depicted in Figure 2.

Transesterification of Ethylene Carbonate or Dimethyl Carbonate with Glycerol. In this reaction, glycerol is reacted with an organic carbonate in the presence of a basic catalyst generally using an excess of the carbonate which acts as both reactant and solvent. EC and DMC are the carbonates

more widely used, although diethyl carbonate has also been employed using hydrotalcite-like compounds activated by calcination and by calcination plus rehydration under ultrasound as catalysts.[30]

As shown in Scheme 4, the reaction proceeds through a glyceryl carbonate intermediate which evolves to GC yielding ethylene glycol (EG) or methanol, depending on the starting carbonate. Typical reaction conditions, conversions, and selectivities relative to glycerol are also given in Scheme 4. Although both strong basic homogeneous and heterogeneous catalysts can be successfully used, heterogeneous catalysts are preferred because they can be easily separated and recycled. As reported by Li and Wang[31] a main difference between using EC or DMC is that the reaction equilibrium constant can decrease with temperature in the first case and increase in the
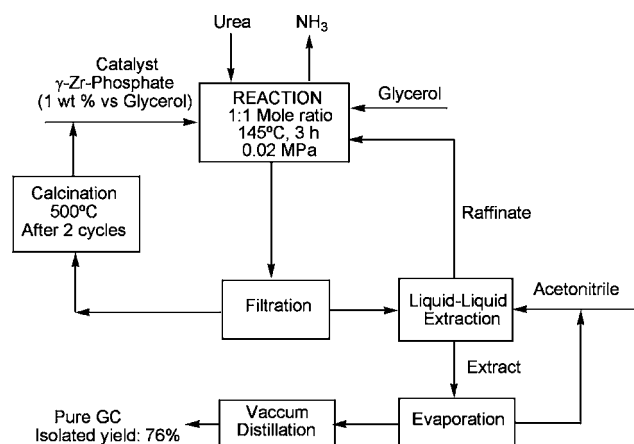
Figure 2. Simplified flow-sheet of the process developed by Aresta et al.[24a,27] for manufacturing GC from glycerol and urea.

second one. Thus, GC can be obtained from EC and glycerol in 89% conversion and 98% selectivity using an Al—Ca mixed oxide as catalyst in 1 h at a temperature as low as 35 °C,[28] whereas temperatures higher than 80 °C are needed when starting from DMC.[32] However, energetic saving during the reaction step in comparison with employing DMC as reactant is counteracted during the separation step by distillation because EC (261 °C) and EG (197 °C) have boiling points much higher than those of DMC (90 °C) and methanol (64.5 °C).

Therefore, from a technical point of view, the key for using one or another carbonate as raw material lies in using a cheap and/or easily recyclable catalyst. Thus, starting from EC, CaO, Al/Ca or Mg-mixed oxides and Li-hydrotalcite,[28] basic resins and zeolites,[33] and immobilized ionic liquids[34] have been used as catalysts with conversions of 85—100% and selectivities of 84—99%. Typical catalysts from DMC are CaO,[31,35] Ca(OH)$_2$, and calcium diglyceroxide,[35a] K$_2$CO$_3$/MgO,[35c] Mg—Al hydrotalcite in DMF as solvent,[36] KF-hydroxyapatite,[37] Mg/Al/Zr mixed oxide,[38] lipases,[39] and ionic liquids,[40] with conversions of 95—100% and selectivities of 95—99%.

The use of lipases as catalysts results in yields ranging between 90% in the solvent-free process[39a] and 100% if tetrahydrofuran is used as a cosolvent.[39b] *Candida antarctica* lipase B and Novozyme 435 exhibited higher catalytic activities. However, a main drawback is that times typically greater than 25 h are needed for completing the reaction, resulting in a low productivity which prevents the accomplishment of criterion 5 for industrial feasibility. Chiappe and Rajamina have reported the synthesis of GC from glycerol and DMC using several basic ionic liquids as both solvents and catalysts.[40] Using *N*-methyl-*N*-butylmorpholinium dicyanamide [Mor$_{1,4}$][N(CN)$_2$] a high mean 95% conversion of glycerol into GC is achieved after four catalyst recycles at 120 °C in 13 h using a DMC/glycerol molar ratio of 3. The main drawbacks of this process are its long reaction time and that catalyst and product separation is carried out by column chromatography on silica using ethyl acetate to elute GC and methanol to elute the ionic liquid. Chromatography is an expensive separation operation not suitable for large-scale production, and two additional evaporation steps are required for separating the solvents used as eluents. Therefore, this process does not accomplish criteria 2 and 5. On the other hand, ionic liquids are currently very expensive materials, and consequently, their stability on the long term under the reactions conditions should be studied before scaling up.

Most of the remaining heterogeneous catalysts are not commercial and must be manufactured through a procedure which usually ends up in an energetically expensive calcination step. Then, recycling of catalyst is a must for industrial feasibility of the process. However, to the best of our knowledge, the catalysts shown to be recyclable have only been tested in 4—5 cycles at most. On the contrary, one of the reported catalysts, CaO, is both very cheap and widely commercially available. As reported by Ochoa-Gómez et al.[32] its activity increases dramatically after calcination due to calcium hydroxide removal from its surface. However, in order to avoid such a highly energy-consuming step, these researchers used a mathematic model obtained from a factorial design of experiments to find operation conditions for achieving a 100% conversion and a 95% yield using uncalcined CaO: 95 °C (autogenous pressure),

