Catalytic hydroconversion of 5-HMF to value-added chemicals: insights into the role of catalyst properties and feedstock purity

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Abstract (up to 150 words)

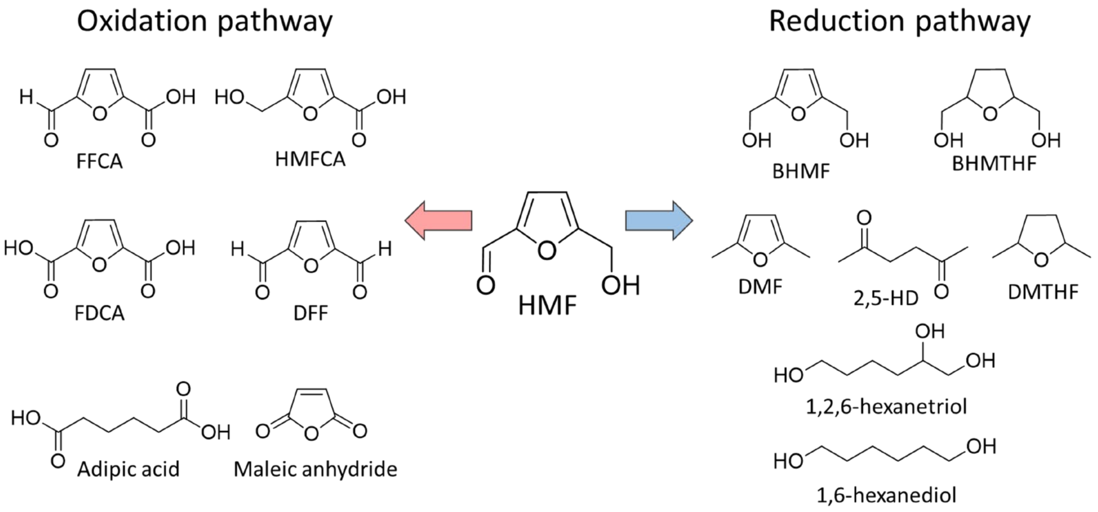
5-hydroxymethylfurfural (HMF) is an important bio-derived platform molecule that is generally obtained from hexoses via acid-catalyzed dehydration. It can be effectively transformed into a variety of value-added derivatives thus being an ideal candidate for fossil replacement. Both HMF oxidation and hydrogenation processes enable the synthesis of numerous chemicals, monomers for polymerization and biofuel precursors. This review summarizes the most recent advances in heterogeneous catalytic hydroconversion of HMF into valuable chemicals with strong focus on 2,5-bishydroxymethyl furan (BHMF), 2,5-bishydroxymethyltetrahydrofuran (BHMTHF), and 2,5-dimethyltetrahydrofuran (DMTHF). In addition, multifunctional catalytic systems that enable a tunable production of various HMF derived intermediates are discussed. Within this chemistry, the surprising impact of HMF purity on the catalytic performance, *viz*. selectivity and activity, during its upgrading is highlighted. Lastly, we summarize and discuss the remaining challenges in the field of HMF hydroconversion to mentioned chemicals, taking into account the knowledge gain of catalyst properties and feedstock purity.

1. Introduction

To reduce the worldwide dependency on non-renewable fossil resources and mitigate the growing environmental pollution and greenhouse gas emissions, it is crucial to develop future chemical industrial processes based on green and sustainable resources. Biomass is a renewable carbon source which possesses a unique combination of characteristics such as environmentally friendliness, low harvesting costs and abundancy. With shrinking cheap fossil resources, biomass is considered to be a perfect renewable substitute for the production of added-value chemicals, carbon-based functional materials or liquid fuels in a more sustainable manner.

Among several others, 5-hydroxymethylfurfural (HMF) is a vital and one of the most promising platform molecules, which can be readily obtained through dehydration chemistry from carbohydrates using acid catalysis.[1–5] Cellulose, sucrose, fructose, glucose, starch, inulin, and some other raw biomass materials are all suitable starting substrates for HMF preparation. However, the selectivity of carbohydrates-to-HMF conversion strongly varies depending on the substrate origin. Fructose generally provides the highest HMF yield due to its higher reactivity, *viz*. the enolisation rate in the solution, and the fact that most reactive groups are internally blocked in its cyclic occurrence, which ultimately leads to less by-products formation. Different approaches of HMF production from various biomass feedstock have been discussed widely in the scientific community.[6,7]

HMF conversion chemistry is extremely versatile and enables an alleyway to numerous useful monomers and chemicals. However, its intrinsic limitations e.g. low chemical stability and high oxygen content need be considered to increase its competitiveness in the sustainable development concepts.[8] Some of the most important chemicals that are produced from HMF are depicted in Scheme 1.



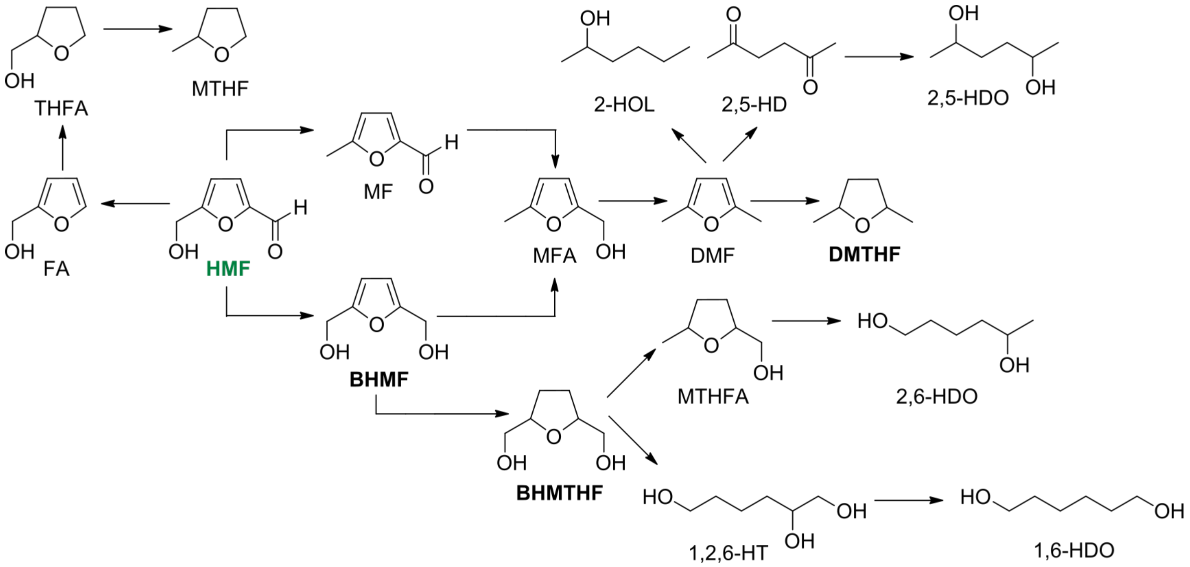
Scheme 1. Oxidation and reduction conversion of HMF into some value-added chemicals

For instance, HMF oxidation allows to produce such valuable furanic compounds as 2,5-diformylfuran (DFF), 5-hydroxymethyl-2-furancarbonxylic acid (HMFCA), 5-formyl-2-furancarboxylic acid (FFCA), 2,5-furandicarboxylic acid (FDCA), maleic anhydride (MA) and adipic acid, which are used for the synthesis of various biochemical compounds and bio-based polymers.[9] The reductive conversion of HMF provides the formation of such important chemicals such as 2,5-bishydroxymethyl furan (BHMF), 2,5-bishydroxymethyltetrahydrofuran (BHMTHF), 2,5-dimethylfuran (DMF), 2,5-dimethyltetrahydrofuran (DMTHF), 1,6-hexanediol (HDO), 1,2,6-hexanetriol (HT) and 2,5-hexanedienone (HD) which serve as green solvents and promising monomers for polymerization.[10] The catalytic upgrading of HMF towards numerous products via oxidation and reduction pathways has been summarized in previous works.[11–13] In the context of organic synthesis, the synthetic methodologies towards complex multifunctional HMF derivatives have also been covered in the literature.[14,15] Production of biofuels is another key pathway of HMF upgrading. Among mentioned chemicals, DMF is the most promising biofuel candidate due to its excellent combustibility, high energy density, low volatility, and low water solubility, while being renewable.[16] Several outstanding reviews on the production of HMF-derived biofuels mainly including DMF has been already reported.[17–20] Generally, transformation of HMF to valuable chemicals proceeds via various techniques of which heterogeneous and biocatalysis are most frequently used compared to other approaches. The topic of HMF biotransformation to numerous derivatives is widely covered in recent literature reports.[21,22]

This review summarizes and discusses the most recent progress in the catalytic hydroconversion of HMF to selected bio-based chemicals such as BHMF, BHMTHF and DMTHF with focus on heterogeneous catalysis. For the first time, we shed some light on the multifunctional catalytic systems providing a simultaneous production of several HMF intermediates, following cascading strategies. Lastly, the review stresses the importance of HMF purity, which has so far been largely overlooked in the HMF literature. Recent examples were selected to demonstrate the impact of purity on conversion rate and selectivity in heterogeneously catalyzed hydroconversion.

