


Review

Catalytic Conversion of Carbohydrates to Furanic Derivatives in the Presence of Choline Chloride

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Abstract: The synthesis of furanic derivatives (5-hydroxymethylfurfural (HMF), furfural . . .) from carbohydrates is of high interest for a wide range of applications. These reactions are carried out in the presence of various solvents, and among them choline chloride can be used. It is a salt that can form a low melting mixture with a carbohydrate (fructose, glucose . . .) or a deep eutectic mixture with carboxylic acid. A review of the studies performed in the conversion of carbohydrates to furanic derivatives in the presence of choline chloride is presented here with the advantages and drawbacks of this solvent. Choline chloride can enhance the selectivity to HMF by stabilizing effect and allows the conversion of highly concentrated feed. However, the extraction of the products from these solvents still needs improvement.

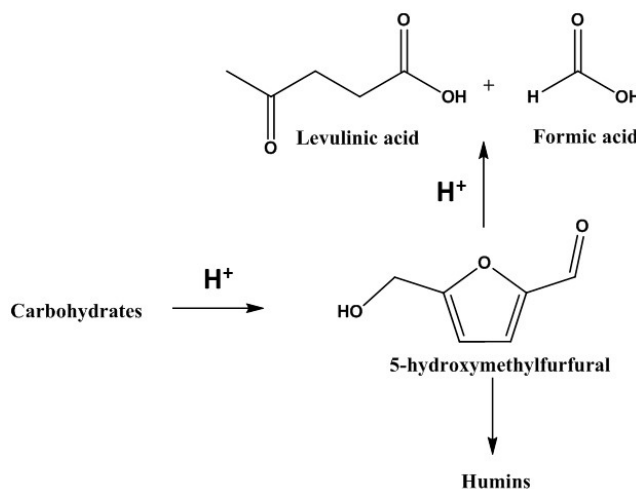
Keywords: carbohydrates; furanic derivatives; choline chloride; low melting mixture; deep eutectic solvent

1. Introduction

With the depletion of fossil reserves and environment concerns related to global warming, a lot of studies are devoted to the synthesis of fine chemicals or fuels from biomass [1,2]. Lignocellulosic biomass is mostly composed of carbohydrates (75%) and represents a huge reservoir of renewable carbon with an annual production estimated at 180 billion metric tons. Biobased chemicals production is challenged by an overabundance of targets. Currently, the industrial demand for new processes/technologies is very high—not only to open novel markets, but also to decrease the cost of bio-derived chemicals, which remain the main bottlenecks limiting their industrial emergence. Among these bio-based chemicals, furanic compounds produced from carbohydrates are of prime interest. 5-Hydroxymethylfurfural (HMF), furfural, and 2,5-furandicarboxylic acid indeed appear in the TOP 10 + 4 described by Bozell [3]. HMF is an interesting compound for the production of monomers, pharmaceuticals, flavors and fragrances, natural products, and fuel components, while furfural can be used as a chemical platform molecule in the manufacture of fuel additives, solvents, polymers, surfactants, perfumes, and pharmaceutical and agrochemical ingredients [1].

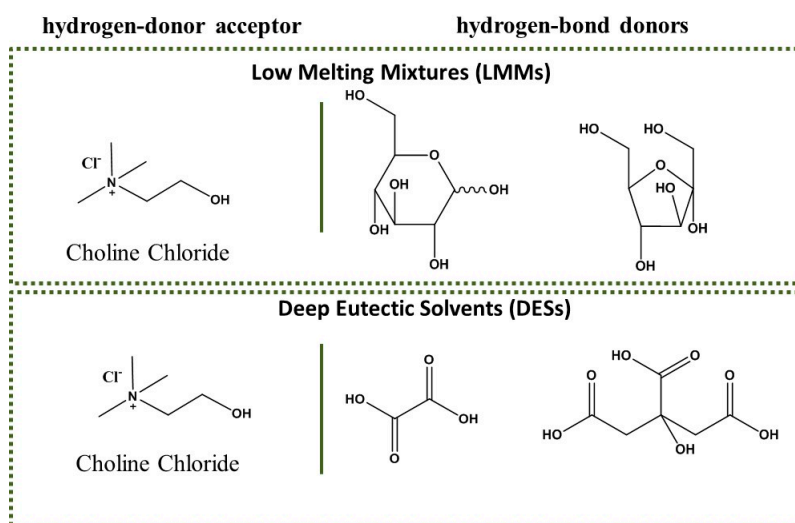
The synthesis of these furanic derivatives is carried out in the presence of homogeneous or heterogeneous acid catalysts. Numerous reviews can be found in the literature on the synthesis of furfural and HMF [4–6]. However, despite extensive literature devoted to the synthesis of furanic derivatives, purification and selectivity issues still hamper further industrialization. For example, in the case of HMF, many secondary reactions can occur, such as the rehydration of HMF to formic and levulinic acids, the condensation of HMF to produce humins, a black solid material (Scheme 1), leading to a lack of selectivity or eco-efficiency in its production/transformation. Moreover, the high dilution of carbohydrate solutions limits the development of application at an industrial level for its derivatives. All these drawbacks are difficult to control by the nature of the catalysts. However, depending on the nature of the solvent used in the synthesis of derivative furanic compounds, the selectivity can