Scheme 4. Synthesis of GC by transesterification of EC or DMC with glycerol with basic heterogeneous catalysts
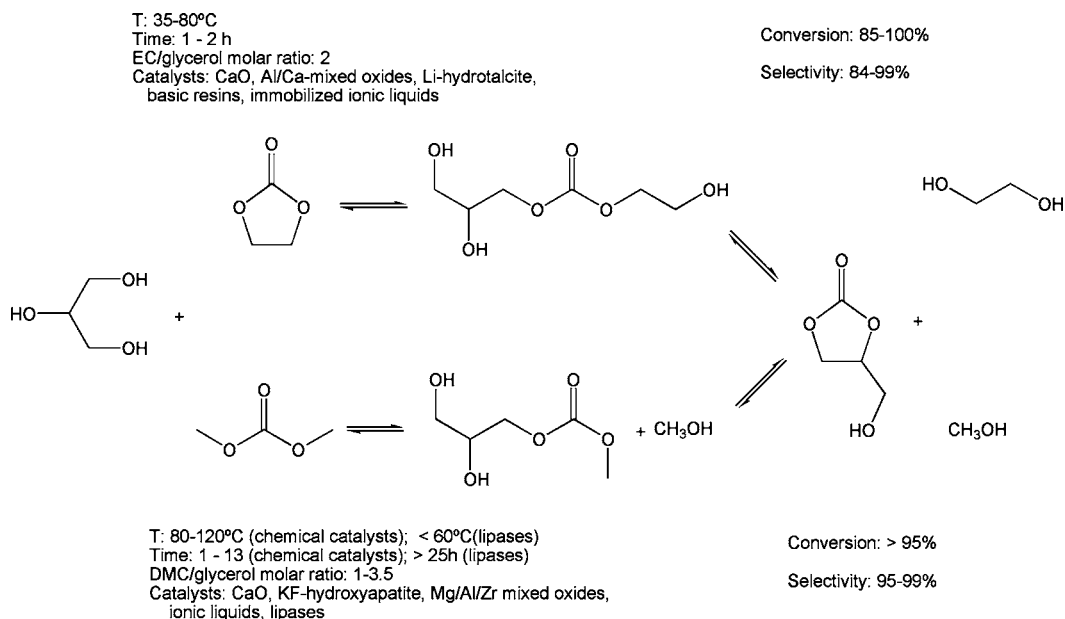
catalyst/glycerol molar ratio = 0.06, reaction time of 1.5 h, and dimethyl carbonate/glycerol molar ratio of 3.5. At first, this process does not meet criterion 1 for industrial feasibility because CaO is not easily recyclable due to its quick deactivation after the first use as it can be seen in Figure 3.
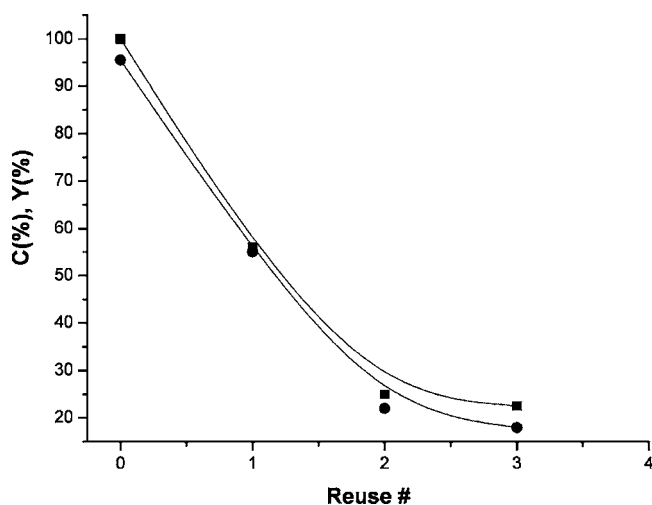

Figure 3. Glycerol carbonate from glycerol and DMC: conversion (C, ■) and yield (Y, ●) as a function of the number of reuses of uncalcined CaO.[32]

According to Li and Wang[35a] the deactivation is due to the conversion of CaO into a basic calcium carbonate $Ca_x(OH)_y(CO_3)_z$. An expensive regeneration step by calcination following every reaction is then needed. Fortunately, on one hand CaO is a very cheap chemical whose incidence on GC production cost is as low as 0.006 €/kg of GC, and on the other hand, the disposal of CaO is not a problematic environmental burden. Therefore, we can conclude that this method meets all criteria for industrial feasibility. A simplified flow diagram of the process with uncalcined CaO as catalyst is depicted in Figure 4.
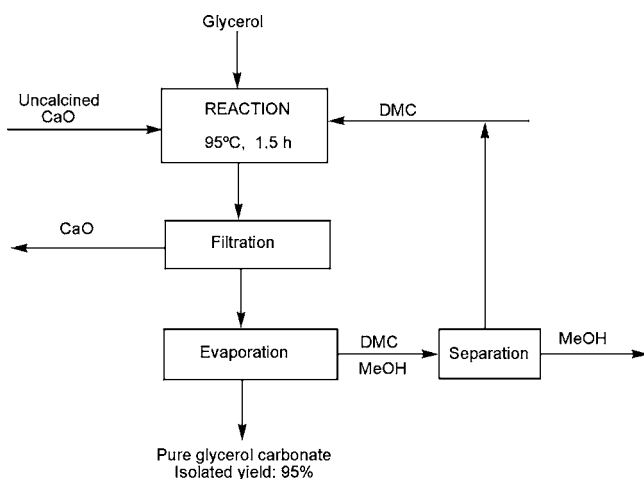

Figure 4. Simplified flow-sheet of the process developed by Ochoa-Gómez et al.[32] for manufacturing GC from glycerol and DMC.

Once the reaction is over, CaO is removed by filtration and sent for disposal. The filtrate is evaporated to remove DMC and methanol, yielding 95% pure glycerol carbonate. Methanol and DMC form an azeotropic mixture at a composition ratio of 30:70 (weight ratio) under normal pressure and must be

separated, recycling the latter compound and marketing the former one. Pervaporation can be a suitable technique.[41]

An advantage of the process depicted in Figure 4 is that the same facility can be used for manufacturing GC from either DMC or EC (and also diethyl carbonate), changing of course the operation conditions in each step.[42] Consequently, the manufacturer may use one or the other raw materials according to their market prices and availability.

Li and Wang[44] have developed a new and interesting process, also with CaO as catalyst, in which the reaction between glycerol and DMC was coupled with an azeotropic distillation to continuously remove methanol through the top of the distillation tower, shifting thereby the equilibrium of the reversible transesterification. At a 1:1 DMC/glycerol molar ratio and a final temperature at the tower bottom of 85 °C, yields as high as 98% are obtained. It is worth remarking that the yield can be retained at a high level using deactivated CaO. Unfortunately, a very toxic chemical such as benzene is used as an azeotropic agent, and this is nowadays industrially arguable.

Reaction of Glycerol Halo-Derivatives with Alkaline (Hydrogen) Carbonates. HAL and EPI have been the two glycerol halo-derivatives used in this reaction. The solvent-free reaction of HAL with potassium (hydrogen) carbonate has been reported by Gómez-Jiménez-Aberasturi et al.[45] As depicted in Scheme 5, the reaction proceeds in two steps. It is fast with a source of carbonation and temperature having a strong influence on the results. Under optimum conditions, GC yield is higher from K_2CO_3 (80%) than from $KHCO_3$ (60%).

Unfortunately, the inevitable formation of KOH and water in the two approaches of Scheme 5 cause respectively the conversion of additional starting material HAL to form glycerol and glycidol in considerable amounts.[46] Concomitant production of the highly valuable glycidol is not a drawback, but production of glycerol decreases dramatically the yield of the overall process because glycerol is the raw material for obtaining HAL, and makes the separation step much more difficult. Then, this process does not meet criteria 2 and 4 and therefore is not suitable for industrial use.