2. Catalytic hydroconversion of HMF

A vast number of intermediates are involved in the hydroconversion of HMF. Due to the presence of many functional groups within one molecule, multiple reactions can take place during the HMF hydrogenation, e.g. the reduction of carbonyl group, the hydrogenation of the furan ring, the hydrogenolysis of hydroxyl or carbonyl groups, and ring-opening reactions (Scheme 2). Given these options, selective hydroconversion of HMF into specific products with high yields is challenging. The product distribution depends heavily on the operational conditions such as contact time, pressure and temperature, but also on the catalyst characteristics such as active metal chemical state, support acid-base and structural properties. Surprisingly, HMF impurities play an overlooked but crucial role in its catalytic upgrading. In this review, we focused mainly on the selective HMF hydroconversion towards BHMF, BHMTHF and DMTHF, while DMF synthesis from HMF is already extensively covered elsewhere[17–20] and thus not discussed in the present work.



Scheme 2. Possible products formed by the hydroconversion of HMF.

2.1. BHMF

BHMF is a versatile biomass-derived platform molecule for the production of polymers, polyurethanes, resins, crown ethers, fibers, and drug synthesis, etc.[23] A great deal of effort has been spent to find appropriate catalytic systems able to selectively produce BHMF from HMF, that is preventing C–O cleavage and furan ring hydrogenation.

Noble metals such as platinum, palladium, iridium, ruthenium and gold are commonly used for BHMF synthesis. In 2012, Balakrishnan et al. investigated the selective hydroconversion of HMF to BHMF over $PtSn/Al_2O_3$ in ethanol.[24] The moderate 82.0% BHMF yield was reached at 60 °C, 13.8 bar H_2 after 5 h. PtSn alloys were found to enhance the selective reduction of the carbonyl to alcohol group. Chatterjee et al.[25] conducted the HMF hydroconversion in aqueous medium over different metals such as Ni, Pt, Pd, Au, Ru, Rh and Ir (1 wt%) supported on MCM–41. BHMF was the major product detected for all the catalysts, except for Pd, but Pt exhibited the superior catalytic activity. Full conversion and 98.9% BHMF selectivity were reached using Pt/MCM–41 as a catalyst at a very low temperature of 35 °C and 8 bar H_2 pressure after 2 h. The solvent properties can strongly influence the catalytic BHMF production. Polar protic, polar aprotic, and nonpolar solvents were tested by the same research group to elucidate the solvent effect on the hydrogenation of HMF. Remarkably, a clear correlation between HMF conversion and solvent δ value, representing the difference between solvent donor and acceptor number, was found. Solvents with negative δ values (e.g. water, methanol, ethanol, etc.) provided better catalytic performance in comparison to solvents with positive δ values (e.g. acetone, hexane, tetrahydrofuran). Among all tested solvents, water showed the highest HMF conversion and BHMF yield, having the lowest δ value. Pt supported on ceria−zirconia mixed oxide was recently suggested as another efficient catalytic system for BHMF production.[26] The maximum 95% BHMF yield was obtained over 1% $Pt/CeO_2–ZrO_2$ catalyst in the ethanol media at room temperature and atmospheric pressure within 2 h. Ethanol provided the highest BHMF yield among the tested solvents, likely due to its optimal hydrogen-bond donation and acceptance abilities for effective binding with the substrate. In this case, no correlation was found between the BHMF yield and the donor and acceptor numbers of solvents. Authors explained it by the fact that the hydrogenation took place at room temperature and atmospheric pressure compared to other works in which experiments were carried out at elevated temperature and pressure. The latter could enhance the decomposition of the intermediate products and HMF aldehyde group adsorption on the catalyst. The catalyst structural defects can act as additional substrate adsorption centers and enhance the HMF hydroconversion. The BHMF yield obtained in the presence of 1 wt% $Pt/CeO_2–ZrO_2$ (95%) significantly exceeded the one achieved over 1 wt% Pt/CeO_2 (60%), 1 wt% Pt/ZrO_2 (23%) and 1 wt% Pt/SiO_2 (36%) catalysts. In all cases, the selectivity to BHMF was 100%. These results led to several suggestions about catalysts performance. First, the substrate can be partially adsorbed on the Pt centers since the conversion of HMF over both Pt/ZrO_2 and Pt/SiO_2 catalysts was observed. Second, higher HMF conversion over $Pt/CeO_2–ZrO_2$ could be attributed to the appearance of defects at the interface between CeO_2 and ZrO_2 phases which provide additional centers for the adsorption of the HMF carbonyl group. Finally, a low-temperature spillover could appear on the catalysts based on individual or mixed cerium oxide. Therefore, hydrogen species formed on the Pt centers undergo a spillover leading to the formation of $Ce_2^{3+}O_3$ oxygen vacancies which can serve as additional adsorption centers of the HMF carbonyl group. This hypothesis was supported by a direct correlation between the HMF conversion and the fraction of Ce^{3+} ions identified by XPS analysis in the 1 wt% and 0.5 wt% Pt/ZrO_2–CeO_2 catalysts. In the following-up work, authors managed to achieve an even higher 97% BHMF yield with full HMF conversion at 170 °C and 10 bar H_2 after 8 h using ultra-low-loaded (0.1%) Pt/CeO_2–ZrO_2.[27]

Similar positive effect of the enhanced substrate adsorption on the catalytic performance was found with Ir catalysts. Use of Ir/TiO_2 allowed the BHMF production from fructose in the one-pot two step system.[28] First, the catalyst-free dehydration of fructose was conducted in 1-butyl-3-methylimdazolium chloride ([BMIm]Cl) ionic liquid which acted as both appropriate solvent and promoter for HMF production. A 75% HMF yield was achieved at 130 °C after 20 min. After adding an additional solvent and catalyst, the hydrogenation reaction was carried out at 50 °C, 60 bar H_2 for 3 h. Among various metal catalysts supported on carbon including Pd, Pt, Ru, Ir, and Ni, Ir/C catalyst showed the highest degree of C=O hydrogenation. A 94% BHMF yield was achieved over Ir/TiO_2 compared to 65% obtained using Ir/C at otherwise similar conditions. The interaction between the TiO_2 support and Ir metal led to the formation of special defect sites (Ti^{3+} or oxygen vacancies on the TiO_2 surface). These sites enable the coordination of the HMF carbonyl group via a lone pair of electrons, hereby activating HMF for selective hydrogenation. Ir–ReO_x/SiO_2 catalyst exhibited high activity and selectivity in the hydrogenation of HMF providing >99% BHMF yield at mild conditions of 30 °C, 8 bar H_2 and 6 hours.[29] In this case, ReO_x was responsible for the promotion of substrate adsorption which was experimentally confirmed by studying the reaction rate dependence on the substrate concentration. Moreover, ReO_x assisted in the heterolytic dissociation of H_2 at Ir surface, thus increasing the catalyst activity.

The acid-base property of the support can strongly affect the product selectivity. The selective hydroconversion of HMF to BHMF using Au supported on various metal oxides was investigated by Ohyama et al.[30] Au catalysts supported on ZrO_2 and TiO_2 primarily formed furan ring-opening products due to the acidic property of the support. Au supported on γ–Al_2O_3 was the most selective towards BHMF providing 96% yield at 120 °C, 65 bar H_2 after 2 hours. Further modification of Au/Al_2O_3 by FeO_x further enhanced the catalytic activity three-to-fourfold.[31] Such change in the catalytic activity with Fe modification was attributed to the variation of the FeO_x species, Au species, and their interface. Low Fe loading (≤10 wt%) led to the formation of highly dispersed γ–Fe_2O_3, where higher loading (>10 wt%) mainly produced α–Fe_2O_3 species. Overall, the supported Fe_2O_3 species promoted the formation of Au clusters and reduction of single Au atoms, thus enhancing the catalytic activity. However, in the case of significantly high Fe loading (≥30 wt%), the reduction treatment led to the reduction of α–Fe_2O_3 species to Fe^0 metal which was considered to form the buried structure of Au clusters in FeO_x. Consequently, the accessibility of Au clusters decreased which was evidenced by the decrease of the catalyst hydrogenation activity at high Fe loading (≥30 wt%). In contrast, for Au/FeO_x/Al_2O_3 with low Fe loading (≤20 wt%), the dispersed α–Fe_2O_3 species were not reduced to Fe^0 metal and maintained the exposed Au clusters on the surface, leading to a superior performance. Particularly, the catalyst with 10 wt% Fe loading had the highest fraction of small Au clusters available for substrate adsorption and showed the highest catalytic activity.

The catalytic hydroconversion of HMF to BHMF can be dependent not only on the donor and acceptor numbers of the solvent but also on its polarity. $Ru(OH)_x$ supported on ZrO_2 showed excellent performance in various n-alcohol solvents.[32] In polar solvents, the C=O bond is more polarized, so the hydrogen adsorbed on Ru active sites can easily attack the HMF molecule. Thus, n-alcohols which have relatively higher polarity, gave superior catalytic performance compared to branched alcohols. For instance, >99% BHMF yield was obtained in 1-butanol at 120 °C within 6 hours. On top of that, the catalyst exhibited minor activity loss after 5 catalytic cycles. Ru–OH active sites seemed to be favorable for BHMF formation due to a specific metal-support interaction. This hypothesis was supported by a significant activity loss of the $Ru(OH)_x/ZrO_2$ catalyst calcined at 700 °C. Such calcination treatment provoked the formation of anhydrous RuO_2, which changed the interaction between ZrO_2 and the Ru–OH active site. The unique surface characteristics of ZrO_2 such as hydroxyl groups and coordinative unsaturated Zr^{4+}–O^{2-} pairs of ZrO_2 could also enhance the catalytic performance of the metal active site.

