Catalytic Aldol Condensation of 5-Hydroxymethylfurfural and its Synthesis from Concentrated Feed of Carbohydrates

Wahiba Ramdani,[a] Inés Rabadán González,[a] Nora Benbakoura,[a] Mohammed Ahmar,[b] Charlie Verrier,[b] Yves Queneau,[b] Marc Pera-Titus,[c] François Jérôme,[a] and Karine De Oliveira Vigier*[a]

1-(5-(Hydroxymethyl)furan-2-yl)-5-methylhex-1-en-3-one was prepared from cellulose or glucose by a sequence of depolymerization/dehydration/aldol condensation reactions. The synthesis of HMF was first performed starting from a highly concentrated feed of glucose and cellulose (31 wt.%) using choline chloride in MIBK/water biphasic media *via* the formation of a glucoside intermediate. Next, the aldol condensation of HMF with MIBK was investigated over alkaline metal oxides. Among the catalysts used, commercial BaO was highly efficient with a yield of aldol product above 90 %. Under air, BaO instantaneously transformed into $Ba(OH)_2$, H_2O and BaO_2 which are regarded as active phases for the reaction. The catalyst basicity and solvent were key parameters to govern the selectivity of the reaction by limiting secondary reactions.

Introduction

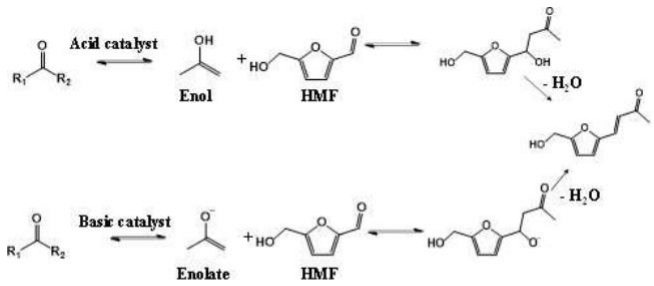
With the sustained increase of population on Earth and man-made activities, fossil carbon resources are expected to decline in the following decades. Thus, the synthesis of renewable and sustainable chemicals and energy sources is becoming more and more important.[1–5] Among renewable raw materials, lignocellulosic biomass is of interest, since a panel of valuable molecules can be obtained. For instance, 5-hydroxymethylfurfural (HMF) is a platform chemical for the synthesis of pharmaceuticals,[6] biofuels like 2,5-dimethylfuran,[7–9] polymers,[10] surfactants[11] Moreover, HMF can be used to produce biomass-derived jet fuel in multiple steps.[12] In this process. hydrolysis/dehydration of the a lignocellulosic carbohydrate to HMF is performed in the presence of an acid catalyst. Then, aldol condensation of HMF with a ketone (mostly acetone) leads to aldolization adducts that are hydrogenated and hydrodeoxygenated to linear alkanes.

The synthesis of HMF is challenging due to its lack of stability in common solvents. Among carbohydrate-based biomass resources, fructose is the most common feedstock for preparing HMF. Over the last years, many organic and inorganic acids such as HCl, H_3PO_4, *p*-toluenesulfonic acid (PTSA) and methanesulfonic acid (MSA) have been used as homogeneous catalysts with good activity towards HMF.[13–15] A more available and cheaper carbohydrate that can be used for preparing HMF is glucose. Glucose can be converted into HMF *via* an acid-catalyzed two-step process, in which it is firstly isomerized into fructose and then dehydrated into HMF. Even better, HMF can be also obtained from cellulose by a sequence of depolymerization, isomerization and dehydration reactions. Homogeneous and heterogeneous catalysts can be used for such reactions.[16] However, in most reported examples, the feed concentration of glucose or cellulose is below 10 wt% which limits the productivity (mole of HMF produced per volume of reactor per h) of the process, and accordingly potential industrial applica-tions. Recently, we demonstrated the association of choline chloride (ChCl) with xylose driven by hydrogen bonding through formation of a deep eutectic solvent (DES). The as-generated xyloside intermediate could afford high furfural yield from a high concentrated feed of xylose (33 to 50 wt%) in biphasic media.[17]

Herein we investigated the use of ChCl to prepare HMF from more recalcitrant and challenging carbohydrates such as glucose and cellulose, starting from highly concentrated solutions, in biphasic media. Further aldol condensation with methylisobutylketone (MIBK), also used to extract HMF during its synthesis, was investigated.

As a rule, aldol condensation reactions can be performed via two mechanisms (Scheme 1). Over basic catalysts, the aldol reaction progresses *via* an enolate mechanism, whereas over acid catalysts it occurs *via* an enol intermediate. The final step is

[a] *Dr. W. Ramdani, I. Rabadán González, N. Benbakoura, Dr. F. Jérôme, Prof. K. De Oliveira Vigier*
IC2MP, UMR CNRS 7285 Université de Poitiers 1 rue marcel Doré
86073 Poitiers Cédex 9 (France) E-mail: karine.vigier@univ-poitiers.fr
Homepage: https://ic2mp.labo.univ-poitiers.fr/membres/de-oliveira-vigier-karine/
[b] *Dr. M. Ahmar, Dr. C. Verrier, Dr. Y. Queneau*
ICBMS, Univ Lyon, ICBMS, CNRS, UMR 5246, Université Claude Bernard Lyon 1, INSA-Lyon, CPE Lyon
Bat. Lederer, 1 rue Victor Grignard
69622 Villeurbanne (France)
[c] *Prof. M. Pera-Titus*
Cardiff Catalysis Institute
School of Chemistry
Cardiff University
Main Building, Park Place
Cardiff CF10 3AT (UK)



Scheme 1. Mechanisms of the aldol condensation of HMF.