be increased. Many studies were devoted to the use of a biphasic media (water/organic solvent) to prevent further rehydration of HMF. Despite an increase in the selectivity to HMF, the concentration of carbohydrate solutions was in most cases below 20 wt %.



Scheme 1. Secondary reactions in the synthesis of 5-hydroxymethylfurfural (HMF) from carbohydrates.

One interesting class of solvents that was used in the conversion of carbohydrates to furanic derivatives is deep eutectic solvent (DES) [7] and low melting mixtures (LMMs) [8]. The concept of natural deep eutectic solvents was first introduced by Abbott et al. in 2003 [9]. In this study, the formation of a eutectic mixture liquid was obtained by mixing two solid organic compounds: choline chloride (ChCl) and urea in a 1:2 molar ratio. In general, DES is formed as a result of hydrogen-bonding interactions between two components. Therefore, one of the constituents is a hydrogen-bond acceptor (usually ChCl or NH_4Cl), whereas the other constituent is a hydrogen-bond donor like natural polyols (glycerol), carboxylic acids (lactic acid (*Lac*), oxalic acid, citric acid) or ureas [7,8,10–17]. If carbohydrates are used as hydrogen-bond donors with ChCl, the name used is “low melting mixtures” (Scheme 2). One can note that these solvents are recognized as biodegradable and biorenewable solvents for most of them.



Scheme 2. Examples of LMMs and DESs.

Here we wish to report a review on the use of ChCl in the catalytic conversion of carbohydrates to furanic derivatives. We wish to show the effect of this hydrogen-bond acceptor to the selectivity to furanic derivatives by preventing secondary reactions in the presence of different catalysts. Moreover, concentrated solutions of carbohydrates can be used in DES or LMM reaction media. The benefits and the drawbacks of the use of this salt will be reported. Several catalysts were used in the presence of ChCl such as Lewis acids, Brønsted acids (homogeneous or heterogeneous) and heteropolyacids. In some studies, DESs composed with ChCl and a carboxylic acid were used as a solvent and an acid source.

2. Synthesis of Furanic Derivatives in the Presence of ChCl (LMM) and a Catalyst

Many studies have reported on the synthesis of furanic derivatives from fructose, glucose, sucrose, and inulin in the presence of choline chloride. The association of choline chloride with one of these carbohydrates leads to the formation of a low melting mixture which is liquid, sometimes at room temperature, allowing the acid-catalyzed conversion of carbohydrates to furanic derivatives.

2.1. Lewis Acids as Catalysts

Lewis acids were investigated in the synthesis of HMF from carbohydrates (Table 1).

Table 1. Synthesis of HMF in the presence of different Lewis acids and choline chloride (ChCl)-derived LMMs [18,19].

Catalysts	Yield to HMF (%)	
	Fructose/ChCl	Glucose/ChCl
FeCl ₃	59	15
ZnCl ₂	8	6
CrCl ₂	40	45
CrCl ₃	60	31
AlCl ₃ ·6H ₂ O	-	70 ¹

¹ Water was added to ChCl-Glucose LMM.

König et al. have studied various Lewis acid catalysts (e.g., FeCl₃, ZnCl₂, CrCl₂) in the conversion of carbohydrates (fructose, glucose, inulin, and sucrose) to HMF [18]. From all carbohydrates investigated, FeCl₃ led to low HMF yield (below 10%). In a mixture of fructose and ChCl (4:6) at 100 °C, CrCl₃ and FeCl₃ led to 60% of HMF after 0.5 h of reaction, whereas 40% were observed in the presence of CrCl₂. From glucose, the best catalyst was CrCl₂ with 45% production of HMF. No explanation on this catalytic activity difference was given in this study. The direct conversion of carbohydrates such as sucrose and inulin to HMF (tandem hydrolysis/dehydration), was also investigated. The authors have shown that 62% of HMF was obtained from sucrose after 1 h of reaction at 100 °C in the presence of CrCl₂ and 46% of HMF was produced from inulin in the presence of CrCl₃ at 90 °C for 1 h. As observed in the presence of fructose, insoluble humins were obtained upon prolonged reaction time or temperature higher than 100 °C. The authors have studied the environmental effects of several solvent systems, such as water, dimethylformamide, dimethyl sulfoxide, acetone/dimethyl sulfoxide, [C₂mim]Cl, [C₄mim]Cl, ethyl acetate/choline chloride/citric acid, and choline chloride. They have shown that in the conversion of carbohydrates into HMF, advantages of the melt systems are in terms of low toxicity and reduced the environmental impact into air due to their negligibly low vapor pressure as well as the inherent low toxicological impact. The authors have also stated that the development of efficient recycling strategies should be addressed for further work, and the use of multiphase reaction systems might be beneficial concerning ecological as well as economic issues.