Catalytic transfer hydrogenation (CTH) is another efficient strategy in biomass upgrading in which a hydrogen donor is used to reduce the substrate instead of molecular hydrogen. There are only few examples of employing this approach to produce BHMF in combination with noble metal catalysts. For instance, Ru/Co_3O_4 was suggested as a catalyst for the conversion of HMF via CTH using isopropanol as the hydrogen source.[33] A 82.8% BHMF yield was obtained at 190 °C in 6 h over Ru/Co_3O_4 catalyst. However, the etherification of the short-chain alcohols with isopropanol could occur due to a certain Lewis acidity of Ru/Co_3O_4, decreasing the BHMF selectivity.

Non-noble metals are frequently used in BHMF production due to their high economic applicability and cost-effectiveness. It is believed that metallic and electrophilic copper species are crucial in the selective formation of BHMF. For instance, efficient HMF hydroconversion to BHMF was performed using a Cu/SiO_2 catalyst.[34] A 97% BHMF yield was obtained after 8 h at 100 °C and 25 bar H_2. The hydrogenation of HMF to BHMF over the Raney Cu catalyst was explored by Lima et al.[35] An average HMF conversion of 94% and 92% BHMF selectivity was obtained over 24 h on stream at 90 °C, 90 bar H_2 using 1 wt% HMF solution in water. No measurable Cu or Al leaching was observed after a longtime on-stream operation. In the recent work of Elsayed et al., a novel copper-iron bimetallic catalyst supported on activated carbon (CuO–Fe_3O_4/AC) was developed for the selective production of BHMF via catalytic hydrogen transfer.[36] 97.5% conversion and 94.8% BHMF selectivity were reached at 150 °C, 7 bar within 5 h using ethanol as both solvent and hydrogen donor. It was experimentally shown that the catalyst was composed of a mixture of CuO, Cu_2O and Fe_3O_4, while having similar surface and bulk compositions. After five cycles, the conversion of HMF slightly decreased by 3.7% while BHMF selectivity remained almost constant. The active metal loading can be a key parameter to control the catalytic activity. For instance, the catalytic performance of Cu/Al_2O_3 catalysts with various Cu loading, prepared through a solvent-free solid-state grinding method, was investigated.[37] Both HMF conversion and BHMF yield increased while increasing the copper content from 10 to 20 mol%. The highest BHMF yield of 93% was achieved after 1 h conversion at 130 °C, 30 bar H_2 over the 20 mol% Cu–Al_2O_3 catalyst. With a further increase of copper loading to 25 mol%, almost identical conversion results were achieved. The superior performance of Cu–Al_2O_3 catalysts with 20 and 25 mol% loading was attributed to the presence of uniformly distributed metallic Cu nanoparticles in these copper-alumina catalysts. Moreover, authors believed that the co-existence of both metallic and electrophilic Cu species was required for selective BHMF formation. The unreduced 20 mol% Cu–Al_2O_3 catalyst in the absence of Cu^0 species provided <5 % yield of BHMF, although the complete HMF conversion was achieved. However, a physical mixture of unreduced 20 mol% Cu–Al_2O_3 catalyst and Cu nanopowder in an equal mass ratio produced BHMF with a 62% yield, which was much higher than that with the 20 mol% Cu–Al_2O_3 or Cu nanopowder alone. Based on the above experimental data and literature reports, authors concluded that electrophilic Cu^{2+} species assisted the adsorption and activation of the HMF carbonyl group, which then was followed by hydrogenation reaction induced by metallic Cu^0 using the dissociated hydrogen on its surface. The importance of simultaneous presence of metallic and oxidized Cu species for selective HMF hydroconversion towards BHMF was also confirmed by Kapustin et al.[38] Copper catalysts supported on CeO_2-ZrO_2 were synthesized via deposition-precipitation with urea. Study of the phase composition of 3% Cu/CeO_2–ZrO_2 catalysts obtained using different amounts of precipitant (urea) showed that this parameter can noticeably alter the catalysts phase composition. For the catalyst synthesized with a small amount of precipitant, the formation of the metallic copper and parameloconite phase (Cu_4O_3 in which copper was in Cu^+ and Cu^{2+} states) was observed, whereas the increased amount of precipitant led to the predominant formation of a tenorite phase (CuO). The Cu/CeO_2–ZrO_2 catalyst with both metallic and oxidized Cu species exhibited much higher catalytic activity and allowed to achieve the 70% HMF conversion and 100% BHMF selectivity at mild reaction conditions of 170 °C, 10 bar H_2 in 2 h. Authors believed that metallic Cu nanoparticles immediately activated hydrogen under the reaction conditions and facilitated the subsequent hydrogenation of HMF to BHMF.

Lewis/Brønsted acid sites balance plays an important role in the catalytic transfer hydrogenation of HMF and affects the BHMF selectivity. An efficient process for the CTH of HMF to BHMF over $ZrO(OH)_2$ catalyst was proposed by Hao et al. using ethanol as both hydrogen donor and solvent.[39] Being a typical acid-base catalyst, $ZrO(OH)_2$ was much more effective for the CTH of HMF compared to other metal hydroxides providing an 83.7% BHMF yield at 150 °C in 2.5 h. The catalyst recycling and calcination process led to a removal of the hydroxyl groups of $ZrO(OH)_2$ with formation of ZrO_2 and increase in the amount of Lewis acid sites. Thus, the etherification of BHMF with ethanol was accelerated and resulted in a drop of BHMF selectivity. In addition, a crude HMF from fructose was also tested as feedstock for BHMF synthesis. Fructose was converted to HMF over $AlCl_3$ catalyst at 373 K in methyl isobutyl ketone, which was recovered by vacuum distillation to obtain a crude HMF product. A slightly lower BHMF yield of 77 % was achieved, indicating that a crude HMF could still be efficiently converted to BHMF through the CTH process. A zirconium/calcium catalyst supported on carbon-nanosheets (ZrCa@CNS) exhibited good catalytic activity at 190 °C in the HMF CTH process.[40] The addition of Ca led to a moderate decrease in HMF conversion compared to non-doped catalyst likely due to the decrease of ZrO_2 content. However, it helped to suppress the etherification of

BHMF by considerably decreasing the amount of Brønsted acid sites and thus improving BHMF selectivity from 84% to 99%. Different temperature treatment during the catalyst synthesis correlated with Lewis/Brønsted acid sites balance and significantly impacted the HMF hydroconversion. With the increase of the calcination temperature from 300 to 600 °C, the amount of Lewis acid sites increased with the corresponding decrease of Brønsted acid sites. Further increase of the calcination temperature to 750 °C led to a decrease in both Lewis and Brønsted acid sites, although the Lewis/Brønsted acid sites ratio slightly increased. The catalytic performance of mentioned catalysts was further evaluated and explained. Catalysts calcined at low temperatures (300 or 450 °C) provided lower BHMF yields (17.0% and 32.3%) likely due to the absence of metal oxides formation (CaO and ZrO_2) which possessed catalytic activity and low Lewis acidity. Zr–Ca catalyst calcined at 600 °C gave the highest BHMF yield of 84.2%. Higher calcination temperature (750 °C) provoked a decrease in BHMF yield (70.4%) which was explained by the structure collapse and decrease of the total amount of acid sites. A summary of the described catalytic processes concerning the HMF to BHMF hydroconversion is reported in Table 1.