GC has been also prepared from EPI (Scheme 6) with alkali metal hydrogen carbonates using quaternary ammonium salts as phase transfer catalysts.[47] This reaction does not meet the above-mentioned criteria for industrial feasibility due to long reaction time, use of a solvent, and difficult recycling of catalyst.

Reaction of HAL with CO_2. This synthesis has been recently reported by Ochoa-Gómez et al.[48] The reaction is carried out in triethylamine (TEA), which acts as solvent, CO_2 fixation–activation agent, and HCl scavenger, and it proceeds in three steps (Scheme 7). TEA hydrochloride is formed as a concomitant product, and a 90% isolated GC yield is obtained. An unexpected result was the glycerol formation in a 5% yield independently of experimental conditions. As shown by the authors, the cause for glycerol formation was not the water always present in trace amounts in the hygroscopic reactants, and remains still unknown.

A simplified flow-diagram of the process is depicted in Figure 5. After workup of the reaction mixture glycerol carbonate is isolated in a purity ≥92 wt %, which is within that of the technical grade commercial glycerol carbonates (90.5−93.5%), and it is high enough for most applications.[49] Considering that the process was not optimized, increases in yield and purity after process optimization are expected.

Scheme 5. Synthesis of GC from 3-chloro-1,2-propanediol (HAL) and K$_2$CO$_3$ or KHCO$_3$[45]
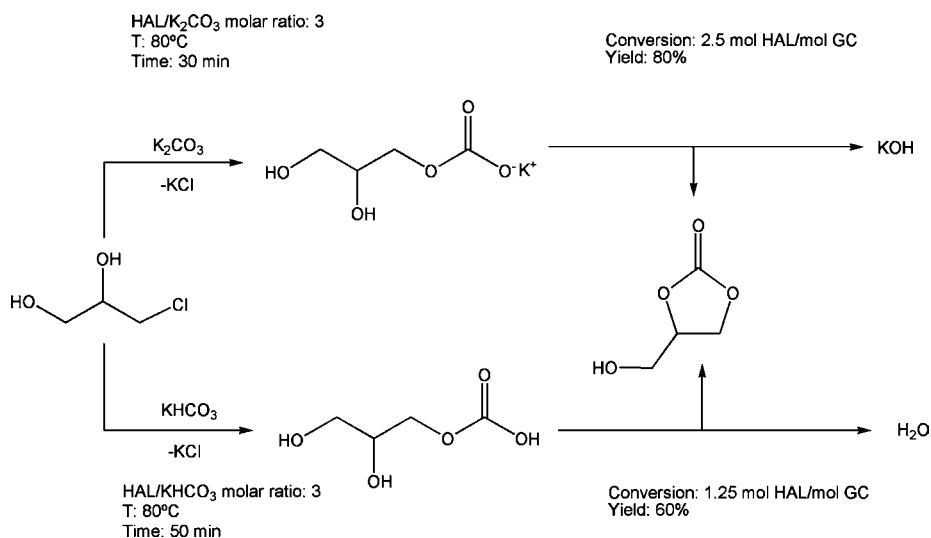
Scheme 6. Synthesis of GC from EPI and KHCO$_3$[47]
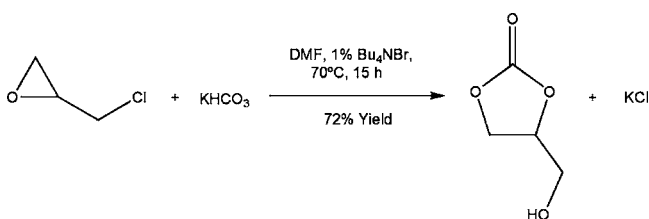
COMPARATIVE ANALYSIS

As stated in the preceding section, it is apparent that routes in which HAL and EPI are reacted with alkaline (hydrogen) carbonates do not meet the selected criteria for industrial feasibility and they will no longer be discussed. In order to compare the remaining processes, a score between 0 (no compliance at all) and 5 (total compliance) has been assigned to each of the six criteria used to analyze their industrial feasibility. Scores for each criterion as well as total scores as a function of the process are given in Table 1.

Related to criterion 1 (if catalytic, a cheap and easily separable and recyclable catalyst) a score of 5 has been assigned to processes 2 and 3 that use CaO as catalyst because it does not need to be recycled due to both its very low price and its low environmental burden. Likewise, a score of 5 has been given to
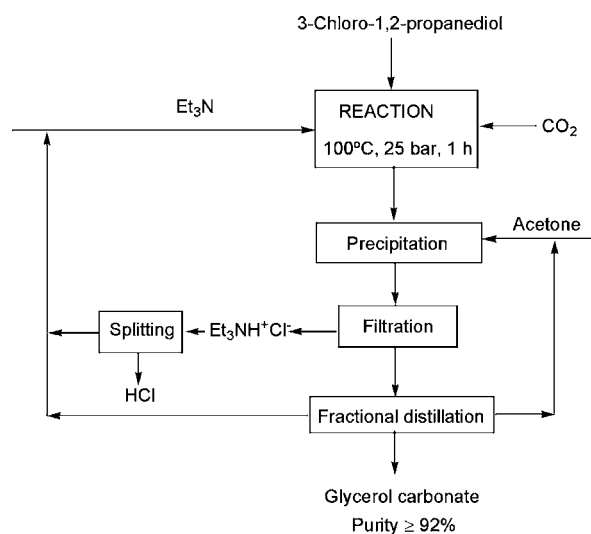

Figure 5. Simplified flow-sheet of the process developed by Ochoa-Gómez et al.[48] for manufacturing GC from 3-chloro-1,2-propanediol and CO$_2$.

process 4 because no catalyst is used. In process 1, the best reported catalyst for the only process in which a separation and purification procedure has been developed to isolate GC[24a,27] is γ-Zr-phosphate which is obtained after a tedious and costly
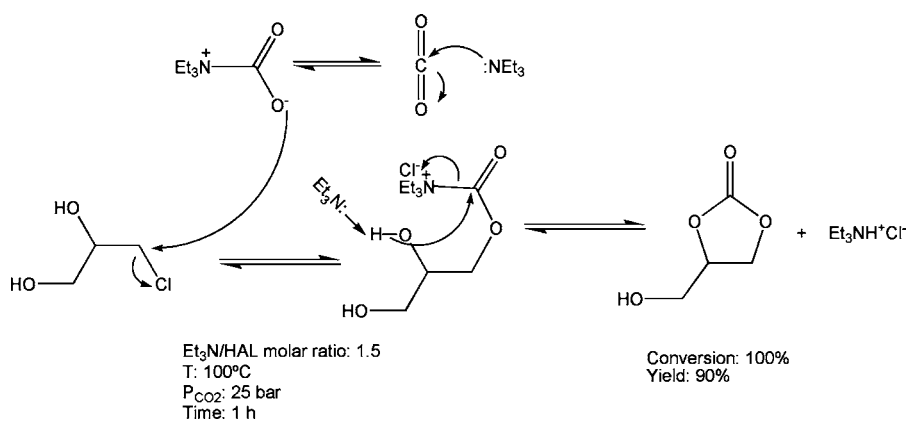
Scheme 7. Synthesis of GC from HAL and CO$_2$ in TEA as CO$_2$ fixation−activation agent

Table 1. Comparative analyses of the industrial feasibility of the reported processes for manufacturing of glycerol carbonate

	scores of criteria						
process #	C1	C2	C3	C4	C5	C6	total
1: glycerol + urea	3	3	4	3	4	4	21
2: glycerol + EG	5	4	5	5	5	5	29
3: glycerol + DMC	5	5	5	5	5	5	30
4: HAL + CO$_2$	5	4	4	4	5	3	25

manufacturing procedure[51] and must been regenerated by calcination after two cycles. Consequently, it has received a score of 3.