In many studies, HMF was extracted in a continuous mode from ChCl-derived low melting mixtures using an organic solvent such as methylisobutylketone (MIBK) to limit the formation of

humins and other by-products. For example, Liu et al. have studied the conversion of glucose to HMF in the presence of various Lewis acid catalysts in water and MIBK mixture [19]. MIBK was used to continuously extract HMF. The conversion of glucose was 90%. The authors have shown that the addition of choline chloride to water/MIBK system plays a key role, increasing the HMF yield to 70% in a mixture of ChCl/H₂O ratio of 1 in the presence of 3 mol % of AlCl₃·6H₂O at 165 °C after 3 h of reaction. When the ChCl/H₂O ratio was increased from 0 to 1, a gradual increase of the HMF yield was observed up to 70%, attributed to the beneficial effect of ChCl on the reaction selectivity. In this concentration range, the partition coefficient of HMF between the aqueous and MIBK phase did not vary (1.2). ChCl plays a role as a stabilizing agent of HMF, allowing high yield in HMF to be obtained. However, the extraction of HMF was more difficult in this case. When the ChCl/H₂O ratio was higher than 1, HMF yield decreased to 50% due to the side rehydration reaction, as depicted in Figure 1.

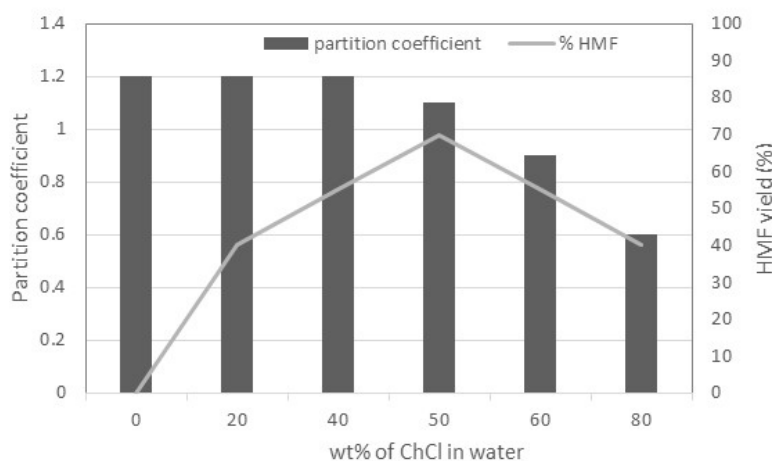
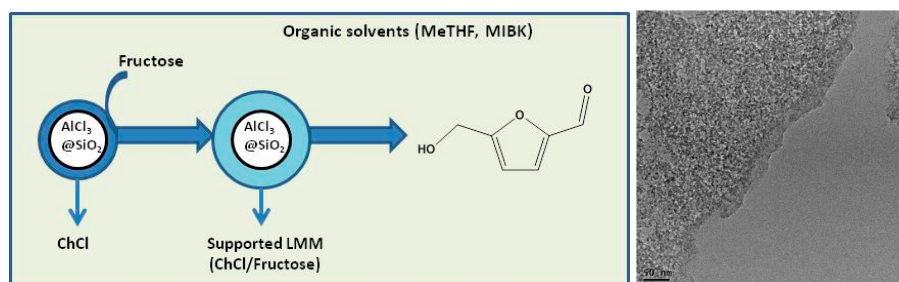


Figure 1. Effect of the wt % of ChCl on the partition coefficient and HMF yield in a H₂O/MIBK (methylisobutylketone) mixture.

A ChCl/H₂O mixture (1/1) was also investigated in the conversion of cellulose using MIBK as extraction solvent leading to 27% of HMF. When cellulose was ball-milled, an HMF yield of 46% was achieved in the presence of FeCl₃ and AlCl₃ as catalysts. In the conversion of cellulose to HMF, three elementary steps are required to convert cellulose to HMF. Thus, the average yield for each step is approximately 80%, showing the good selectivity of this process.