Table 1. Representative results for the hydroconversion of HMF to BHMF

Entry	Catalyst	Solvent	HMF loading (wt. %)	H-donor	Reaction conditions	BHMF yield (%)	Ref.
1	$PtSn/Al_2O_3$	Ethanol	5.9	H_2	60 °C, 5 h, 13.8 bar	82.0	24
2	Pt/MCM-41	Water	20.0	H_2	35 °C, 2 h, 8 bar	98.9	25
3	Pt/CeO_2-ZrO_2	Ethanol	3.1	H_2	20 °C, 2 h, 1 bar	95.0	26
4	Pt/CeO_2-ZrO_2	Ethanol	3.1	H_2	170 °C, 8 h, 10 bar	97.0	27
5	Ir/TiO_2	[BMIm]Cl	0.4	H_2	50 °C, 3 h, 60 bar	94.0	28
6	$Ir–ReO_x/SiO_2$	Water	11.2	H_2	30 °C, 6 h, 8 bar	98.9	29
7	Au/Al_2O_3	Water	2.5	H_2	120 °C, 2 h, 65 bar	96.0	30
8	$Ru(OH)_x/ZrO_2$	1-butanol	4.8	H_2	120 °C, 6 h, 15 bar	99.0	32
9	Cu/SiO_2	Methanol	20.2	H_2	100 °C, 8 h, 25 bar	97.0	34
10	Cu/Al_2O_3	Methanol	0.8	H_2	130 °C, 1 h, 30 bar	93.0	37
11	Cu/CeO_2-ZrO_2	Ethanol	2.4	H_2	170 °C, 2 h, 10 bar	70.0	38
12	Ru/Co_3O_4	Isopropanol	0.5	Isopropanol	190 °C, 6 h, 1 bar	82.8	33
13	$CuO−Fe_3O_4/AC$	Ethanol	0.8	Ethanol	150 °C, 5 h, 7 bar	92.4	36
14	$ZrO(OH)_2$	Ethanol	2.5	Ethanol	150 °C, 2.5 h, 1 bar	83.7	39
15	ZrCa@CNS	Isopropanol	1.0	Isopropanol	190 °C, h, 1 bar	84.2	40

2.2. BHMTHF

BHMTHF serves as a precursor in the production of important monomers (e.g., 1,6-hexanediol, 1,2,6-hexanetriol, caprolactam) that are currently obtained from non-renewable sources.[41–44] BHMTHF production requires both the aldehyde group and the HMF furan ring hydrogenation to occur without the hydrogenolysis of –OH groups (Scheme 2). Therefore, more attention should be paid to the choice of the active metal as well as to reaction conditions to achieve the selective reduction of specific groups at full substrate conversion. The degree of ring opening versus ring saturation depends on the strength of interaction between the ring and the metal. In hydrogenation of furanic compounds, the base metal catalysts have been reported to be active for both furan ring opening and saturation reactions, while noble metals such as Pd, Ru and Rh preferentially carry out furan ring saturation.[45–47] Remarkably, Pt was reported to provide a higher selectivity towards ring-opening products. The difference in selectivity among noble metals is explained by different bonding (σ or π) of furanic compounds to these metals. The π-bonding is preferred for Pd, Rh and Ru for Pt, being conducive to ring saturation, whereas σ-bonding is favourable for Pt, promoting ring opening reactions.

Among noble metals, Pd catalysts are commonly used for this purpose due to their high intrinsic hydrogenation activity. For instance, Pd/C provided a 89.0% BHMTHF yield at 50 °C, 60 bar H_2 after 3 h in [BMIm]Cl ionic liquid.[28] For other tested noble metals (Ru, Pt, Ir) BHMF was the primary product under similar conditions. 90.0% BHMTHF yield was obtained in the water-butanol system using Pd/C at 130 °C for 8 h under 27 bar H_2.[48] Superior activity of Pd was also confirmed by another research group that achieved high BHMTHF yields in ethanol using Pd/C (89.0%) and Pd/Al_2O_3 (>99%) at 120 °C 70 bar H_2 for 3 h while conducting the screening of commercial catalysts.[49] Chen et al. proposed a highly efficient catalyst of palladium supported on amine-functionalized metal-organic framework (Pd/MIL–101(Al)–NH_2).[50] Almost quantitative BHMTHF yield (96.0%) was achieved using Pd/MIL–101(Al)–NH_2 catalyst in aqueous medium at 30 °C, 10 bar H_2 after 12 h. The observed high selectivity towards BHMTHF was suggested to be attributed to the cooperation between Pd metallic sites and free amine moieties in the MIL–101(Al)–NH_2 framework providing the formation of highly dispersed palladium nanoparticles. MIL–101(Al)–NH_2 support exhibited preferential adsorption to intermediate BHMF compared to reactant HMF, which was likely caused by higher hydrophilic nature of BHMF and its enhanced hydrogen-bond interaction with MOF support. The latter promoted a subsequent BHMF hydrogenation to BHMTHF upon its in situ formation and improved obtained BHMTHF yield. Authors also believed that the presence of the amine group and the weak basicity of the MIL–101(Al)–NH_2 support suppressed the formation of ring-opening products that are formed through acid catalyzed reactions. Bimetallic Pd-catalysts also exhibit high catalytic activity for the HMF hydroconversion towards BHMTHF. For instance, co-impregnation of Pd and Ni (molar ratio Ni/Pd = 7) on silica allowed to synthesize highly active Ni–Pd alloy with homogeneous composition.[51] Due to synergetic effects, Ni–Pd/SiO_2 catalyst exhibited superior catalytic performance compared to the sole Pd/SiO_2, Ni/SiO_2 catalysts or their physical mixture. The 96.0% BHMTHF yield was reached at 40 °C, 80 bar H_2 after 2 h in the presence of acetic acid. However, the catalyst had poor reusability due to the substantial Ni leaching (16% after the first cycle) likely due to the activation of an oxidized particle surface induced by an acid. The same research group later reported Pd–Ir/SiO_2 bimetallic catalyst, which is able to achieve 95.0% BHMTHF yield at milder conditions of 2 °C, 80 bar H_2 in 4 h.[52] Again, the activity of Pd–Ir/SiO_2 was higher compared to monometallic Pd/SiO_2, Ir/SiO_2 or their physical mixture. The incorporation of Ir was believed to promote the adsorption of the HMF carbonyl group, whereas the Pd strongly interacted with the HMF furan ring and conducted the hydrogenation towards final BHMTHF.

Ru-based catalysts possessing high C=C hydrogenation capability are also employed in HMF hydroconversion towards BHMTHF. Fulignati et al. tested commercial Ru, Pd and Pt carbon-supported catalysts in the hydrogenation of HMF aqueous solutions to obtain BHMTHF.[53] Pt/C mainly promoted the hydrodeoxygenation and ring-opening reactions, whereas Pd/C and Ru/C favored hydrogenation reactions leading to higher BHMTHF yields (55.8 and 88.6% for Pd/C and Ru/C, respectively). After further reaction conditions optimization, the highest BHMTHF yield of 95.3 mol% was reached over Ru/C catalyst at 100 °C, 50 bar H_2 after 3 h. It is noteworthy that a high BHTMHF yield was achieved using 3 wt% HMF aqueous solution which is more concentrated compared to other works, reporting comparable BHMTHF yields. Catalyst recycling experiments revealed a slight decrease of the catalytic activity and an increase in the Ru particle size. However, acetone washing of the recovered catalyst with drying at 40°C allowed for almost fully restoration of the catalytic performance. These results proved that the increase of Ru particle size did not influence the catalytic activity and pointed to humins adsorption on the catalyst surface as main reason for catalyst deactivation. In the following-up work, the hydroconversion of HMF towards BHMTHF in a continuous flow reactor over a commercial Ru/C catalyst was attempted.[54] The highest yield of 93.7% was obtained at the WHSV value of 0.2 h^{-1} at similar reaction conditions used earlier for the batch system. The isoelectric point of the catalyst support can strongly affect the selectivity towards BHMTHF. High BHMTHF yields (88–91%) were reported using Ru supported on materials with high isoelectric points.[55] Compared to sole Ru-black catalyst, the addition of solid materials with high isoelectric point, e.g. Al_2O_3 and MgO, led to a significant increase in BHMTHF selectivity (from 46 to 85% and 89%, respectively). Among Ru catalysts supported on metal oxides such as CeO_2, MgO–ZrO_2, and γ–Al_2O_3, Ru/CeO_x provided the highest BHMTHF yield of 91% at 130 °C, 27.6 bar H_2 after 12 h. In line with these results, a lower BHMTHF yield (53%) was achieved using Ru/SiO_2 catalyst since silica has a lower isoelectric point compared to CeO_x. Remarkably, Pt and Pd carbon-supported catalysts were not as selective for BHMTHF formation as the Ru catalyst, despite a similar loading of the active metal. This result differs from the one previously discussed, in which Pd/C catalyst showed the highest BHMTHF selectivity, compared to Ru and Pt carbon-supported catalysts.[28] Pt is known to catalyze both C=C hydrogenation and C–O hydrogenolysis reactions which can account for the lower selectivity to BHMTHF. Pd showed higher rate of HMF hydrogenation compared to Pt and Ru during the experimental studies at low catalyst amounts and reaction times. However, this behavior could be detrimental to the overall BHMTHF production. If the rate of the intermediate BHMF formation is high while the rate of its hydrogenation is low, this reactive primary product will undergo degradation reactions. The latter corresponds with the experimental results obtained in this report since the majority of products obtained using Pd/C was not identified and did not consist of BHMF, BHMTHF or C_6-polyols. Such a difference could also be related to the catalyst preparation procedure, since in both cases catalysts were self-synthesized by incipient wet impregnation. Besides using different carbon materials, the catalyst temperature treatment procedure also differed. Alamillo et al. included the passivation step with 2% O_2 in He at room temperature which was not done by the group of Cai. It is known that Ru nanoparticles are extremely active and can be oxidized by O_2 even at room temperature, thus modifying the chemical and surface properties of the catalyst.[56] This can also explain the higher BHMTHF yield obtained by the group of Alamillo while using the Ru/C catalyst. Recently, Ru/$MnCo_2O_4$ was reported to be an efficient catalyst to produce BHMTHF.[57] Among a series of metal oxide, single- and bimetal-based mixed oxide catalyst support, Ru/$MnCo_2O_4$ exhibited superior results providing 97.3% BHMTHF yield in methanol at 100 °C, 82 bar H_2 after 16 h. Trace amounts of BHMTHF were obtained during the separate hydrogenation of BHMF in the presence of $MnCo_2O_4$, indicating the crucial role of Ru in the BHMF ring hydrogenation. Higher activity of Ru/$MnCo_2O_4$ in HMF hydroconversion was attributed to the redox ability and structural defects (M^{2+} species and surface oxygen vacancies) arisen from the spinel structure of the catalyst. In addition, Ru modification led to an increase in the amount of both Brønsted and Lewis acid sites, which can also affect the BHMTHF selectivity.