With respect to criterion 2 (simple separation and purification methods), the scores have been associated to the number of steps needed for isolating GC as depicted in the Figures 2, 4, and 5. A score of 5 has been given to process 3 (Figure 4), the one with the lower number of separation steps (3). Process 2 (Figure 4) also has three separation steps, but the evaporation step requires much more energy because the boiling point of EG is much higher than that of DMC. Consequently, its score has been 4, the same as that of process 4 (Figure 5) because, although it has four steps, the fractional distillation requires a low input of energy due to the low boiling points of acetone (56 °C) and TEA (89 °C). Finally, process 1 (Figure 2) has five separation steps (including calcination needed for catalysts), and therefore, its score (3) has been the lower one.

All processes are solvent-free in the reaction step, but processes 1 and 4 employ solvents (acetonitrile and acetone, respectively) in the separation steps. Consequently, taking into account that these solvents are industrially acceptable and easily recyclable, a score of 4 has been assigned to them in criterion 3 (avoiding or minimizing the use of solvents), whereas a score of 5 has been given to the other processes. Isolated yields for processes 1, 2, 3, and 4 are 76%, 95%, 95%, and 90%, respectively, and consequently they have received scores of 3, 5, 5, and 4, respectively, for criterion 4 (high conversion and selectivity). Likewise, with reference to criterion 5 (low reaction time) all processes have a low reaction time and have received the maximum score except process 1 (score of 4) because its reaction time (3 h) is at least double than that of the others. Finally, processes 2 and 3 use nontoxic materials and are carried out under not dangerous
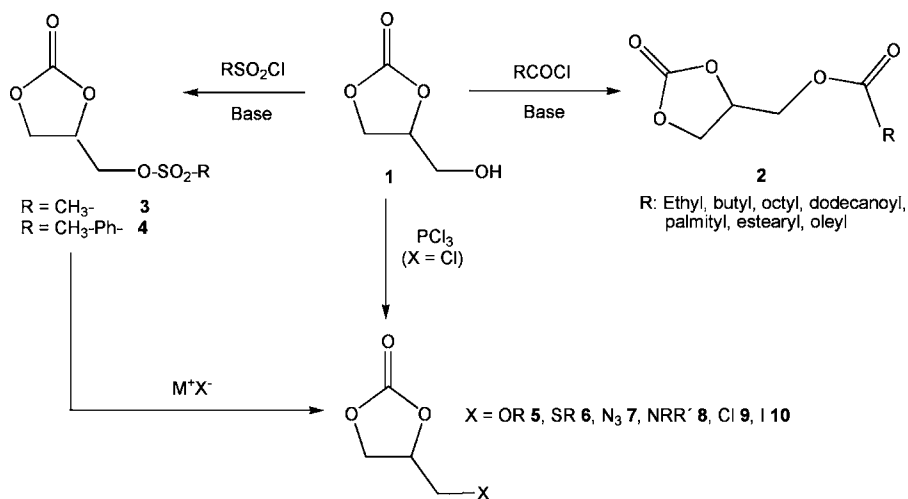
operation conditions; thus, scores of 5 have been assigned to them for criterion 6 (intrinsically as safe as possible). In process 1 an extremely irritant gas (ammonia) must be evacuated at vacuum, and consequently its score (4) is slightly lower. The score for process 4 is 3 because reaction must be conducted under pressure (25 bar) and the starting raw material 3-chloro-1,2-propanediol is carcinogenic, although its very low volatility (bp 213 °C) makes it easy to avoid its inhalation.

According to results given in Table 1, transesterification of DMC or EC with glycerol are the more suitable processes for industrial manufacturing of GC. However, it must be taken into account that score of the still not optimized process # 4 is only slightly lower, so it could become a feasible alternative to produce GC. Likewise, there are clear opportunities for improving the performance of process # 1, mainly in the separation procedure because nonisolated yield (up to 88%) is relatively much higher than the isolated yield (76%). On the other hand, it is worth remembering that this simple comparative study has been carried out by using some technical criteria, but deciding to build an industrial facility requires a careful economic analysis, the results of which are strongly dependent on raw material prices, and the socioeconomic environment.

■ GLYCEROL CARBONATE AS AN INTERMEDIATE IN CHEMICAL SYNTHESIS

Unlike other cyclic carbonates, the reactivity of GC lies not only in the ring but also in the pendant hydroxyl moiety. Consequently, GC undergoes all the reactions of cyclic carbonates[52] plus those of alcohols. GC can react both as a nucleophile through its hydroxyl group, and as an electrophile through its ring carbon atoms. The following is not intended to be a comprehensive study of the applications of GC as intermediate in chemical synthesis but a picture about its potentiality. Some examples of reactions in which GC acts as a nucleophile via its hydroxyl group are given in Scheme 8.

Mouloungui and Pelet[53] have reported the synthesis of glycerol carbonate esters **2** by acylation of GC with aliphatic acyl chlorides in the presence of TEA as HCl scavenger using dichloromethane as solvent. Yields are not given, but typically this kind of reaction results in yields higher than 90%. The obtained esters have good thermal and oxidation stability, and some of them (octanoate, dodecanoate, and oleate) exhibit surfactant properties.