Based on this study, the same authors have investigated the heterogeneously catalyzed conversion of hexoses to HMF in low-boiling-point organic solvents such as methyltetrahydrofuran (MeTHF) and MIBK [20]. The use of these organic solvents limits the side rehydration of HMF and favors the recovery of HMF. However, carbohydrates are not soluble in these organic solvents. The authors have thus investigated the coating of a solid acid catalyst (AlCl₃@SiO₂) with ChCl (Scheme 3). This supported catalyst allowed the in situ formation of an LMM with hexoses on the catalyst surface, thus facilitating the contact between the two suspensions of silica and carbohydrates. They have shown that 51% of HMF was obtained in MeTHF (in the presence of 39 wt % ChCl on AlCl₃@SiO₂) and 65% of HMF in MIBK (in the presence of 17 wt % ChCl on AlCl₃@SiO₂). The recycling of AlCl₃@SiO₂ coated with ChCl was investigated. Despite the deposition of a small amount of fructose (2.8 mol %), HMF (1.3 mol %), and some humins, the authors have shown that it was recycled at least three times without significant change of its activity. This deposition did not hamper the activity of the AlCl₃@SiO₂ coated with ChCl catalyst. Thus, the AlCl₃@SiO₂ coated with ChCl was successfully recycled without significant decrease of activity owing to the insolubility of ChCl in MeTHF or MIBK. More than 95 wt % of produced HMF was recovered from MeTHF or MIBK phase because of the use of a catalytic amount of ChCl. Different carbohydrates, such as glucose, xylose, and inulin, were also converted to HMF with 38%, 43%, and 45% yield, respectively.



Scheme 3. Conversion of fructose to HMF in organic solvents (MIBK or methyltetrahydrofuran, MeTHF) using a supported LMM.

Recently, 5-chloromethylfurfural (CMF) was synthesized in a biphasic ChCl/MIBK system using metal chlorides as catalyst ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$). CMF was obtained in 50% yield along with 8% HMF at 120 °C in 5 h [21]. The authors have shown that HMF was produced in the LMM (ChCl/fructose) and was then extracted to the MIBK phase. The halogenation of HMF to CMF was catalyzed by HCl in situ generated in the MIBK phase by the hydrolysis of $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$. Yields of CMF higher than 50% CMF were obtained for a weight ratio of ChCl to fructose of four. A suitable content of ChCl promoted the conversion process from fructose to 5-CMF and high content of ChCl have a promoting function on the total yield of 5-HMF and 5-CMF. One can note that if MIBK was used as the extractant and formed a biphasic system, 5-CMF yield decreased significantly with an enhanced 5-HMF yield, due to the loss of HCl in the organic phase owing to the transfer of extraction solvent. The recycling of the catalyst and ChCl were studied, and a slight decrease of 5-CMF yield was observed in the successive two cycles. A 5-CMF yield of 41% and a 5-HMF yield of 12% were still achieved in the third run. Despite lower CMF yield compared to previous works, the major advantage of this study was that a combination of metal chlorides and ChCl was suitable for the conversion of fructose into CMF.

2.2. Brønsted Acids as Catalysts

Several Brønsted acid catalysts were used, and the different results are reported in Table 2.

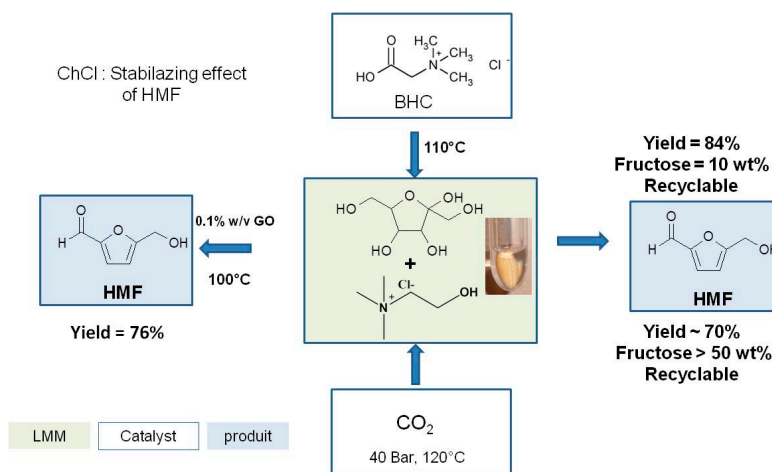
Table 2. Synthesis of HMF in the presence of different Brønsted acids and ChCl-derived LMMs from fructose [18,22–26]. BHC: betaine hydrochloride; GO: graphene oxide nanosheets; p-TSA: p-toluene sulfonic acid monohydrate; p-TsOH: p-toluenesulfonic acid.