The variety of non-noble metal catalysts for BHMTHF production is less broad since the active metal needs to possess sufficient activity to hydrogenate the HMF furan ring. Thus, higher metal loadings or more severe reaction conditions are often required to reach yields comparable to those in the case of noble metals. For instance, Ni/Al_2O_3 was shown to provide 71.0% BHMTHF yield in water at 80 °C 20 bar H_2 after 6 h.[58] Authors claim that even quantitative yields were achieved at longer reaction times (8–12 h) or when increasing the catalyst loading. 96.0% BHMTHF yield was obtained over Raney Ni catalyst at 100 °C, 15 bar H_2, and reaction time of 30 h.[59] High catalytic performance was ascribed to the weak acidity of Raney Ni, since metal catalysts with high acidity could catalyze C–O hydrogenolysis reaction more effectively, thus decreasing the BHMTHF yield. Moreover, moderate reaction temperature could also limit the deoxygenation ability of the catalyst. Very recently, Ni–Ce/Al_2O_3 catalyst was proposed to be an efficient catalyst for BHMTHF synthesis.[60] In this study, the highest BHMTHF selectivity of 88% at full conversion was achieved in 1-butanol at 190 °C 50 bar H_2 after 3 h. Authors also believed that the isoelectric point of the catalyst support is a crucial aspect in the hydroconversion of HMF. To support this hypothesis, oxides with different isoelectric points (ZnO, CaO, MgO) were added for catalytic activity tests. Remarkably, the addition of such oxides led to a decrease in BHMTHF yields and an increase in ring-opening products, which is contrary to the results obtained by Alamillo et al. discussed above, who reported a substantial improvement in BHMTHF yield when similarly adding MgO into the reaction mixture together with 1 wt% Ru/CeO_2 catalyst.[55] These results indicated that intermediates formed on the catalyst surface can desorb and further react on different sites located on the separate metal oxide particles with high isoelectric point. Overall, the surface charge of the catalyst is an important factor in HMF hydroconversion process, although requiring further detailed investigation for more clarification. The aforementioned catalytic processes concerning the HMF to BHMTHF transformation are summarized in Table 2.

Table 2. Representative results for the hydroconversion of HMF to BHMTHF

Entry	Catalyst	Solvent	HMF loading (wt. %)	H-donor	Reaction conditions	BHMTHF yield (%)	Ref.
1	Pd/C	[BMIm]Cl-water	0.4	H_2	50 °C, 3 h, 60 bar	84.0	28
2	Pd/C	Water–1-butanol	1.7*	H_2	130 °C, 8 h, 27 bar	90.0	48
3	Pd/Al_2O_3	Ethanol	3.1	H_2	120 °C, 3 h, 1 bar	99.0	49
4	(Pd/MIL-101(Al)-NH_2	Water	1.2	H_2	30 °C, 12 h, 10 bar	96.0	50
5	Ni-Pd/SiO_2	Water	5.9	H_2	40 °C, 2 h, 80 bar	96.0	51
6	Ir-Pd/SiO_2	Water	5.9	H_2	2 °C, 4 h, 80 bar	95.0	52
7	Ru/C	Water	3.0	H_2	100 °C, 3 h, 50 bar	95.3	53
8	Ru/CeO_x	Water–1-butanol	1.4*	H_2	130 °C, 12 h, 27.6 bar	91.0	55
9	Ru/$MnCo_2O_4$	Methanol	4.0	H_2	100 °C, 16 h, 82 bar	97.3	57
10	Ni/Al_2O_3	Water	0.5	H_2	80 °C, 6 h, 20 bar	71.0	58
11	Raney Ni	1,4-dioxane	4.0	H_2	100 °C, 30 h, 15 bar	96.0	59
12	Ni–Ce/Al_2O_3	1-butanol	3.0	H_2	190 °C, 3 h, 50 bar	88.0	60

* The weight concentration was calculated relative to the total amount of solvent

2.3. DMTHF

The selective production of DMTHF has gained a lot of attention during the last years in the context of sustainable development. It serves as a valuable organic solvent and renewable feedstock for the production of valuable chemicals, such as 2,5-hexanediol and 2,4-hexadiene that enables new routes towards bio-based polymers.[61,62] However, there is a moderate number of investigations focused on its production. DMTHF synthesis is prone to significant selectivity issues due to many side products that can be formed during the hydroconversion of HMF. The mechanism of DMTHF formation is still under debate. To produce DMTHF from HMF both complete hydrogenation and C–O hydrogenolysis have to occur. The majority believes that firstly the hydrogenolysis of hydroxyl groups occurs leading to the formation of DMF, followed by the hydrogenation of the DMF furan ring (Scheme 2).[59,63–66] However, some authors propose that DMTHF is formed from the C–O hydrogenolysis of the ring saturated furans e.g. BHMTHF and MTHFA.[53,67]

DMTHF can be obtained directly from the dehydration of carbohydrates with HMF being an intermediate product. Sen et al. reported a homogeneous $RhCl_3$/HI catalyst in a water-C_6H_5Cl biphasic system providing a high 86.0% DMTHF yield starting from fructose.[16,68] When the intermediate HMF was tested with $RhCl_3$ catalyst without HI, DMTHF was formed with only 8% yield, compared to 32% yield, while using the combination of two catalysts. However, $RhCl_3$ was more susceptible to deactivation compared to RhI_3 due to the precipitation of metal Rh particles in the aqueous solution containing HCl. This is probably due to the difference in solubility, since $RhCl_3$ is soluble in water, whereas RhI_3 is insoluble and undergoes reduction at a slower rate. The iodine formed as a byproduct is hydrogenated to HI by catalytic amounts of $RhCl_3$ or RhI_3 under the reaction conditions employed for fructose conversion. Authors believed that HI acts as dehydration agent in converting fructose to HMF and reducing agent to transform HMF to MF, whereas the Rh catalyst was necessary for the hydrogenation of C=C and C=O bonds of the intermediates assisting the formation of final product DMTHF. Nevertheless, this process suffers from the formation of corrosive I_2 during the reaction as well as from the usage of chlorobenzene, not an environmentally friendly solvent.

There are only few reports dedicated to the selective HMF hydroconversion towards DMTHF. Noble metals exhibit good catalytic performance carrying out both C–O hydrogenolysis and furan ring hydrogenation reactions. Mitra et al. investigated Pd/C-catalyzed reactions of HMF and the role of various additives in selectivity.[67] A 64% DMTHF yield was achieved after 15 hours by using a Pd/C catalyst without additives at mild reaction conditions, viz.120 °C, 2 bar H_2. The addition of formic acid, acetic acid, dimethyl carbonate or CO_2/H_2O decreased the DMTHF yield and led to the accumulation of DMF and BHMF, suggesting that the ring hydrogenation was suppressed by the presence of such additives, although no real understanding was presented. A comparative study of HMF hydroconversion using different metal catalysts in a continuous flow reactor carried by Luo et. al also confirmed the primary formation of DMTHF over Pd catalyst.[69] All carbon-supported metal catalysts including Pt, Pd, Ir, Ru, Ni, Co with 10 wt% loading were able to produce DMF as the intermediate/final product, but only Pd/C was able to further hydrogenate the furan ring and form DMTHF. Even though having slightly lower activity compared to Pt and Ir catalysts, Pd/C provided the highest DMTHF yield (53%) at the highest WHSV value of approximately 0.06 h^{-1}. However, authors did not take into account the presence of dimethyl sulfoxide (DMSO) in their commercial HMF sample (*vide infra*), and therefore the results, particular selectivity, should be taken with caution. Indeed, recently, the Ru/C catalyst was shown to efficiently carry out both HMF hydrogenation and C–O hydrogenolysis towards DMTHF, and this work was able to show, in contrast to the previous work, 78% DMTHF yield in presence of Ru/C at 180 °C, 50 bar H_2 after 16 h.[70] These authors found that the presence of trace amounts of DMSO in the reaction mixture has a dramatic effect on the aromatic hydrogenation activity, thus hampering DMTHF formation. In presence of DMSO, only DMF was formed as a reaction product even at long reaction times. This drastic shift in selectivity, *viz*. avoidance of ring hydrogenation, was attributed to the specific Ru site poisoning by DMSO leading to irreversible change of the catalytic Ru properties. This poisoning effect will be discussed into more detail later, but this observation may shed a different light on earlier interpretations and conclusions are to be taken with caution. It also conclude that the DMSO content and HMF purity should be mentioned in future research.