Scheme 8. Potential of further functionalization of GC via its hydroxyl moiety (for experimental conditions and results see text)


R = CH$_3$- **3**
R = CH$_3$-Ph- **4**

R: Ethyl, butyl, octyl, dodecanoyl, palmityl, estearyl, oleyl

X = OR **5**, SR **6**, N$_3$ **7**, NRR′ **8**, Cl **9**, I **10**

Simão et al[54a] and Rousseau et al[54b] have synthesized mesyl glycerol carbonate **3** and tosyl glycerol carbonate **4** in 92%−99% yields by reaction between GC and mesyl and tosyl chlorides, respectively, at −10 °C to room temperature in dichloromethane and with pyridine or TEA as HCl scavengers. **3** and **4** are multielectrophilic synthons in which all the carbon atoms of the glycerol carbonate moiety are activated and consequently are prone to undergo nucleophilic substitutions by reacting with a miscellaneous of oxygen-, nitrogen-, and sulfur-nucleophiles. Thus, a wide range of cyclic and acyclic, aliphatic and aromatic ethers **5**, tioethers **6**, azides **7**, and amines **8** can be synthesized with potential applications as solvents, energetic carriers (azide derivatives), and herbicides, for instance.[54]

4-Chloromethyl-1,3-dioxolan-2-one **9** and 4-iodomethyl-1,3-dioxolan-2-one **10** have been synthesized by Dibenedetto et al.[17] and Ochoa-Gómez et al. (results published herein for first time), respectively.[55] Both chemicals are good intermediates in chemical synthesis, especially the iodine atom of **10** is a very good leaving group to introduce nucleophilic moieties into the hydroxymethyl group of GC by means of S_N2 reactions. Both have been proposed as solvents for ionically conductive polymeric gel electrolytes in solid batteries.[56] An unexplored potential application of **10** could be the manufacturing of new hydrosoluble iodine derivatives to be used as radiologic markers.

A very interesting chemical which can be obtained from GC is glycidol. It is used as a raw material for obtaining polyglycerols, polyglycerol esters, glycidyl ethers, energetic matrices for solid propellants, pharmaceuticals as well as in perfumes and cosmetics, detergents, drugs, paints, UV curing agents for semiconductors, stabilizer for natural oils and vinyl polymers, demulsifier, dye-leveling agent, etc. Currently, it is a high value chemical and, consequently, a wider range of applications are to be expected if a more economic synthetic route for its production is developed. Such a route could be the decarboxylation of

GC (Scheme 9) which is usually carried out by continuously distilling glycidol at vacuum at temperatures of 180−200 °C in

Scheme 9. Synthesis of glycidol from glycerol carbonate[57a]
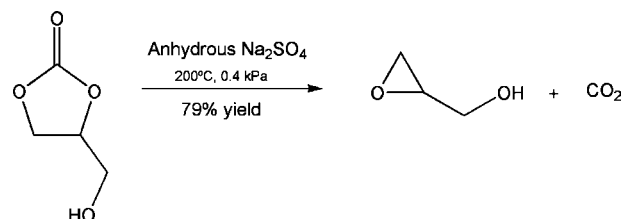

the presence of catalysts such as anhydrous sodium sulphate[57a] and zeolites[57b] in 70−85% yields.

It is worth mentioning that one of the most promising applications of GC as chemical intermediate is in the manufacturing of polymers taking advantage of its ring reactivity. Thus, Bevinakatti et al.[58] have obtained new polyglycerol esters (Scheme 10) by reacting C_6−C_{22} fatty carboxylic acids with glycerol carbonate in combination with cyclic diol carbonates, such as ethylene or propylene carbonates in the presence of base catalysts such as NaOH, KOH, K_2CO_3, and DBU. The polyglycerol esters are claimed to be useful in a wide variety of applications such as food and/or cosmetic, emulsifiers, solubilizers, emollients, dispersants, and rheology modifiers, among others.

Rokicki et al[59] have described the base-catalyzed ring-opening polymerization of glycerol carbonate using partially deprotonated trimethylolpropane as an initiator. Polymerization proceeds with CO_2 evolution and yields hyperbranched aliphatic polyethers (Scheme 11) which are claimed as useful intermediates in the synthesis of new amphiphilic materials for biomedical applications and hydrogels.

Scheme 10. Synthesis of polyglycerol esters derived of C_6−C_{22} fatty acids
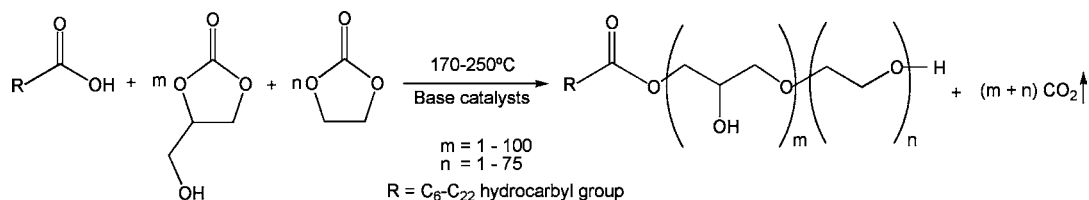

Scheme 11. Synthesis of hyperbranched aliphatic polyethers from glycerol carbonate
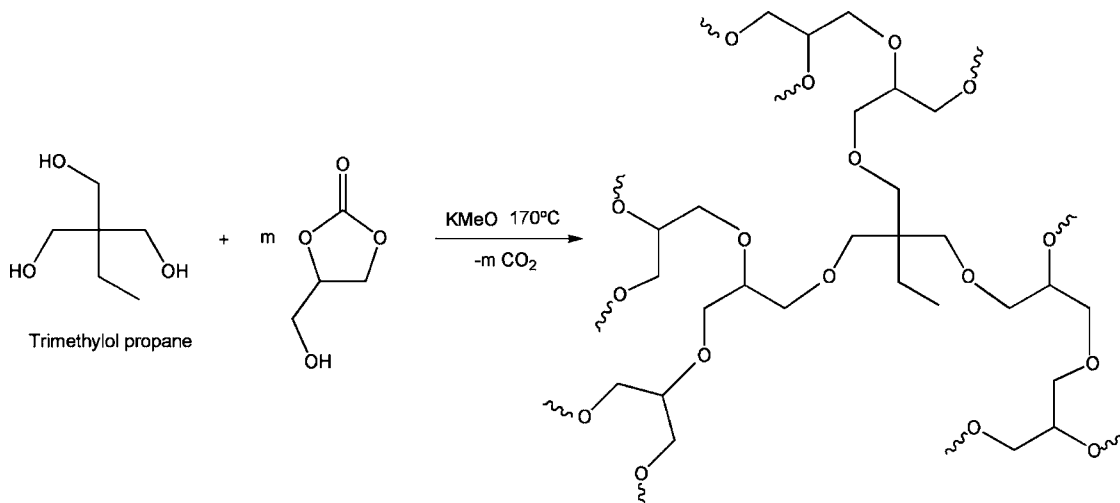
Due to the toxicity of isocyanates, new routes are currently looking for producing polyurethanes. Non-isocyanate polyurethanes (NIPUs)[60] are attracting increasing attention due to their improved properties over conventional polyurethanes and because they are synthesized by reaction of organic dicarbonates and diamines, avoiding the use of toxic isocyanates. Thus, by reacting derivatives of glycerol carbonate, such as the ones depicted in Scheme 12, with diamines, NIPUs