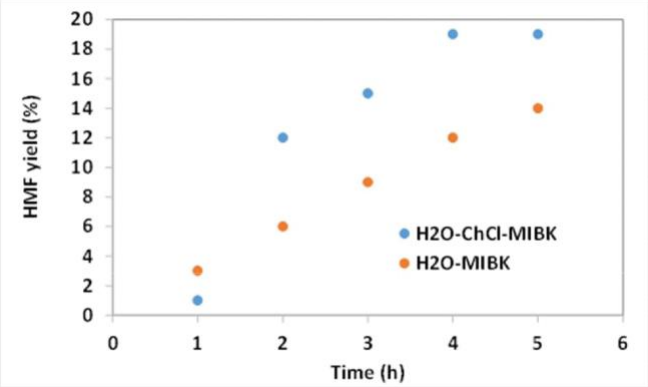


Figure 1. Synthesis of HMF from glucose. Conditions: 1 g of glucose, 1.2 g of ChCl, 2 g of aqueous HCl (pH = 1.28), 5 mol% of $AlCl_3$, 40 g of MIBK, 120 °C.

the dehydration of the enol intermediate (i. e. crotonization) to the condensation product.[18]

A wide range of basic catalysts have been studied for the aldol condensation of HMF with acetone, including surface-modified zeolite,[8] zirconium carbonate,[9] mixed oxides like MgZr and MgAl[10] and $Cu/MgAl_2O_4$,[11] $Al_{0.66}$-DTP@ZIF-8,[12] and CO_2.[13] These catalysts require long reaction times (from 6 to 24 h) which decreases the productivity. Additional studies have focused on ketones, including 2-pentanone and methylisobutyl-ketone (MIBK).[6]

Alkaline earth metal oxides (MgO, CaO, SrO, and BaO) have been studied as basic catalysts for isomerization reactions,[19] Claisen-Schmidt condensations,[20] Knoevenagel condensation,[21] Michael additions,[22] Tishchenko reactions,[23] aldol condensation of aromatic aldehydes,[24] and transesterifi-cation reactions.[25] One example was reported by Zhang and co-workers on CaO in the aldol condensation of HMF with promising results.[26] Here we investigated BaO as catalyst to selectively perform the aldol condensation of HMF with MIBK, and the reaction conditions, with emphasis on the solvent, were optimized. The scope of the reaction was also investigated using other ketones.

Results and Discussion

Synthesis of HMF in the presence of ChCl

First, we performed the synthesis of HMF starting from 1 g of glucose and 1.2 g of choline chloride (ChCl), 2 g of an aqueous solution of HCl (pH 1.28, measured at room temperature, 250 µL of HCl 37 % in 250 mL of water), 5 mol% of $AlCl_3$ and 40 g of MIBK. In this reaction, $AlCl_3$ was used as Lewis acid catalyst to promote the isomerization of glucose to fructose. In our reaction system, the glucose concentration was 31 wt.% which is three times higher than common values used in the literature. The reaction kinetics was studied at 120 °C in the presence of MIBK to extract continuously the HMF produced (Figure 1). The HMF yield is 19 % after 4 h at full glucose conversion, meaning that by-products are generated which are probably humins. For comparison, the reaction kinetics was also studied without ChCl in neat water. The HMF yield is lower (12 %) after 4 h. A similar effect was observed in the synthesis of furfural from a high concentrated feed of xylose.[17] It can be pointed out that it takes 1 h to start to observe HMF which is due to the formation of fructose before its dehydration to HMF.

In order to assess the role of ChCl on the reaction mechanism, we monitored the reaction by ^{1}H NMR at different times (1 h, 2 h, 4 h, 7 h) (Figure 2). We compared the ^{1}H NMR spectra to that obtained on choline glucoside synthesized by reaction of chloroethyl glucoside with trimethylamine.[27] The ^{1}H NMR spectrum of the as-obtained choline glucoside exhibits a doublet centered at 4.4 ppm (β stereoisomer), while a second doublet appears at 4.9 ppm (α stereoisomer). Interestingly, both doublets appear in our reaction system after 2 h of reaction, confirming that choline glucoside is formed during the reaction. This observation points out a similar dehydration mechanism as that previously observed in the synthesis furfural from xylose.[17] One can mention that starting from fructose, choline fructoside is not observed (Figure S1). Indeed, choline fructoside could not be obtained by reaction of chloroethyl fructoside with trimeth-