Among non-noble metals, Ni and Cu-based catalysts attract great interest in the DMTHF production from HMF. A proper metal-acid sites ratio can greatly enhance the selective DMTHF formation due to the balance between C=C hydrogenation and C–O hydrogenolysis reactions. Kong et al. reported highly active Ni-based catalysts derived from hydrotalcite.[71] A 97.4% DMTHF yield was obtained over the Ni catalyst calcined at 850 °C after 20 h at 180 °C, 12 bar H_2. Such a high selectivity was achieved by balancing the surface metallic Ni and acid sites (mainly Al^{3+} species) through the high-temperature calcination and by extending the reaction time for the furan ring hydrogenation to occur. The superior performance of Ni catalyst calcined at 850 °C was attributed to the lowest Ni/acid sites ratio of the catalyst. However, the catalyst was susceptible to deactivation likely resulting from the deposition of carbonaceous species and weight loss of the catalyst. The same research group also reported nickel phyllosilicate inlaid with Ni nanoparticles to be an efficient bifunctional catalyst able to selectively form DMTHF at moderate conditions.[72] An 89.7% DMTHF yield was achieved after 8 h at 150 °C, 15 bar H_2. The synergy of highly dispersed nickel nanoparticles and substantially formed acid sites due to coordinatively unsaturated Ni (II) sites near the edges/surfaces of the phyllosilicate structure made the hydrogenolysis of hydroxyl groups feasible at a lower temperature compared to their previous research work. A similar Ni–Cu hydrotalcite-supported (HT) catalyst was applied for catalytic hydroconversion of HMF and BHMF.[73] A 32.0% DMTHF yield was reached in THF starting from HMF feedstock at 90 °C, 10 bar H_2 after 15 h. Addition of small concentration of H_2SO_4 along with hydrogen minimized DMF over-hydrogenation, so no DMTHF was formed. Authors suggested that sulfuric acid might have deactivated some active sites of metal and suppressed the ring-hydrogenation. When performing additional experiments using BHMF as a substrate, a higher DMTHF yield of 78.0% over Ni–Cu/HT was observed in the presence of formic acid at 130 °C and 20 bar H_2. Remarkably, monometallic Ni/HT catalyst converted BHMF to DMTHF with a 93.0% yield in acetonitrile at milder conditions of 85 °C, 6 bar H_2 after 16 hours, whereas in the presence of Cu/HT catalyst, formate esters and formylated compounds were predominant products. These results suggested that Ni tends to over-hydrogenate BHMF to DMTHF, while Cu does not possess the hydrogenation ability to form either DMF or DMTHF from BHMF at applied reaction conditions. In the case of bimetallic catalyst, Cu diminishes the ring hydrogenating ability of Ni which is less beneficial for DMTHF synthesis. Ni/SBA–15 was used by Chen et al. for the selective production of DMTHF.[65] A 96.6% yield was obtained at 180 °C under 30 bar H_2 after 10 h. After the catalyst preparation and reduction at 550°C, only metallic Ni was identified by XRD and XPS analysis. These results are in contradiction with the ones discussed above using other Ni catalysts. In this case, a non-promoted monometallic Ni/SBA–15 catalyst afforded both hydrogenolysis and hydrogenation reactions despite a probably low concentration or absence of acid sites. However, it is worth to mention that the catalyst acidity was suggested in their explanation, but it was not measured in this work.

Various approaches can be applied to reach the desired balance between hydrogenation and hydrogenolysis reactions. For instance, the catalyst hydrogenation activity can be enhanced through the incorporation of a second active metal. Wang et al. studied the conversion of HMF to DMTHF over copper-based catalysts with multiple interfaces derived from the reduction of layered double hydroxides.[64] Cu/MgAlO$_x$ was only active in C=O hydrogenation, while Co@Cu/3CoAlO$_x$ (Co/Cu ratio = 3:1) sequentially catalyzed the C–O hydrogenolysis and furan ring hydrogenation. The enhanced activity of Co–Cu catalyst was attributed to the formation of interfacial Co oxygen vacancies, acting as additional adsorption sites, and Co−Cu metallic interfaces that were shown to chemically adsorb and hydrogenate C=C bonds. Finding the optimal balance of Co/Cu ratio allowed to control the C=C hydrogenation step, reaching 83.6% yield of DMTHF at 180 °C, 15 bar H_2 after 20 h using Co@Cu/5CoAlO$_x$ (Co/Cu ratio = 5:1) catalyst. The hydrogenation of the furan ring was proved to be related to the concentration of the newly formed Co−Cu sites. This may explains a higher activity of the catalyst with higher Co/Cu ratio, which had more of such Co−Cu metallic interfaces. Changing the chemical state of the catalyst active metal can influence its hydrogenolysis activity. Gao et al. studied the green catalytic transfer hydrogenation of HMF to DMTHF using a nitrogen-doped decorated copper-based catalyst (NC–Cu/MgAlO) with cyclohexanol as both hydrogen source and solvent.[74] The nitrogen doping of the carbon support led to an increase in the amount of accessible base sites on the catalyst surface, which facilitated transfer hydrogenation reactions, thus providing high activity in HMF conversion. NC–Cu/Al_2O_3 and Cu/MgAlO catalysts possessed lower C–O hydrogenolysis ability, compared to NC–Cu/MgAlO, which is though essential to effectively produce DMF as the DMTHF precursor. The increase of reaction temperature from 160 to 220 °C led to a gradual increase in DMTHF selectivity with the decrease of DMF and 5-MFA selectivity. However, temperatures above 220 °C were detrimental for DMTHF production because of excessive byproducts formation. Thus, a DMTHF yield of 94.6 % was reached by using NC–Cu/MgAlO catalyst at 220 °C after 200 min. Notably, the correlation between DMF selectivity and the catalyst $Cu^+/(Cu^0 + Cu^+)$ molar ratio was found. The DMF selectivity approximately increased linearly with increasing $Cu^+/(Cu^0 + Cu^+)$ molar ratio, indicating that the high $Cu^+/(Cu^0 + Cu^+)$ molar ratio likely enhances C–O hydrogenolysis leading to high selectivity to DMF and ultimately DMTHF. Moreover, strong interaction between Cu nanoparticles and the support prevented the aggregation of Cu nanoparticles and thus greatly enhanced the stability of the catalyst, which showed minor loss of activity after five consecutive cycles. The previously discussed processes of HMF to DMTHF upgrading are summarized in Table 3.

Table 3. Representative results for the hydroconversion of HMF to DMTHF

Entry	Catalyst	Solvent	HMF loading (wt.%)	H-donor	Reaction conditions	DMTHF yield (%)	Ref.
1	Pd/C	1,4-dioxane	1.2	H_2	120 °C, 15 h, 2 bar	64.0	67
2	Ru/C	1,4-dioxane	1.2	H_2	180 °C, 4 h, 50 bar	78.0	70

3	NiAl-850	1,4-dioxane	4.0	H_2	180 °C, 20 h, 12 bar	97.4	71
4	NiSi-PS	1,4-dioxane	3.7	H_2	150 °C, 8 h, 15 bar	89.7	72
5	Ni/SBA-15	1,4-dioxane	1.8	H_2	180 °C, 10 h, 30 bar	96.6	65
6	Co@Cu/5CoAlO$_x$	1,4-dioxane	2.8	H_2	180 °C, 20 h, 15 bar	83.6	64
7	NC-Cu/Al_2O_3	Cyclohexanol	4.9	Cyclohexanol	220 °C, 3.3 h, 1 bar	94.6	74

3. Multifunctional catalytic systems

The catalyst properties along with suitable reaction conditions play a big role in the controlling of HMF hydroconversion pathway and product selectivity. The hydroconversion of HMF to DMF involves C=O hydrogenation with subsequent C–O hydrogenolysis, while DMTHF formation requires furan ring saturation. In contrast, for the synthesis of BHMF and BHMTHF, C–O hydrogenolysis reactions should be suppressed and only the hydrogenation of unsaturated bonds needs to occur. Therefore, the synthesis of HMF intermediates requires different catalyst active sites. In many cases, the specific catalyst with a fixed composition is only suitable for a certain type of reaction. In this chapter, we want to shed some light on the multifunctional catalytic systems offering a possibility to pivot selectivity towards the desired end-product by only slightly varying the composition of the catalyst and/or reaction conditions.