	Brønsted Acids				
	p-TsOH	p-TSA	CO ₂	BHC	GO
Yield to HMF (%)	59	91	74	84	76

For example, König et al. have carried out the synthesis of HMF using p-toluenesulfonic acid (p-TsOH) and 59% of HMF was obtained in the presence of a mixture of fructose and ChCl (4:6) at 100 °C for 0.5 h [18]. The authors have also shown that 62% of HMF was obtained from sucrose after 1 h of reaction at 100 °C and 57% of HMF was obtained from inulin in the presence of p-TsOH at 90 °C for 1 h. Another study used p-toluene sulfonic acid monohydrate (p-TSA) to dehydrate fructose to HMF in ChCl [22]. Ninety-one percent of HMF was obtained from fructose at a feed ratio of 2.5 wt %, using a ChCl/p-TSA molar ratio of 1, a temperature of 80 °C, and 1 h of reaction. p-TSA acts as a catalyst but also as a hydrogen bond donor in this case. However, the separation of HMF from the ChCl/p-TSA was not evaluated in this study.

Another Brønsted acid studied was carbonic acid, generated in the presence of CO₂. F. Liu et al. showed that under pressure of CO₂, fructose and inulin can be converted to HMF in a ChCl/fructose LMM [23]. As previously shown by B. Han [24], CO₂ can form with water, carbonic acid that has

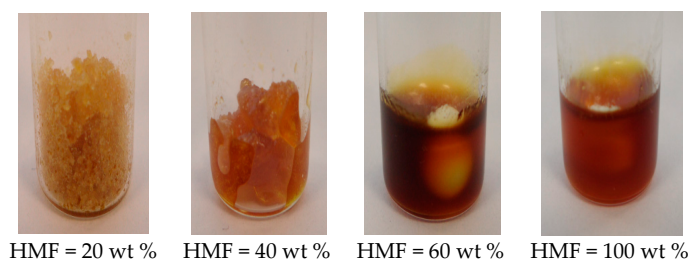
a pK_a low enough to catalyze the dehydration of fructose to HMF. CO_2 initially reacted with water contained in fructose and $ChCl$, resulting in the formation of carbonic acid in a sufficient amount to dehydrate fructose to HMF. A yield of 74% of HMF was obtained from 20 wt % of fructose at 120 °C under 4 MPa of CO_2 after 90 min of reaction (Scheme 4). At the end of the reaction (after release of the CO_2 pressure), more than 88% of HMF was extracted from the reaction medium with MIBK. When the catalytic reaction was carried out in a biphasic $ChCl$ -fructose/MIBK system, a significant drop of the yield of HMF from 74% to 52% was observed. This decrease in the HMF yield can be due to a higher solubility of CO_2 in MIBK than in $ChCl$ -derived LMM. Hence, in this case, the extraction of HMF should be performed only at the end of the reaction.



Scheme 4. Synthesis of HMF in the presence of recyclable Brønsted acid catalysts.

Remarkably, the present system was tolerant to very high loading of fructose (above 50 wt %) whereas most of reported solvents suffer from a low selectivity to HMF when the fructose loading was higher than 30 wt %.

The tolerance of this system to high loading of fructose was ascribed to strong interactions between produced HMF and $ChCl$, resulting in the stabilization of HMF in the reaction media. When neat HMF and $ChCl$ were mixed together, a melt was readily obtained at HMF content higher than 60 wt % (Scheme 5) which can explain the surprising stability of HMF. It is indeed known that a chemical's reactivity is drastically reduced when it is engaged in the formation of a eutectic mixture.



Scheme 5. Formation of a melting mixture of HMF and $ChCl$.

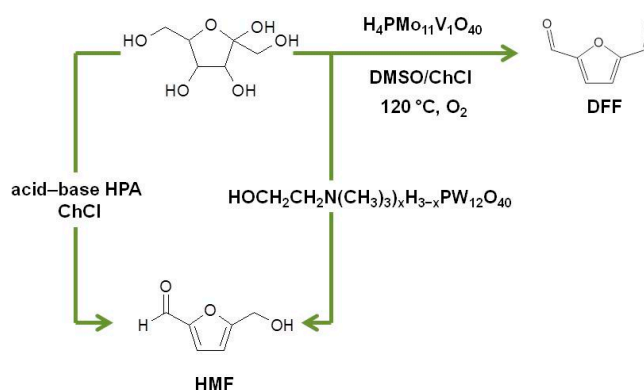
In 2012, De Oliveira Vigier et al. reported that betaine hydrochloride (BHC, a co-product of the sugar beet industry) in combination with $ChCl$ and water can act as an acid catalyst for the production of HMF from fructose and inulin (Scheme 4) [25]. BHC is an ionic, safe, cheap (3 € kg), and biodegradable carboxylic acid (metabolite of $ChCl$) with a pK_a of 1.9. In a $ChCl$ /BHC/water (10/0.5/2) mixture, HMF was produced with 63% yield (at 130 °C from 40 wt % of fructose). When the reaction was performed in a biphasic system using methylisobutylketone (MIBK) as an extraction