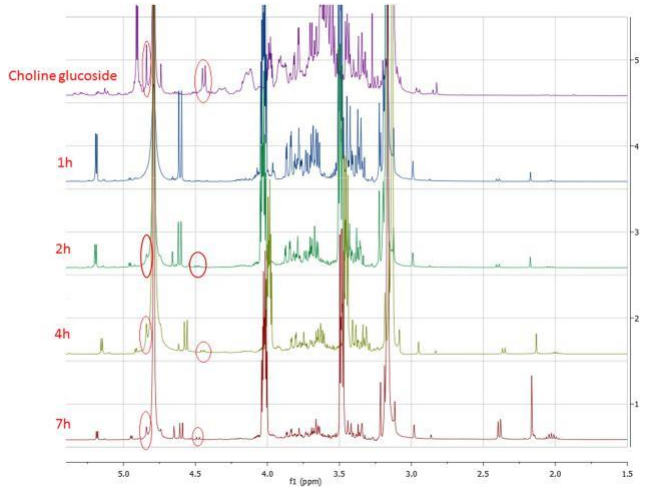


Figure 2. ^{1}H NMR spectra of the reaction system during the conversion of glucose to HMF. Conditions: 1 g of glucose, 1.2 g of ChCl, 2 g of aqueous HCl (pH = 1.28), 40 of g MIBK, 120 °C.

ylamine, showing a radically different reactivity of fructose as compared to glucose in the presence of ChCl.

We further studied the effect of the temperature. The HMF yield increases to 67 % after 1 h at 180 °C in the presence of ChCl, whereas the glucose conversion is complete after only 30 min. This result reinforces the benefits of the ChCl H_2O MIBK system for preparing HMF starting from concentrated glucose. Based on these results, we investigated the conversion of cellulose to HMF. A balance is required between cellulose depolymerization and glucose degradation. To avoid glucose degradation, cellulose depolymerization was performed by ball milling, a technique that was already applied by our team.[28] Two types of acids were used, i. e. sulfuric acid and Aquivion® PW98. Aquivion® PW98 is a perfluorosulfonic acid ionomer with a proton exchange capacity of 1.0 mmol/g. Aquivion® PFSA PW98 is a solid superacid with a Hammett acidity function of 12 which is similar to that of H_2SO_4. This solid was chosen since it is efficient in the synthesis of cello-oligosaccharides from cellulose as was demonstrated previously in our group.[28] The ball milling was performed using a Retch PM 100 at 200 rpm for 24 h. In the case of sulfuric acid, 10.7 wt
% relative to cellulose was used. Typically, cellulose was suspended in 15 ML of diethylether with the acid solution. The solvent was removed using vacuum and the cellulose was milled. The recovered acidified low molecular weight cellooligo-saccharide (0.15 g) with H_2SO_4 was added to 0.2 g of ChCl, 1 g of water, 5 mol% of $AlCl_3$ and 6 g of MIBK at 180 °C. The results were compared to the ball milled cellulose with Aquivion® PW98 (1.5 mol% of H^+). (Figure 3). The HMF yield reaches 26% and 34%, respectively. These results demonstrate that ChCl can be used to prepare HMF starting from a high concentration feed of glucose or ball milled cellulose. One can mention that choline chloride can be recovered using the experimental procedure used for the synthesis of furfural from xylose.[17]

Aldol condensation of HMF with MIBK

Next, we studied the aldol condensation of a commercial HMF with MIBK over 20 wt% of BaO using different solvents, targeting the synthesis of 1-(5-(hydroxymethyl)furan-2-yl)-5-methylhex-1-en-3-one (product **1**, Table 1). With only MIBK, no HMF conversion is observed (Table 1, entry 1). This result shows that the aldol condensation reaction cannot be conducted just after HMF synthesis. This result matches earlier results in the solvent-free condensation of cyclopentanone and furfural.[29] Indeed, weak bases cannot activate cyclopentanone to form enolate which is necessary for condensation. It is known that water pre-adsorption can transform Lewis basic sites into hydroxyl groups, increasing the activity for acetone self-condensation, while a very high water amount inhibits the reaction.[30] Thus, water formed during the aldol condensation reaction can condition the selectivity during the reaction by limiting the self-aldol condensation of the ketone.

Different solvents were added to the HMF/MIBK solution at a HMF/MIBK/solvent weight ratio of 1: 10: 10 using 20 wt% of BaO (Table 1). Adding 2-propanol, full HMF conversion is achieved with 38 % selectivity to product **1** (Table 1, entry 2). Using acetonitrile (MeCN), no aldol product is observed due to formation of humins (Table 1, entry 3).[31] In DMSO, full HMF conversion is obtained with 36 % selectivity to **1** (Table 1, entry 4). In this case, the lack of selectivity can be attributed to the formation of by-products such as humins.[31,32] Depending on the solvent used, the HMF can react or not with MIBK in order to produce the product **1**. It can be point out that the degradation probably occur from HMF since this compound was less stable than the aldol product **1**. Finally, ethanol affords 82 % selectivity at full HMF conversion **(**Table 1, entry 5). BaO is slightly soluble in ethanol and 2-propanol, but is completely heterogeneous in the other solvents. The reaction is more selective in ethanol than in 2-propanol despite the lower solubility. These results show that the BaO solubility does not directly correlate to the selectivity of product **1**, but the solvent may help to control secondary reactions leading to humins. Consequently, using an appropriate solvent, the reaction can be favored over BaO and the selectivity of the reaction can be controlled.