Scheme 12. Synthesis of NIPUs from di(glycerol carbonate)s and diamines
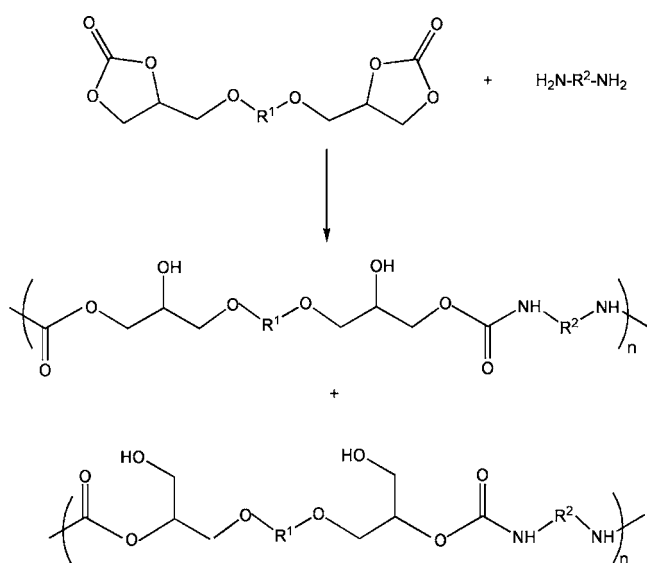
with primary and secondary hydroxyl groups which render them reactive polyurethanes can be obtained. In some applications, the pendant hydroxyl groups can improve coating adhesion or be used as grafting sites. By changing the structures of R^1 and R^2 groups the properties of the obtained NIPUs can be tailored to the desired application. Methods for synthesizing the organic dicarbonates are reported by Guan et al.[60]

Finally, GC can be used for manufacturing polycarbonates with pendant hydroxyl moieties useful for manufacturing compositions which have applications in motor vehicle and industrial lubricants and lubricating additives, mold-release agents, wood treatment products, additives for drilling mud, detergency, pharmacy, cosmetics, and so on.[61]

■ CONCLUSIONS

Glycerol carbonate is a glycerol-derived chemical whose physical and chemical properties make it an industrial target molecule with applications in cosmetics, pharmaceuticals, detergents, intermediate in chemical synthesis and in the production of useful polymeric materials such as polycarbonates, polyglycerol esters, hyperbranched polyols, and non-isocyanate polyurethanes. The interest for developing synthetic procedures for GC manufacturing is growing in parallel with its applications. The direct synthesis from glycerol and CO_2 is not currently industrially possible due to low CO_2 reactivity resulting in yields below 32%. Consequently, indirect synthetic approaches are needed at present. The following processes have been analyzed: (a) carbamoylation/carbonation of glycerol with urea; (b) transesterification of ethylene carbonate or dimethyl carbonate with glycerol; (c) reaction of glycerol halo-derivatives (3-chloro-1,2-propanol and epichlorohydrin) with alkaline

(hydrogen) carbonates; and (d) reaction of 3-chloro-1,2-propanediol with CO_2. A comparative study of these processes has been carried out in light of six criteria for industrial feasibility. As a result, three alternatives have been selected. Transesterification of ethylene carbonate or dimethyl carbonate with glycerol using uncalcined CaO as catalyst appears to be the most suitable route to GC industrial manufacturing. Reaction between 3-chloro-1,2-propanediol and CO_2 in triethylamine as solvent, CO_2 fixation—activation agent, and HCl scavenger could be an alternative in the near future due to the high yield obtained (90%) and the easy isolation of GC, especially considering it is not optimized. The carbamoylation/carbonation of glycerol with urea using heterogeneous catalysts is a third alternative, but further improvements in the recyclability of the catalysts and in the GC isolation procedure are required.

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Notes
The authors declare no competing financial interest.

■ REFERENCES

(1) Bher, A.; Eilting, J.; Irawadi, K.; Leschinski, J.; Lindner, F. *Green Chem.* **2008**, *10*, 13−30.

(2) Technical Bulletin. Jeffsol Glycerine Carbonate. 2008, 2009, 2010.http://www.huntsman.com/performance_products/Media/JEFFSOL%20Glycerine%20Carbonate.pdf.

(3) Glycerol carbonate. http://www.ube.es/chemicals/fine.asp?id=17&marcarr=13.

(4) Kerton, F. M. *Alternative Solvents for Green Chemistry*, RSC Green Chemistry Book Series; RSC Publishing: Cambridge, 2009; pp 103−104.

(5) Kahre, J.; Loehl, T.; Tesmann, H.; Hensen, H. Surface-active compositions, specially cosmetics, containing glycerol carbonate as emulsifier. DE 19756454, 1999.

(6) Jeffsol GC, Glycerine Carbonate in Beauty & Personal Care, Huntsman Technical Bulletin, 2011, http://www.huntsman.com/performance_products/Media/JeffsolGCMar2011.pdf.

(7) Abraham, D. P. Electrolytes for lithium and lithium-ion batteries. U.S. Patent Appl. 2011/0117445A1, 2011.

(8) Magniont, C.; Escadeillas, G.; Oms-Multon, C.; De Caro, P. *Cem. Concr. Res.* **2010**, *40*, 1072−1080.

(9) Brooker, A. T. Solid detergent composition comprising glycerol carbonate. EP 2 380 958 A1, 2011.

(10) For instance, the reaction between glycerol and phosgene,[11] those starting from carbon monoxide,[12,13] or the CO_2 insertion into an oxirane ring (glycidol in this case), a well-known route for obtaining cyclic carbonates, will not be discussed due to the hazardous and environmental concerns related to the use of phosgene and CO in chemical synthesis in the first case, and because glycidol is much more expensive than GC in the second one. In fact, as discussed later herein, one of the applications of glycerol carbonate as an intermediate in chemical synthesis is the manufacturing of glycidol, which could allow lowering the current price of the latter, thereby extending its field of applications.

(11) McKetta, J. J., Cunningham, W. A., Eds. *Encyclopedia of Chemical Processing and Design*; Marcel Decker: New York, NY, 1984; Vol. *20*; p 177.

(12) Teles, J. H.; Rieber, N.; Harder, W. Preparation of glyceryl carbonate., U.S. Patent 5,359,094, 1994.

(13) Hu, J.; Li, J.; Gu, Y.; Guan, Z.; Mo, W.; Ni, Y.; Li, T; Li, G. *Appl. Catal., A* **2010**, *386*, 188−193.

(14) Aresta, M.; Dibenedetto, A.; Nocito, F.; Pastore, C. *J. Mol. Catal. A: Chem.* **2006**, *257*, 149−153.