solvent, HMF was recovered with a purity higher than 95% (isolated yield of 84% from 10 wt % of fructose). Moreover, the ChCl/BHC/water system was successfully recycled up to seven times. ChCl helps in this study to dissolve carbohydrates and acts as a solvent.

All the previous studied were carried out in the presence of homogeneous catalysts. However, graphene oxide nanosheets (GO) was also investigated as a heterogeneous acid catalyst in this reaction performed under microwave irradiation (MW) (Scheme 4) [26]. HMF was extracted using ethyl acetate as an organic solvent. If ethyl acetate was solely used, no HMF was observed. However, 76% of HMF was produced from the dehydration of 2.5% *w/v* fructose in the presence of 0.1% *w/v* of GO, 1% *w/v* of ChCl at 100 °C for 30 min under MW irradiation. In neat ChCl without GO, 22% of HMF was reached indicating that GO acts as a catalyst in this process. If ChCl was replaced by another additive such as betaine hydrochloride, an HMF yield of up to 70% was achieved. BHC is an ionic, safe, cheap (3 E€ kg), and biodegradable carboxylic acid (metabolite of ChCl) with a pKa of 1.9. The authors have shown that in the presence of GO additives (BHC or ChCl), the HMF yield was highest when fructose was used as substrate, followed by glucose, sucrose, mannose, and galactose. The solvent was recycled and successfully reused. During the course of reaction, GO was reduced to produce six layered graphene nanosheets (96% recovery). In this study, the recycling of the catalyst was not evaluated. This study shows again the benefit of choline chloride or such salt in this reaction.

2.3. Heteropolyacids as Catalysts

In some studies, heteropolyacids (HPA) were used in combination with ChCl (Scheme 6).



Scheme 6. Synthesis of furanic derivatives in the presence of heteropolyacids (HPA). DFF: diformylfuran.

For example, a series of acid–base HPA ($(\text{C}_6\text{H}_{15}\text{O}_2\text{N}_2)_{3x}\text{H}_x\text{PW}_{12}\text{O}_{40}$) containing double NH_2 groups from amino acids as base functional groups and a $\text{H}_3\text{PW}_{12}\text{O}_{40}$ fragment as the acid one were investigated in the production of HMF from fructose in the ChCl solvent [27]. Up to 92% yield of HMF was obtained using $(\text{C}_6\text{H}_{15}\text{O}_2\text{N}_2)_2\text{H}_1\text{PW}_{12}\text{O}_{40}$ as a catalyst in ChCl within 1 min. It was reported that the enolisation of fructose was the rate-determining step of fructose dehydration. This study demonstrated that the co-existence of hydrogen-bond donors ($-\text{NH}_2$) and protons in $(\text{C}_6\text{H}_{15}\text{O}_2\text{N}_2)_2\text{H}_1\text{PW}_{12}\text{O}_{40}$ gave synergic potentials for the selective and efficient conversion of fructose to HMF. The catalyst was recovered after centrifugation and washing with water. It was then calcinated to dry for 4 h at 60 °C. The IR spectrum of the reused catalyst showed the stability of the catalyst with the four characteristics asymmetric stretching vibrational peaks of heteropolyanions (W–Od, W–Ob–W, W–Oc–W, and P–Oa). Thus, the catalyst was recycled six times without significant change in the catalytic activity. The total amount of leaching of $(\text{C}_6\text{H}_{15}\text{O}_2\text{N}_2)_{3x}\text{H}_x\text{PW}_{12}\text{O}_{40}$ catalyst was 5% of the starting materials after six runs.