A series of alkaline earth metal oxides were further screened at 120 °C in ethanol using 20 wt% of catalyst starting from 1 g of HMF in 20 g of MIBK/ethanol mixture at a MIBK/EtOH weight ratio of 1: 1 (Table 2). Without catalyst and using CuO, MnO or ZnO, no HMF conversion is observed. Over MgO and Al_2O_3, the HMF conversion is 14 % and 4%, respectively, with 4% and 1%

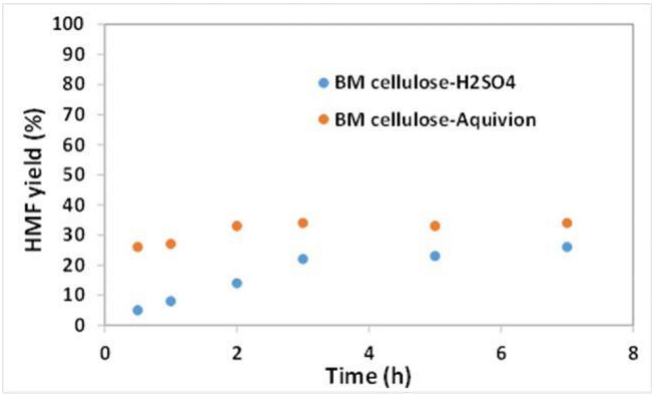
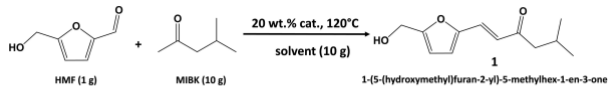


Figure 3. Conversion of ball milled cellulose to HMF. Conditions: 0.15 g of ball milled cellulose, 0.2 g of ChCl, 1 g of H_2O, 6 g of MIBK, 180 °C.

Table 1. Effect of the solvent on the aldol condensation of HMF with MIBK.

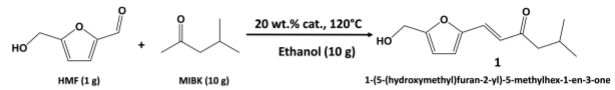


Entry	Solvent	HMF conv. [%]	Selectivity of **1** [%]	BaO solubility [wt.%]
1	–	0	0	
2	2-Propanol	100	38	8
3	MeCN	100	0	0
4	DMSO	100	36	0
5	EtOH	100	82	4

Conditions: 1: 10: 10 HMF/MIBK/solvent weight ratio, 20 wt% of BaO, 120 °C, 1 h.

)

Table 2. Effect of the alkaline metal oxide on the aldol condensation of HMF with MIBK.



Entry	Catalyst	Time [h]	HMF conv. [%]	Yield of **1** [%]
1	–	16	0	0
2	CuO[a]	16	0	0
3	MnO[c]	16	0	0
4	ZnO[b]	16	0	0
5	MgO[b]	16	14	4
6	Al_2O_3[b]	16	4	1
7	CaO [a]	16	97	79
8	BaO[a]	1	100	82

Conditions: 1: 10: 10 HMF/MIBK/ethanol weight ratio, 20 wt% of catalyst, 120 °C, [a] no treatment; [b] treated under air at 500 °C during 6 h; [c] treated under air at 600 °C during 6 h.

yield of product **1**. A much higher HMF conversion (over 97 %) is achieved over CaO and BaO after 16 h and 1 h reaction, respectively. The yield of product **1** is around 80 % over both catalysts. The yield of aldol product **1** evolves in the order: CuO=MnO=ZnO < Al_2O_3 < MgO < CaO ◆ BaO. One can mention that the catalysts were calcinated under air. However in the case of BaO and CaO the results were similar with or without treatment. That is the reason why no treatement was applied for the further studies using these two catalysts. The difference in the activity of these oxides can be ascribed to the difference in active species and basicity (see below).

Given these results, the kinetic profiles of the reaction were measured over both CaO and BaO (Figure 4) (timescale in h for CaO and in min for BaO). The initial reaction rate was calculated as the number of moles of HMF converted per mole of catalyst per h at time zero. CaO shows an initial reaction rate of 0.35 h^{-1}, whereas that of BaO is 26.30 h^{-1}. Over CaO, it was necessary to extend the reaction time to 16 h to reach 97 % yield of product **1**. In contrast, over BaO, the yield of **1** is above 90 % after 1 h. These results confirm the higher activity of BaO compared to CaO.