(15) (a) Aresta, M.; Dibenedetto, A.; Pastore, C.; Angelini, A.; Aresta, B.; Pápai, I. *J. Catal.* **2010**, *269*, 44−52. (b) Aresta, M.; Dibenedetto, A.; Pastore, C.; Cuocci, C.; Aresta, B.; Cometa, S.; De Giglio, E. *Catal. Today* **2008**, *137*, 125−131. (c) Dibenedetto, A.; Aresta, M.; Fragale, C.; Distaso, M.; Pastore, C.; Venezia, A. M.; Liu, C. J.; Zhang, M. *Catal. Today* **2008**, *137*, 44−51.

(16) George, J.; Patel, Y.; Muthukumaru, S.; Munshi, P. *J. Mol. Catal. A: Chem.* **2009**, *304*, 1−7.

(17) Dibenedetto, A.; Angelini, A.; Aresta, M.; Ethiraj, J.; Fragale, C.; Nocito, F. *Tetrahedron* **2011**, *67*, 1308−1313.

(18) Vieville, C.; Yoo, J. W.; Pelet, S.; Mouloungui, Z. *Catal. Lett.* **1998**, *56*, 245−247.

(19) Nguyen, N. T.; Demirel, Y. *Int. J. Chem. React. Eng.* **2011**, *9*, Article A108.

(20) Both HAL and EPI are glycerol derivatives. The synthesis of HAL by reacting glycerol and HCl is known since 1922.[21] The synthesis of glycerol chlorohydrins has attracted attention in the last years[22] because they are key intermediates in the current process developed by Solvay (Epicerol Technology; Solvay has applied for 38 patents) for manufacturing EPI.[23]

(21) Conant, J. B.; Quayle, O. R. *Org. Synth.* **1922**, *2*, 33−34; *Org. Synth.* **1941**, *1*, 294−295.

(22) (a) Tesser, R.; Santacesaria, E.; Di Serio, M.; Di Nuzzi, G.; Fiandra, V. *Ind. Eng. Chem. Res.* **2007**, *46*, 6456−6465. (b) Santacesaria, E.; Tesser, R.; Di Serio, M.; Casale, L.; Verde, D. *Ind. Eng. Chem. Res.* **2010**, *49*, 964−970. (c) Tesser, R.; Di Serio, M.; Vitiello, R.; Russo, V.; Ranieri, E.; Speranza, E.; Santacesaria, E. *Ind. Eng. Chem. Res.* **2011**, DOI: 10.1021/ie201629z.

(23) Krafft, P.; Gilbeau, P.; Gosselin, B.; Claessens, S. Process for producing dichloropropanol from glycerol, the glycerol coming eventually from the conversion of animal fats in the manufacture of biodiesel. PCT Patent WO 054167 A1, 2005.

(24) (a) Aresta, M.; Dibenedetto, A.; Nocito, F.; Ferragina, C. *J. Catal.* **2009**, *268*, 106−114. (b) Calvino-Casilda, V.; Mul, G.; Fernández, J. F.; Rubio-Marcos, F.; Bañares, M. A. *Appl. Catal., A* **2011**, *409−410*, 106−112.

(25) Hammond, C.; Lopez-Sanchez, J. A.; Hasbi Ab Rahim, M.; Dimitratos, N.; Jenkins, R. L.; Carley, A. F.; He, Q.; Kiely, Ch.J.; Knight, D. W.; Hutchings, G. H. *Dalton Trans.* **2011**, *40*, 3927−3937.

(26) (a) Claude, S.; Mouloungui, Z.; Yoo, J. W.; Gaset, A. Method for preparing glycerol carbonate. U.S. Patent 6,025,504, 1999. (b) Okutsu, M.; Kitsuki, T. Process for the preparation of glycerol carbonate. U.S. Patent 6,495,703, 2002.

(27) Dubois, J. L.; Aresta; M. Synthesis process of polyol carbonate from polyols, conducted in using a solvent selective for polyols carbonates. EP 2 174 937 A1, 2010.

(28) Climent, M. J.; Corma, A.; De Frutos, P.; Iborra, S.; Noy, M.; Velty, A.; Concepción, P. *J. Catal.* **2010**, *269*, 140−149.

(29) Wang, L.; Ma, Y.; Wang, Y.; Liu, S.; Denng, Y. *Catal. Commun.* **2011**, *12*, 1458−1462.

(30) (a) Alvarez, M. G.; Segarra, A. M.; Contreras, S.; Sueiras, J. E.; Medina, F.; Figueras, F. *Chem. Eng. J* **2010**, *161*, 340−345. (b) Alvarez, M. G.; Plíšková, M.; Segarra, A. M.; Medina, F.; Figueras, F. *Appl. Catal., B* **2012**, *113−114*, 212−220.

(31) Li, J.; Wang, T. *J. Chem. Thermodyn.* **2011**, *43*, 731−736.

(32) Ochoa-Gómez, J. R.; Gómez-Jiménez-Aberasturi, O.; Maestro-Madurga, B.; Pesquera-Rodríguez, A.; Ramírez-López, C.; Lorenzo-Ibarreta, L.; Torrecilla-Soria, J.; Villarán-Velasco, M. C. *Appl. Catal., A* **2009**, *336*, 315−324.

(33) Mouloungui, Z.; Yoo, J. W.; Gachen, C.; Gaset, A. Process for the preparation of glycerol carbonate from glycerol and a cyclic organic carbonate, specially ethylene or propylene carbonate. EP 0739888, 1996.

(34) Cho, H.-J.; Kwon, H.-M.; Tharun, J.; Park, D.-W. *J. Ind. Eng. Chem.* **2010**, *16*, 679−683.

(35) (a) Li, J.; Wang, T. *Reac. Kinet. Mech. Catal.* **2011**, *102*, 113−126. (b) Simanjuntak, F. S. H.; Kim, T. K.; Lee, S. D.; Ahn, B. S.; Kim, H. S.; Hyunjoo, L. *Appl. Catal., A* **2011**, *401*, 220−225. (c) Du, M.; Li, Q.; Dong, W.; Geng, T.; Jiang, Y. *Res. Chem. Intermed.* **2011**, DOI: 10.1007/s11164-011-0443-3.

(36) Takagaki, A.; Iwatani, K.; Nishimura, S.; Ebitani, K. *Green Chem.* **2010**, *12*, 578−581.

(37) Bai, R.; Wang, S.; Mei, F.; Li, T.; Li, G. *J. Ind. Eng. Chem* **2011**, *17*, 777−781.

(38) Malyaadri, M.; Jagadeeswaraiah, K.; Sai Prasad, P. S.; Lingaiah, N. *Appl. Catal., A* **2011**, *401*, 153−157.