The presence of acid sites is required for both DMF/DMTHF and BHMF/BHMTHF formation, though their amount is crucial for steering the HMF conversion towards a specific derivative. In 2014, Kong et al. first reported a switchable and selective synthesis of BHMTHF and DMF over the same non-noble catalyst, by tuning reaction conditions.[59] All the Raney metals (Cu, Co and Ni) having the metal loadings higher than 93% were initially screened. Raney Ni catalyst exhibited the superior activity compared to other catalysts providing full HMF conversion and 88.5% DMF selectivity at 180 °C, 15 bar H_2 after 15 h. Changing the reaction temperature and time to 100 °C and 30 h, respectively, allowed to synthesize BHMTHF with a yield of 96.0% over the same Raney Ni catalyst. Authors ascribed the high BHMTHF yield to the weak acidity of Raney Ni catalyst and proved it experimentally by employing a physical mixture of Raney Ni with solid acid (HZSM–5) in HMF hydroconversion. The addition of HZSM–5 increased BHMTHF yield from 67.4 to 86.5% after 15 h of reaction when the intermediate BHMF was not fully converted. However, after 30 h the enhanced formation of MTHFA was observed, indicating that cleavage in the hydroxymethyl group was also promoted. Consequently, the overall BHMTHF yield using the combination of Raney Ni and HZSM–5 decreased from 96.0 to 85.9%. These results clearly suggest the crucial role of acid sites to control product selectivity

The manipulation of metal–acid sites balance in combination with the control of reactions conditions can allow for selectively transforming HMF towards several intermediates. The aforementioned group of Kong et al. investigated HMF hydroconversion over Ni–Al_2O_3 catalysts derived from the hydrotalcite-like compound (HT).[71] First, the NiAl–HT precursor was prepared by a constant-pH co-precipitation and then calcined at different temperatures (300, 450, 600, 750 and 850 °C), so the NiAl–CT (CT indicated the calcination temperature in Celsius) catalysts were obtained. The catalysts calcined at high temperatures (NiAl–600, NiAl–750, NiAl–850) showed the hindered reducibility as a result of both enhanced NiO–Al_2O_3 interactions and slightly increased NiO particle size. H_2-TPD and NH_3-TPD measurements allowed to determine the amounts of surface metallic Ni and acid sites associated with Al^{3+} species (Figure 1). Low-temperature treatment led to a high concentration of metallic Ni sites with a low amount of acid sites. On the contrary, calcination at high temperatures (>750 °C) decreased the amount of surface metallic Ni sites due to a decreased reducibility of the catalysts, while increasing the density of surface acid sites.

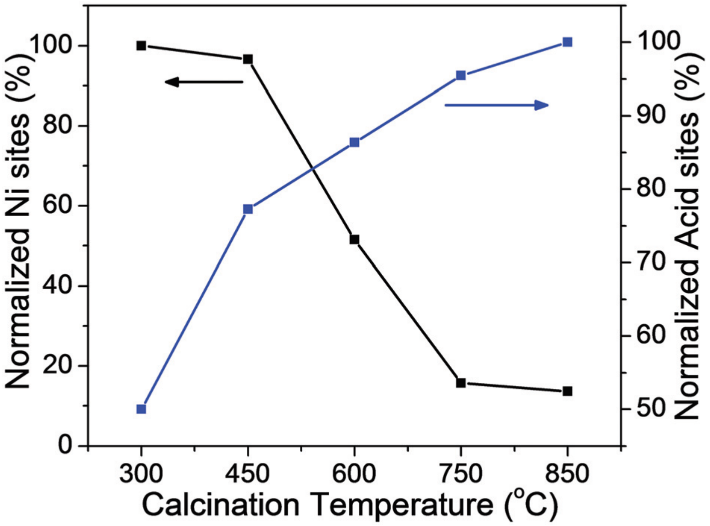


Figure 1. The normalized Ni and acid sites of reduced NiAl–CT catalysts. Reprinted with permission from Ref. [[71]]. Copyright 2015, Royal Society of Chemistry.

While testing catalysts at optimal conditions for DMF synthesis, large amounts of MFA and BHMF were obtained over NiAl–300 catalyst, indicating its insufficient hydrodeoxygenation ability. DMF yield significantly increased using NiAl–450, NiAl–600 and NiAl–750 catalysts (up to 80.1% over NiAl–750). However, the total DMF yield was lowered due to the formation of fully hydrogenated product DMTHF. Finally, NiAl–850 exhibited the highest DMF yield of 91.5% after 4 hours at 180 °C, 12 bar H_2. Therefore, balanced Ni–acid sites efficiently promoted both hydrogenation of the aldehyde group and the subsequent hydrogenolysis of hydroxymethyl groups to produce DMF, while not being keen to furan ring hydrogenation. The sole change of reaction time from 4 to 20 h over the same NiAl–850 catalyst resulted in 97.4% DMTHF yield, which was the highest obtained for all the catalysts. Lastly, the same catalytic systems were used to optimize BHMTHF synthesis. Catalysts calcined at higher temperatures (NiAl–600, NiAl–750 and NiAl–850) showed lower hydrogenation ability due to decreased surface Ni sites, and thus provided lower HMF conversion and BHMTHF selectivity. However, both NiAl–300 and NiAl–450 catalysts exhibited 100% HMF conversion and high BHMTHF yields (>90%) under mild reaction conditions of 60 °C, 6 h, 6 bar H_2. Overall, through the fine modulation of metal-acid sites and control of reaction conditions, various intermediates of HMF conversion were obtained with high selectivity. Similar effect of tuning Ni/NiO ratio to control the catalyst hydrogenolysis/hydrogenation activity was reported by Zhang et al.[75] Authors used sucrose-derived hydrothermal carbon (HC) with a large surface area as a support for Ni catalyst. The HMF conversion was conducted over both unreduced and reduced catalysts under the H_2 gas stream at 450 °C for 2 h. In both cases, full conversion was reached but the product selectivity strongly differed. The unreduced catalyst contained both metallic Ni and NiO and provided higher C–O hydrogenolysis activity resulting in the total DMF + DMTHF selectivity of 85.7% at 240 °C, 15 bar H_2 after 15 h. After reduction, metallic Ni was the predominant phase, so the product selectivity changed towards unsaturated furanic alcohols, while DMTHF was not formed. According to TEM analysis, the particle size did not show a substantial change. Different calcination temperatures (from 350 to 550 °C) of 5%–Ni/HC catalyst were studied to determine the effect of metal-metal oxide ratio on HMF hydroconversion selectivity (Figure 2). The highly dispersed Ni metal sites possess high hydrogenation ability while NiO Lewis acid sites primarily promote C–O hydrogenolysis reactions. The increase of calcination temperature led to a decreased activity in Ni metal sites which lowered the catalyst hydrogenation capability and thus resulted in the increased selectivity towards products with unsaturated furan ring. Speaking of DMF and DMTHF products, increasing the calcination temperature from 350 to 500 °C led to an increase in their total selectivity: the DMF selectivity strongly increased at the expense of DMTHF. Further increase of calcination temperature to 550 °C led to a decrease in total DMF and DMTHF yield with almost no DMTHF being formed. This result was attributed to the aggregation of Ni nanoparticles and thus lower C–O hydrogenolysis capability of the catalyst.

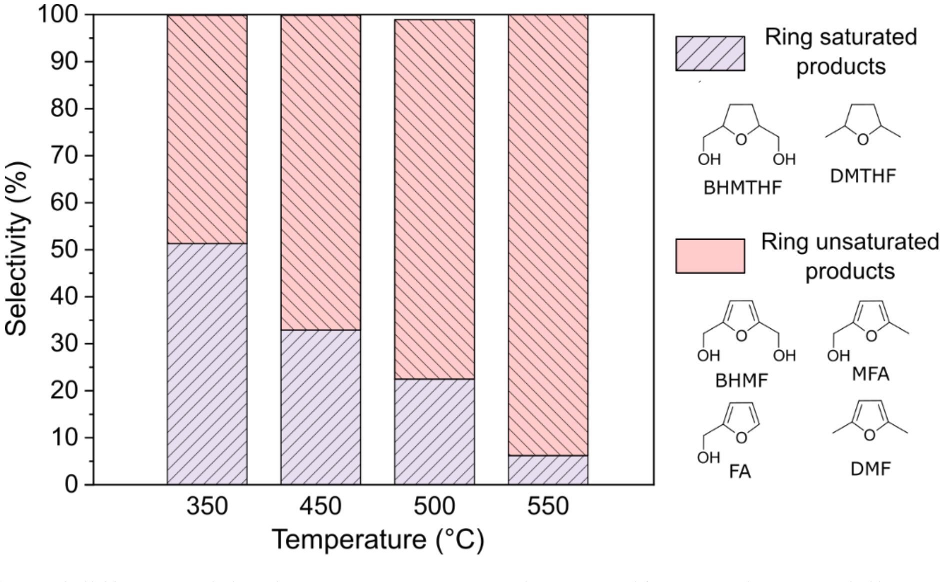


Figure 2. Effect of different calcination temperatures on the 5%–Ni/HC catalyst at a full HMF conversion, reaction conditions: 0.2 g catalysts, 0.5 g the HMF, 35 mL 1.4-dioxane, 15 bar H_2, 300 rpm/min, 10 h, 220 °C. Reworked with permission from Ref. [[75]]. Copyright 2020, Springer

To selectively obtain BHMF, authors increased the Ni loading since it is known from literature data that large Ni particle size suppresses hydrogenolysis reactions. Moreover, the increase in Ni loading also increased the NiO/Ni ratio according to XPS and H_2-TPR analysis. This technique allowed to upgrade BHMF yield from 42% using 5%–Ni/HC to 76% using 10%–Ni/HC. Even higher BHMF yield of 88% was achieved by modifying the reaction conditions to 160 °C, 15 bar H_2 and 24 h.