BaO and CaO were further characterized to rationalize their different activity. The basicity of both catalysts was measured by CO_2-TPD (Figure 5). CaO exhibits a desorption band at 604 °C with a CO_2 uptake of 63.4 $\mu mol_{CO2}/g_{cat}$ ascribed to strong basic sites as reported in the literature [34]. BaO exhibits two desorption bands centered at 400 °C and 603 °C, pointing out a combination of sites with moderate and strong basicity. BaO contains a higher density of strong basic sites compared to CaO (109.3 $\mu mol_{CO2}/g_{cat}$ at around 600 °C), with a total amount of sites about 258.4 $\mu mol_{CO2}/g_{cat}$, matching earlier reports.[33] A density of 149.1 $\mu mol_{CO2}/g_{cat}$ of moderate basic sites is present for BaO whereas no moderate basic sites was observed for CaO. In this view, the higher activity of BaO can be correlated to a moderate density of strong basic sites.

The specific surface area of CaO and BaO powder, as measured from N_2 physisorption, is 23 m^2/g and below 5 m^2/g, respectively. HR-TEM shows partial agglomeration, with elementary particles in the range 20–50 nm (Figure S2). BaO shows

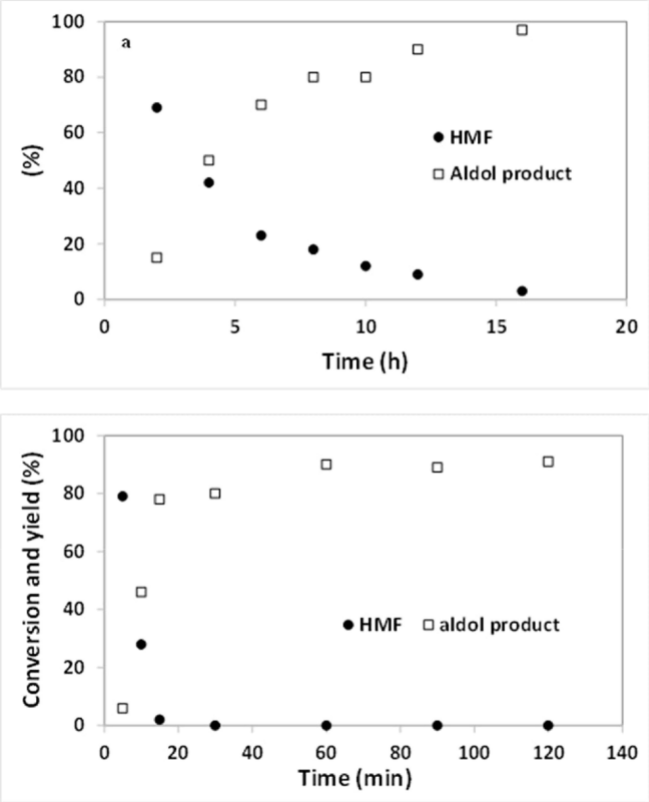


Figure 4. Kinetic profile of the aldol condensation of HMF with MIBK. Conditions: 1 g of HMF, 1 : 10: 10 HMF/MIBK/ethanol weight ratio, 20 wt.% of (a) CaO and (b) BaO, 120 °C.

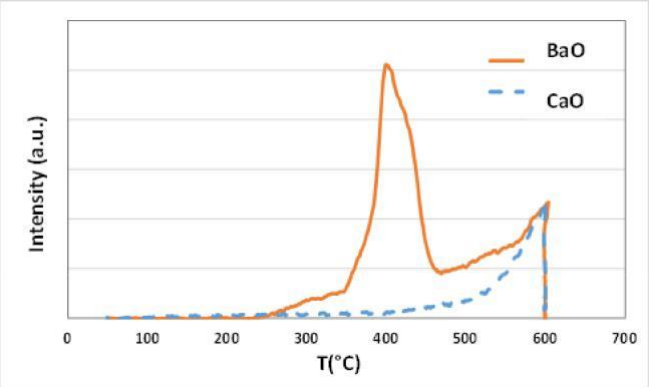


Figure 5. CO_2-TPD profiles (normalized by the sample mass) of CaO and BaO.

larger elementary particles (range from 500 to 2000 nm) due to particle agglomeration (Figure S3). The BaO sample is com-posed of different phases (upon exposure to air), including $Ba(OH)_2$ and BaO_2 while CaO includes CaO, $CaCO_3$ and $Ca(OH)_2$, as inferred from XRD (Figures S4–S5). Noteworthy, under air, BaO is not carbonated, preventing deactivation of basic sites. Moreover, it is known that $Ba(OH)_2$ is more basic than Ca-$(OH)_2$.[33] allowing better operation in the presence of water, as is the case of aldol condensation reactions since water is generated *in situ during the reaction.* The catalytic performance

BaO was studied in a second run with or without calcination at 300 °C after separation form the reaction mixture by centrifuga-tion and filtration. Although no product **1** is observed, a total conversion of HMF was obtained (Table S1). A complex mixture of by-products was generated, which could be hardly identified. XRD analysis of the spent catalyst show that the main species present are BaO_2 (Figure S5). Thus, $Ba(OH)_2$ are no longer present on the catalyst. This can be due to the dissolution of $Ba(OH)_2$ in the reaction media and thus these species were not recovered and the catalyst was not selective to the targeted product.

We also investigated the scope of BaO for the aldol condensation of HMF with other ketones (i. e. acetone, 2-heptanone) at comparable reaction conditions. The HMF conversion is complete for both ketones with 90 % yield of the aldol product after 15 min and 10 min for acetone and 2-heptanone, respectively.