(39) (a) Lee, K. H.; Park, C. H.; Lee, E. Y. *Bioprocess Biosyst. Eng.* **2010**, *33*, 1059−65. (b) Kim, S. C.; Kim, Y. H.; Lee, H.; Yoon, D. Y.; Song, B. K. *J. Mol. Catal. B: Enzym.* **2007**, *49*, 75−78.

(40) Chiappe, C.; Rajamani, S. *Pure Appl. Chem.* **2011**, DOI: 10.1351/PAC-CON-11-07-06.

(41) Wang, L.; Li, J.; Lin, Y.; Chen, C. *J. Membr. Sci.* **2007**, *305*, 238−246.

(42) In the evaporation step EC and EG are obtained instead of DMC and MeOH. EC and EG also form an azeotrope (bp 155 °C at 110 mmHg)[43] which must be suitably separated for recycling unconverted EC and obtaining pure EG for marketing.

(43) Duranleau, R. G.; Nieh, E. C. Y.; Knifton, J. F. Process for production of ethylene glycol and dimethyl carbonate. U.S. Patent 4,691,041, 1987.

(44) Li, J.; Wang, L. *Chem. Eng. Process.* **2010**, *49*, 530−535.

(45) Gómez-Jiménez-Aberasturi, O.; Ochoa-Gómez, J. R.; Pesquera-Rodríguez, A.; Ramírez-López, C.; Alonso-Vicario, A.; Torrecilla-Soria, J. *J. Chem. Technol. Biotechnol.* **2010**, *85*, 1663−1670.

(46) Under the optimum conditions for GC formation, 0.84 and 0.56 mol of glycerol/mol of GC are formed from K_2CO_3 and $KHCO_3$, respectively; and, 0.59 and 0.25 mol of glycidol/mol of GC are likewise obtained from K_2CO_3 and $KHCO_3$, respectively. It is worth noting that GC yields have been calculated based on K_2CO_3 and $KHCO_3$ as limiting reactants. HAL is used in a 3-fold stoichiometric excess, and it is converted into products not only through the reaction leading to GC but also through side reactions with KOH and water. Consequently, if calculations are carried out based on reactions resulting in GC, HAL conversions are higher than 100% which makes no sense. Consequently, HAL conversions in Scheme 5 and glycerol and glycidol yields have been reported as mass ratios relative to that of GC in order to avoid misleading the reader.

(47) Koseev, K. S.; Koseva, N. S.; Troev, K. D. *React. Kinet. Catal. Lett.* **2003**, *79*, 11−18.

(48) Ochoa-Gómez, J. R.; Gómez-Jiménez-Aberasturi, O.; Ramírez-López, C.; Nieto-Mestre, J.; Maestro-Madurga, B.; Belsué, M. *Chem. Eng. J.* **2011**, *175*, 505−511.

(49) Triethylamine hydrochloride can be treated in a splitting step with aqueous NaOH to release triethylamine which in turn can be easily separated by distillation and recycled to the reaction step. Alternatively, it can be split in aqueous solution by electrohydrolysis with bipolar membranes[50] generating a useful aqueous HCl stream at the same time. After a suitable treatment for separating HCl gas, it may be reacted with glycerol for synthesizing the starting material, HAL.

(50) Strathmann, H.; Bauer, B.; Rapp, H. J. *CHEMTECH* **1993**, *23*, 17−24.

(51) Reaction between $ZrOCl_2 \cdot 8H_2O$ and $NaH_2PO_4 \cdot H_2O$ in water to give a gel, which is heated in an autoclave at 180 °C for a week; separation of the formed crystals which are washed with HCl; and drying of the crystals at 25 °C in the air over P_2O_5.

(52) Clements, J. H. *Ind. Eng. Chem. Res.* **2003**, *42*, 663−674.

(53) Mouloungui, Z.; Pelet, S. *Eur. J. Lipid. Sci. Technol.* **2001**, *103*, 216−222.

(54) (a) Simão, A.-C.; Lynikaite-Pukleviciene, B.; Rousseau, C.; Tatibouët, A.; Kasel, S.; Šačkus, A.; Rauter, A. P.; Rollin, P. *Lett. Org. Chem.* **2006**, *3*, 744−748. (b) Rousseau, J.; Rousseau, C.; Lynikaite, B.;

Šačkus, A.; de Leon, C.; Rollin, P.; Tatibouët, A. *Tetrahedron* **2009**, *65*, 8571−8581.

(55) **9** was obtained by direct chlorination of GC with PCl$_3$ in CH$_2$Cl$_2$ at reflux. The reaction mixture was extracted with toluene with the product being obtained in 92% yield after vacuum evaporation of toluene at 20 °C. **10** was synthesized through a Finkelstein reaction from **4** which was reacted with NaI in acetone at reflux for 6 h. After separation of sodium *p*-toluenesulphonate by filtration and evaporation of acetone, **10** was obtained as a solid (mp 63.5−65 °C) in 90% yield. Product identity was confirmed by ^{1}H NMR (CDCl$_3$ (ppm): 3.4−3.5 (2H, m), 4.3−4.65 (2H, m), 4.9 (1H, m)) and ^{13}C NMR (CDCl$_3$ (ppm): 7 (I-CH$_2$), 72 (−CH$_2$−O), 76.9 (−CH−), 156.2 (C=O)) and elemental analysis (found: C 20.68%, H 2.16%; calculated: C 21.07%, H 2.21%).

(56) Taniuchi, M.; Inoue, T.; Ohsawa, T.; Yokoyama, K.; Hiwara, A.; Toriida, M. Ionically conductive polymeric gel electrolyte and solid battery containing the same. U.S. Patent 5,925,283, 1999.

(57) (a) Uno, M.; Okutsu, M. Process for production of glycidol. U.S. Patent 7,888,517 B2, 2011. (b) Yoo, J.-W.; Mouloungui, Z.; Gaset, A. Method for producing an epoxide in particular glycidol, and installation for implementation. U.S. Patent 6,316,641 B1, 2001.

(58) Bevinakatti, H. S.; Waite, A. G.; Frank, J. Method for making polyglycerol esters. WO 2008/142374 A1, 2008.

(59) Rokicki, G.; Rakoczy, P.; Parzuchowski, P.; Sobiecki, M. *Green Chem.* **2005**, *7*, 529−539.

(60) Guan, J.; Song, Y.; Lin, Y.; Yin, X.; Zuo, M.; Zhao, Y.; Tao, X.; Zheng, Q. *Ind. Eng. Chem. Res.* **2011**, *50*, 6517−6527.

(61) Dinh, N. T.; Mouloungui, Z.; Marechal, P. Glycerol polycarbonate, organic compositions containing same and method for obtaining said compositions. U.S. Patent 7,928,182 B2, 2011.