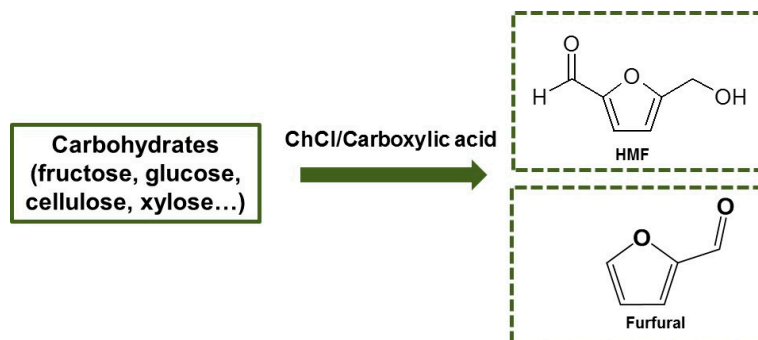
In another study, a series of heteropolyacid catalysts $(\text{HOCH}_2\text{CH}_2\text{N}(\text{CH}_3)_3)_x\text{H}_{3-x}\text{PW}_{12}\text{O}_{40}$, abbreviated as $\text{Ch}_x\text{H}_{3-x}\text{PW}_{12}\text{O}_{40}$, $x = 1, 2$, and 3) synthesized using choline chloride and $\text{H}_3\text{PW}_{12}\text{O}_{40}$

were used as heterogeneous catalysts in the conversion of cellulose to HMF in a solvent containing MIBK and water [28]. An HMF yield of 75% was achieved in the presence of $\text{ChH}_2\text{PW}_{12}\text{O}_{40}$ at 140 °C after 8 h of reaction in the presence of MIBK to extract HMF. This activity was ascribed to its thermoregulatory property. $\text{ChH}_2\text{PW}_{12}\text{O}_{40}$ is insoluble in water at room temperature, and its solubility in water increased with the increase of temperature from 60 to 140 °C. Therefore, $\text{ChH}_2\text{PW}_{12}\text{O}_{40}$ acts as homogeneous catalyst in higher temperature. Moreover, its moderate Brønsted acidity allows no further degradation of HMF to levulinic acid, and the extraction of HMF MIBK protects HMF from further degradation. Using this biphasic system, lignocellulosic biomass straw gave HMF yields of 28%. Moreover, such heteropolyacid catalyst was recycled up to 10 times by lowering the reaction temperature to room temperature without loss of its weight. More than 94% was recovered after 10 cycles, and the leaching of the catalyst was evaluated, showing only 0.1% of leaching amount. The IR spectrum of the catalyst showed that the Keggin structure was maintained.

Using a Mo-Keggin heteropolyacid catalyst, Ghezali et al. studied the direct conversion of fructose to diformylfuran (DFF) [29]. During this reaction, the acid and the oxidative sites of the catalysts were used to dehydrate fructose to HMF and to oxidize HMF to DFF. In this reaction, the authors have demonstrated that the substitution of DMSO by choline chloride led to a DFF yield of 84% at 120 °C after 6 h of reaction under 10 mL/min of O_2 . ChCl plays several roles, including the enhancement of the selectivity to HMF by stabilizing effect, but it also helps to solubilize oxygen. In this study, the catalyst was not recyclable, the main objective being the determination of the effect of ChCl in the synthesis of DFF from fructose.

3. Synthesis of Furanic Derivatives in the Presence of a DES Composed of ChCl and a Carboxylic Acid

Some studies were devoted to the use of ChCl associated with carboxylic acids to produce furanic derivatives in acidic DESs (Scheme 7).



Scheme 7. Synthesis of furanic derivatives in ChCl /carboxylic acid mixture (DESs).

Han and co-workers have synthesized HMF from fructose with 45%, 61%, and 84% selectivity in the presence of ChCl /malonic acid, ChCl /oxalic acid, and ChCl /citric acid monohydrate, respectively, at 80 °C for 1 h [30]. HMF was found to be relatively stable at this temperature, particularly in a mixture of ChCl /citric acid monohydrate. When ethyl acetate was used to extract HMF, 87% of HMF yield was observed in the presence of ChCl /citric acid monohydrate. HMF is soluble in ethyl acetate, while the solubility of ChCl -based DES and fructose in ethyl acetate is negligible. One can note that the HMF extraction was less than 65% due to the distribution of HMF between the DES and ethyl acetate. They have also studied the one pot conversion of inulin and 56% and 51% HMF yield were observed in the presence of, respectively, ChCl /oxalic acid or ChCl /citric acid [31]. The yield of HMF in the ethyl acetate/ ChCl /oxalic acid biphasic system was higher (64% vs. 56%) than in the absence of ethyl acetate. The DES phase was recycled (up to six cycles) directly after removing the ethyl acetate

phase containing HMF. These studies show that a DES can be an interesting solvent and catalyst for the conversion of carbohydrates to HMF.