Table 3 compares the catalytic performance of CaO and BaO with reported solid basic catalysts for the aldol condensation of HMF with acetone. CaO is slightly less active than BaO and the selectivity of the aldol product is 71 % (Table 3, entry 1). BaO, $Cu/MgAl_2O_4$ and $Zr(CO_3)_x$ lead to full HMF conversion and a high selectivity to the aldol product, above 86 % (Table 3, entries 2–4). The remaining listed basic catalysts (MgO ZrO_2, Ni NaY, MgZr, MgAl) exhibit lower HMF conversion and aldol product selectivity (Table 3, entries 5–8). Among the different catalysts, BaO displays the highest activity with 159 $mmol.g^{-1}.h^{-1}$. Overall, these results point out that BaO is an efficient and cost-effective catalyst for the aldol condensation of HMF with ketones.

Table 3. Comparison of the catalytic properties of CaO and BaO with catalysts reported in the literature for the aldol condensation of HMF with acetone.

Entry	Cat.	T [°C]	t [h]	HMF conv. [%]	Yield of aldol product [%]	Activity [mmol/g/h]
1 this study	CaO	120	5	89	63	7
2 this study	BaO	120	0.25	100	90	159
3 [11]	$MgAl_2O_4$	140	7	100	86	44
4 [9]	$Zr(CO_3)x$	54	24	100	92	0.21
5 [8]	MgO-ZrO_2	120	24	68	34	1.5
6 [8]	Ni-NaY	120	24	51	33	1.1
7 [10]	MgZr	50	24	68	14	0.03
8 [10]	MgAl	50	24	32	4	0.07

Synthesis of the aldol compound 1 from glucose

With these results in hand, we performed the synthesis of product **1** directly from glucose. To this aim, HMF was first prepared starting from 1 g of glucose, 1.2 g of ChCl, 2 g of an aqueous solution of HCl (pH = 1.28), 40 g of MIBK, 180 °C and 30 min. After the reaction, HMF was recovered by extracting the aqueous phase several times with MIBK using acetone to precipitate ChCl. The recovered HMF is not pure, since humins are also formed during this reaction as shown on Figure S11. Then, MIBK was partially removed using a vacuum rotavapor pump, and 10 g of fresh MIBK and 10 g of ethanol were added together with 200 mg of BaO. Then, the aldol condensation reaction was carried out at 120 °C for 1 h. After the reaction, ethanol and MIBK were removed under vacuum rotavapor pump. The results shows that product **1** was produced with only 2 % yield (GC analysis) with concomitant formation of many by-products that could be hardly identified. Moreover, slight acidity is still present after the first step that can be detrimental for the aldol condensation reaction. Traces of HCl (100 µL) was, thus, added at the beginning of the aldol condensation of commercial HMF with MIBK. 87 % of **1** was obtained showing that the acidity is not the main issue of the synthesis of **1** from glucose. The addition of $AlCl_3$ at the beginning of the aldol condensation of HMF with MIBK afforded a yield of 68% of **1**. This reaction shows that $AlCl_3$ should be fully removed in order to avoid any poisoning of BaO. An experiment was carried out using 1: 2: 2 synthesized HMF/MIBK/ solvent weight ratio in order to increase the concentration of HMF in the solvent and 20 wt.% of BaO. The reaction of aldol condensation was carried out at 120 °C for 2 h and 5% of **1** was observed. 20 wt% of BaO was further added to this reaction media and we were pleased to see that 22 % of aldol product **1** was obtained after 3 h of reaction at 120 °C which shows that BaO is poisoned by compounds that are still present in the synthesized HMF which can be some traces of $AlCl_3$. Thus another catalyst should be used for the synthesis of HMF in order to avoid any poisoning of BaO. This will be the topic of further investigation in our group.

Conclusion

We showed along this study that ChCl can help to selectively convert highly concentration feeds of glucose and ball milled cellulose into HMF by the formation of an intermediate choline glucoside. In parallel, the aldol condensation of HMF with MIBK (and other ketones) could be performed over BaO using ethanol as a co-solvent. BaO exhibits a competitive activity and high selectivity to 1-(5-(hydroxymethyl)furan-2-yl)-5-methylhex-1-en-3-one, compared to earlier reported solid basic catalysts. The recyclability of the catalyst was not possible, and when the reaction is performed in two steps starting from a highly concentrated feed of glucose, the yield of the aldol product is about 20 %. This yield was due to a poisoning of BaO by some traces of $AlCl_3$.

Experimental Section

Chemicals

Glucose (≥ 99%), MCC cellulose (Avicel), HCl (36.5-38.0 %), Choline chloride (≥ 99%), HMF (99%), 4-Methyl-2-Pentanone (≥ 99 %, FCC), $AlCl_3$, were all purchased from Sigma–Aldrich. CaO were purchased from sigma Aldrich and BaO from Acros Organic.

General procedure for the dehydration of glucose or cellulose to HMF

A mixture of glucose or ball milled cellulose in acidified water (pH = 1.28 measured at room temperature, 250 µL of an aqueous solution of HCl (37 wt.% in 250 mL of water), ChCl, $AlCl_3$ (5 mol.%) and methylisobutylketone (MIBK) with a weight ratio of acidified water: MIBK of 1 : 20 was heated at the desired temperature in a close reactor. The reaction was performed under biphasic con-dition.

General procedure for aldol condensation reaction

The catalytic tests were performed in a 30-mL tubular glass reactor with a sealable arrangement on top. The reaction was performed using a mixture of 5-hydroxymethylfurfural/ketone/EtOH with a weight ratio of 1 :10 : 10) over 20 wt.% of catalyst in a glass tube placed in a preheated oil bath (120 °C) at 600 rpm. The solvent was evaporated and a brown liquid was obtained.

Analytical methods

Glucose was quantified by external calibration at 25 °C by high-performance liquid chromatography using a Shimadzu HPLC equipped with a NH_2 column, a RID detector, and using a mixture of water/acetonitrile (3: 7) as mobile phase (0.8 mL.min ^{1}). HMF was also analyzed by HPLC at 25 °C using an ICECoregel107H column (300 ×8 mm), a Varian Prostar UV V detector (284 nm), and Varian Prostar pumps (model 210), and 7 mmol of sulfuric acid in water as a mobile phase (0.8 mL.min ^{1}). 1-(5-(Hydroxymethyl)furan-2-yl)-5-methylhex-1-en-3-one was analyzed and quantified by gas chromatography on an Agilent GC equipped with a HP-5 capillary column with 5 wt% phenyl groups, a FID detector, and a split/splitless injector. N-dodecane was used as internal standard The calibration curve of the hydroxymethyl)furan-2-yl)-5-methylhex-1-en-3-one is represented on Figure S6. NMR spectra were recorded on a Bruker Advance DPX 400 spectrometer. The samples were collected periodically for analysis. ^{1}H and ^{13}C NMR analysis were performed on all the aldol products using d-DMSO as a solvent (Figure S7–10).

Characterizations of the catalyst

Nitrogen adsorption-desorption isotherms were measured at 77 K were measured on a TriStar 3000 instrument to determine specific surface area using the multipoint Brunauer-Emmet-Teller (BET) method. Prior to the measurements, the samples were outgassed at 300 °C on a Micromeritics VacPrep061 to remove adsorbed water and vapors. CO_2-TPD analysis were performed using a Micromeritrics Autochem 2910 device. Before the CO_2-TPD experiment, the samples (50 mg) were treated *in situ* in a 50 ml/min O_2 flow at 200 °C for 2 h for BaO and 700 °C for 2 h for CaO, cooled down to 50 °C in a 50 ml/min He flow. The temperatures were chosen accordingly to the thermal analysis (Figures S5 and S6). The samples were exposed to CO_2 (20 ml/min) at that temperature for 60 min, kept again in a 50 ml/min flow of He for 30 min, cooled to 50 °C, and then heated from 50 °C to 600 °C in the He gas flow at a rate of 10 °C/min ^{1} while monitoring CO_2 desorption. HR-TEM analysis was performed on a JEOL JEM 2100 UHR equipped with a LaB6 filament with a punctual resolution of 0.19 nm. The samples were prepared in ethanol using a sonication bath, and some drops were deposited on a carbon grid (Holey Carbon grids). XRD analysis was performed using an EMPYREAN PANalytical Instrument with a CuK_α as x-ray radiation within 10–80° 2Θ angle with a step of 0.02° (2Θ) in all 2 s.

Acknowledgements

The authors acknowledge the ANR for the funding of the project FurCaB (ANR-15-CE07-0016). They are grateful to the region Nouvelle Aquitaine for the CPER and EU-FEDER support, to INCREASE Federation. They also thanks the Erasmus program for the grant allocated to Inés Rabadan Gonzales.

Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords: carbohydrates · aldol condensation · 5-hydroxymethylfurfural · BaO · Choline chloride