Other DESs composed of choline salts and carboxylic acids (succinic acid, malic acid, glycolic acid, mandelic acid, salicylic acid, oxalic acid, benzoic acid) were investigated by Hara et al. in the conversion of glucose to HMF [32]. Boric acid $B(OH)_3$ was added as a promoter to isomerize glucose to fructose before the dehydration of fructose to HMF. Unfortunately, the HMF yields remained very low (below 5%) due to the formation of strong acid (probably HCl) in the reaction media, leading to condensation products such as humins when the reaction was carried out at 140 °C for 2 h in the presence of boric acid. To circumvent this result, ChCl was replaced by choline dihydrogen citrate, another inexpensive and commercially available choline salt. In this case, the mixtures were melted even at room temperature, except for benzoic acid. A HMF yield of 42% was achieved in the presence of glycolic acid/ChCl and $B(OH)_3$. The authors explained that the isomerization pathway from glucose to fructose goes through the complexation with $B(OH)_3$. The role of $B(OH)_3$ is dual: (i) to decrease the energy barrier for the formation of the intermediate species and (ii) to increase the exothermicity for the overall isomerization. When neat choline dihydrogen was used in the presence of $B(OH)_3$, the HMF yield was very low (7%), showing that carboxylic acids are required for the production of HMF since they are involved in the dehydration of fructose to HMF. The effect of the strength of the acid was investigated and they have demonstrated that the strength of the acid should be low to limit side reactions during the production of HMF. The authors have demonstrated that the addition of water positively impacted the formation of HMF—a yield of 60% being obtained at 140 °C for 4 h. However, no explanation was given on the exact role of water.

ChCl/citric acid DES containing $AlCl_3 \cdot 6H_2O$ was used to produce furfural from xylan or xylose by Zhang and Yu [33]. The synergistic effect between the Brønsted and Lewis acids led to the conversion of xylan and xylose to 59% and 54%, respectively, of furfural at 140 °C after 15 and 25 min of reaction. $AlCl_3 \cdot 6H_2O$ is supposed to catalyze the isomerization of xylose to xylulose, while citric acid promoted the dehydration of xylulose to furfural. As previously shown in various studies, if the reaction is carried out in a biphasic system (DES/methylisobutylketone), the furfural yield was increased to 73% and the DES phase containing $AlCl_3 \cdot 6H_2O$ was recycled at least five times. At temperature higher than 140 °C, the recycling was hampered by the degradation of the DES phase. No detail was provided on the leaching of Al in the reaction media.

Several eutectic mixtures such as choline chloride/urea, choline chloride/oxalic acid, choline chloride/betaine, and tetraethylammonium chloride were studied in the conversion of native cellulose and lignocellulosic residues into HMF and furfural (coming from the hemicellulose part of lignocellulosic biomass) [34]. The reaction was carried out at 170 °C for 2 min. The best HMF and furfural yields were attained for the ChCl/oxalic acid mixture. The authors have shown that depending on the eutectic mixtures, the nature of the DESs and the catalyst used are different. Thus, in the presence of ChCl/betaine eutectic mixture HMF and furfural yields of 23% and 4% were respectively achieved in the presence of KOH, without organic diluents. The ChCl/urea mixture led to very low yields in the conversion of native cellulose (below 2%), and the same happened to tetraethylammonium chloride when it is employed in combination with basic oxides. On the opposite, the use of a tungstic acid in the presence of tetraethylammonium chloride improved the yield (14%). HMF and furfural yields of 22% and 10%, respectively, were obtained in ChCl/oxalic acid mixture in the presence of TiO_2 (which is an amphoteric oxide), catalyst, and triethylene glycol as diluent. This result indicated that the density of acidic and basic sites is important for breaking down cellulosic chains and for the dehydration of glucose into HMF. Moreover, the authors have shown that the highest HMF yield is obtained at 200 °C, whereas the highest furfural yield is observed at 140 °C.

4. Conclusions

In all the studies reported, it was shown that choline chloride can be used as a solvent in the conversion of carbohydrates to furanic derivatives. In some studies, acid catalysts such as Lewis or

Brønsted acids can be used. In this case, a low melting mixture is formed between choline chloride and the carbohydrate. In other studies, the reaction is carried out in the presence of a deep eutectic mixture composed of choline chloride and a carboxylic acid. It was demonstrated that ChCl enhances the yield of furanic derivatives by stabilizing effect. As a consequence, furanic derivatives can be produced with high yield from high carbohydrates loading. Catalysts were recycled in most cases, showing the potential of such solvent. However, the main remaining challenge is the extraction of furanic derivatives from this reaction media. Hence, the solubility of HMF in ChCl-derived solvent can hamper its full extraction. Moreover, depending on the amount of ChCl used, the partition coefficient can change. This issue still needs to be addressed.

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