[1] E. Kwon, H. Yi, Y. J. Jeon, *Environ. Sci. Technol.* **2013**, *47*, 2817–2822.
[2] S. Siankevich, Z. Fei, R. Scopelliti, P. G. Jessop, J. Zhang, N. Yan, P. J. Dyson, *ChemSusChem* **2016**, *9*, 2089–2096.
[3] X. Zhang, K. Wilson, A. F. Lee, *Chem. Rev.* **2016**, *116*, 12328–12368.
[4] P. Bhanja, A. Bhaumik, *Fuel* **2016**, *185*, 432–441.
[5] Y. Queneau, B. Han, *The Innovation* **2022**, *3*, 100184.
[6] T. Wang, M. W. Nolte, B. H. Shanks, *Green Chem.* **2014**, *16*, 548–572.
[7] B. Saha, M. M. Abu-Omar, *ChemSusChem* **2015**, *8*, 1133–1142.
[8] H. Li, S. Yang, A. Riisager, A. Pandey, R. S. Sangwan, S. Saravanamurugan, R.Luque, *Green Chem.* **2016**, *18*, 5701–5735.
[9] W. Shen, G. A. Tompsett, K. D. Hammond, R. Xing, F. Dogan, C. P. Grey, W.C. Conner Jr., S. M. Auerbach, G. W. Huber, *Appl. Catal. A* **2011**, *392*, 57–68.
[10] J. Cueto, L. Faba, E. Díaz, S. Ordóñez, *Appl. Catal. B* **2017**, *201*, 221–231.
[11] K. Pupovac, R. Palkovits, *ChemSusChem* **2013**, *6*, 2103–2110.
[12] R. S. Malkar, H. Daly, C. Hardacre, G. D. Yadav, *ACS Sustainable Chem. Eng.* **2019**, *7*, 16215–16224.
[13] R. Lee, J. R. Vanderveen, P. Champagne, P. G. Jessop, *Green Chem.* **2016**, *18*, 5118–5121.
[14] M. Qiu, C. Bai, L. Yan, F. Shen, X. Qi, *ACS Sustainable Chem. Eng.* **2018**, *6*, 13826–13833.
[15] R. T. Woodward, M. Kessler, S. Lima, R. Rinaldi, *Green Chem.* **2018**, *20*, 2374–2381.
[16] see this review for instance. Kaur, Ramandeep; Kaur, Puneet, *Cellul. Chem. Technol.* **2021**, *55*, 207–222.
[17] S. Jiang, C. Verrier, M. Ahmar, J. Lai, C. Ma, E. Muller, Y. Queneau, M. Pera-Titus, F. Jérôme, K. De Oliveira Vigier, *Green Chem.* **2018**, *20*, 5104– 5110.
[18] A. Nielsen, W. Houlihan, *Org. React.* **2011**, *16*, 1–438.
[19] a) K. Tanabe, N. Yoshii, H. Hattori, *J. Chem. Soc. Chem. Commun.* **1971**, *78*, 464–465; b) F. Figueras, J. Lopez, J. Sanchez-Valente, T. T. H. Vu, J. M. Clacens, J. Palomeque, *J. Catal.* **2002**, *211*, 144–149.
[20] a) M. J. Climent, A. Corma, S. Iborra, J. Primo, *J. Catal.* **1995**, *151*, 60–66; b) M. T. Drexler, M. D. Amiridis, *Catal. Lett.* **2002**, *79*, 175–181.
[21] A. Corma, S. Iborra, J. Primo, F. Rey, *Appl. Catal. A* **1994**, *114*, 215–225.
[22] H. Kabashima, H. Tsuji, H. Hattori, *Appl. Catal. A* **1997**, *165*, 319–325.
[23] T. Seki, H. Kabashima, K. Akutsu, H. Tachikawa, H. Hattori, *J. Catal.* **2001**, *204*, 393–401.
[24] a) C. Noda, G. P. Alt, R. M. Werneck, C. A. Henriques, J. L. F. Monteiro, *Braz. J. Chem. Eng.* **1998**, *15*, 120–125; b) G. Zhang, H. Hattori, K. Tanabe, *Appl. Catal.* **1988**, *36*, 189–197; c) A. M. Frey, T. van Haasterecht, K. P. de Jong, J. H. Bitter, *ChemCatChem* **2013**, *5*, 3621–3628.
[25] D.-W. Lee, Y.-M. Park, K.-Y. Lee, *Catal. Surv. Asia* **2009**, *13*, 63–77.

[26] S. Li, F. Chen, N. Li, W. Wang, X. Sheng, A. Wang, Y. Cong, X. Wang, T. Zhang, *ChemSusChem* **2017**, *10*, 711–719.
[27] K. Erfurt, I. Wandzik, K. Walczak, K. Matuszek, A. Chrobok, *Green Chem.* **2014**, *16*, 3508–3514.
[28] a) F. Boissou, N. Sayoud, K. De Oliveira Vigier, A. Barakat, S. Marinkovic, B. Estrine, F. Jérôme, *ChemSusChem* **2015**, *8*, 3263–3269; b) A. Karam, K. De Oliveira Vigier, S. Marinkovic, B. Estrine, C. Oldani, F. Jérôme, *ChemSusChem* **2017**, *10*, 3604–3610.
[29] Q. Deng, J. Xu, P. Han, L. Pan, L. Wang, X. Zhang, J.-J. Zou, *Fuel Proces. Technol.* **2016**, *148*, 361–366..
[30] D. Tichit, M. N. Bennani, F. Figueras, R. Tessier, J. Kervennal, *Appl. Fuel Proces. Technol.* **2016**, *148*, 361–366.
[31] O. Kikhtyanin, D. Kadlec, R. Velvarská, D. Kubička, *Clay Sci.* **1998**, *13*, 401–415.
[32] H. Shen, H. Shan, L. Liu, *ChemSusChem* **2020**, *13*, 436.
[33] J. H. Park, D. J. Min, *Metall. Mater. Trans. A* **1999**, *30B*, 689–694.
[34] B. Zhao, J. Wang, D. Zhu, G. Song, H. Yang, L. Chen, L. Sun, S. Yang, H. Guan, X. Xie, *Catalysts* **2019**, *9*, 757.

)