Bimetallic catalysts can also be considered to be tunable catalytic systems able to steer HMF hydroconversion towards different directions. For instance, the selective hydrogenation and rearrangement of HMF towards BHMTHF and 3-hydroxymethyl-cyclopentone (HCPN) was studied over MOFs-derived bimetallic Ni-Cu catalyst.[76] The Ni/C and Ni-Cu/C catalysts were prepared by pyrolysis of Ni-MOF-74 and Ni-Cu-MOF-74 material under N_2 atmosphere. The experiments were carried in water at 140 °C 20 bar H_2. The monometallic Ni/C achieved >99% conversion with 79.1% yield to BHMTHF, suggesting completely hydrogenation of C=O groups and unsaturated C=C groups in furan ring. Introduction of Cu as a secondary metal significantly altered the catalytic performance, providing a 93.8% conversion and 87.2% yield of rearrangement products (50.4% yield to HCPN) over Ni-Cu/C catalyst at otherwise similar reaction conditions. Slightly decreasing feedstock/catalyst ratio allowed to achieve 70.3% yield of HCPN and 99.8% yield for rearrangement products. Thus, Cu was believed to suppress the hydrogenation activity of Ni and slowing C=C hydrogenation, though no proper explanation of this observation was given. Remarkably, the choice of the solvent could also steer the HMF hydroconversion pathway. Changing the solvent from water to organic solvents like ethanol, tetrahydrofurfural alcohol or 1,4-dioxane significantly shifted the selectivity from rearrangement products (89.5% yield) towards BHMF formation (>70% yield). The isotopic experiments in $H_2{}^{18}O$ with MS analysis showed that water behaved as a nucleophile in rearrangement reactions and also acted as a proton donor to create slightly acidic conditions, and thus promoted the ring-rearrangement reaction. It is known that the ring rearrangement generally occurs via dehydration in the presence of acid sites. In this case, water could be speculated to serve as the main source of acidity since Ni-Cu/C catalyst was shown to have no acidic sites according to NH_3-TPD results. Kumalaputri et al. investigated the tunable conversion of HMF to BHMF and DMF/DMTHF over copper-doped porous metal oxides (PMOs) modified with small amounts (0.6 wt%) of ruthenium.[77] Firstly, the optimal conditions for selective reduction of HMF carbonyl group to produce BHMF were found. A 98% BHMF selectivity at full conversion was achieved in ethanol over CuRu–PMO catalyst at 100 °C and 50 bar H_2 after 3 hours. Nevertheless, the same BHMF yield was achieved at identical reaction conditions over Cu–PMO catalyst without Ru modification. Increasing the reaction temperature and time up to 220 °C and 12 h, respectively, led to 65% total yield of DMF and DMTHF over Cu–PMO, of which DMF was the prevailing product (DMF to DMTHF ratio of 3.4). Higher reaction temperature and time favored the C–O hydrogenolysis reactions since even at 180 °C products with hydroxyl groups, e.g. BHMF and MFA, were still present. However, an improved total DMF and DMTHF yield of 79% with the same DMF to DMTHF ratio was achieved at identical reaction conditions over CuRu–PMO. This was explained by the cooperativity effect between Cu and Ru, since ruthenium is highly active for C–O bond hydrogenolysis which is beneficial for the production of DMF and DMTHF. Wang et al. managed to control the product selectivity of HMF hydroconversion over bimetallic Cu–Co catalyst by modulating the Cu to Co ratio and tuning the structural properties of the metal catalyst support.[64] Cu/MgAlO$_x$ and Co@Cu/CoAlO$_x$ catalysts were synthesized via facile reduction of CuMAl (M = Mg, Co) layered double hydroxide (LDH) precursors. In situ EXAFS and HAADF-STEM data confirmed that spatial distributions and proportions of multiple Co–Cu interfaces can be modulated by varying the element composition and Cu to Co ratio. Higher Co content in bimetallic catalysts led to a higher contribution of metallic Co which equaled to 25% for Co@Cu/3CoAlO$_x$ and 40% for Co@Cu/5CoAlO$_x$, calculated by linear combination XANES fitting in reference to the standard Co foil, CoO, and Co_3O_4. The Cu/MgAlO$_x$ showed the lowest C−O hydrogenolysis activity among other catalysts and thus was chosen to maximize the BHMF yield. Lowering the pressure allowed to slow down the hydrogenolysis of hydroxyl groups since this step is reported to strongly depend on the reaction conditions. A 97.3% HMF conversion with 95.3% BHMF selectivity were achieved under the optimal conditions of 180 °C, 10 bar H_2 after 5 h. When the MgAlO$_x$ support was replaced with CoAlO$_x$, the C−O hydrogenolysis rate increased significantly for both Co@Cu/3CoAlO$_x$ and Co@Cu/5CoAlO$_x$ catalysts, synthesized from $CuCo_3Al_2$–LDH and $CuCo_5Al_2$–LDH precursors, respectively. Co@Cu/3CoAlO$_x$ showed the highest DMF yield of 98.5% at 5 h, whereas Co@Cu/5CoAlO$_x$ produced 60.6% DMF together with 30.5% DMTHF. DMTHF formation over Co@Cu/5CoAlO$_x$ indicated that the furan ring hydrogenation is fast over this catalyst. The extension of the reaction time to 20 h allowed to achieve 83.6% DMTHF yield over Co@Cu/5CoAlO$_x$, compared to 17.2% over Co@Cu/5CoAlO$_x$. The detailed difference in selectivity over tested catalysts is summarized in Figure 3. The C=O hydrogenation which is crucial for the formation of BHMF and DMF, was promoted by all catalysts, while the C−O hydrogenolysis was enhanced only with the assistance of the CoAlO$_x$ support. In situ IR experiments provided deep understanding of the reaction intermediates formation which was dependent on the multiple interfacial sites of the catalyst. In the case of Co@Cu/CoAlO$_x$, the interfacial unsaturated Co oxygen vacancy sites preferably adsorbed HMF molecules leading to DMF formation (and DMTHF at longer reaction times), while preferential HMF adsorption on metallic Cu over Cu/MgAlO$_x$ resulted in primary BHMF production.

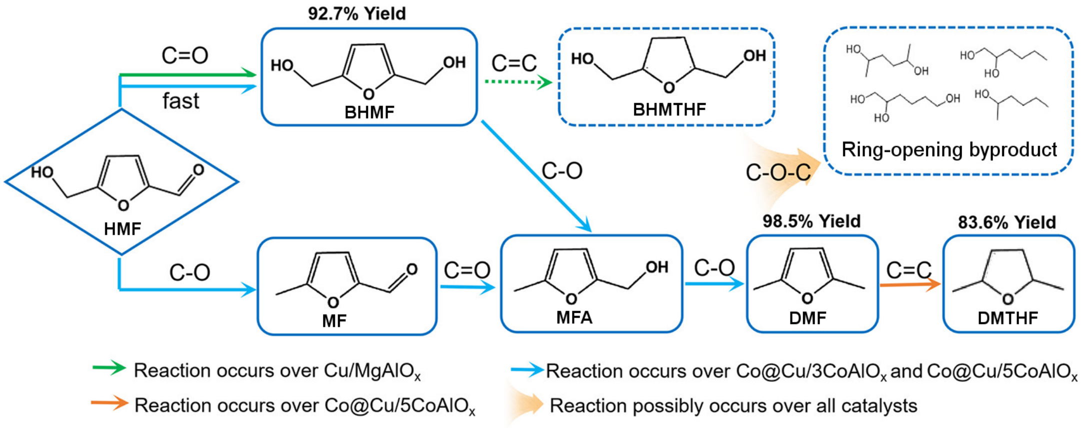


Figure 3. Reaction pathway for hydrogenation of HMF on different Cu-catalysts. Reworked with permission from Ref. [[64]]. Copyright 2020, American Chemical Society

To identify the role of active sites in the catalytic performance, $MgAlO_x$ and $Co/CoAlO_x$ derived from MgAl–LDHs and CoAl–LDHs were employed as reference samples. $Co/CoAlO_x$ provided only a 56.2% HMF conversion with BHMF being a primary product, whereas $MgAlO_x$ was totally inactive. This pinpoints the importance of Cu as an active metal to activate H_2. The Cu mean particle size differed slightly across the catalysts (from 2.1 to 3.2 nm), and therefore the differences in selectivity cannot be related to the particle size. In addition, imp–$Cu/MgAlO_x$ and imp–$Cu/CoAlO_x$ prepared by an impregnation method showed the same product distribution as the corresponding LDH-derived catalysts, but with an increased amount of ring-opening products. This was explained by the stronger metal-support interaction of the LDH-derived catalysts originated from the formed oxide-trapped structures with the geometric intimacy of the metal and support.

Feedstock impurities

Although not paid much attention to in the scientific community, the presence of process-derived impurities can arise many challenges in the efficient catalytic hydroconversion of biomass-derived HMF.[78] The application of acids makes the HMF production by dehydration a complicated process due to the possibility of many side reactions including the formation of levulinic and formic acids through HMF rehydration.[79] One of the strategies to mitigate such side reactions is to add an apolar aprotic solvent to stabilize HMF in the organic phase. It has been shown that utilization of DMSO as a co-solvent enables high (>80%) HMF yields.[80–84] The HMF solvation by DMSO reduces its susceptibility to nucleophilic attack and minimizes undesirable hydration and humin-formation reactions.[85] Nevertheless, the separation of HMF from DMSO, e.g. by distillation, is complicated. Both substances have high boiling points which makes it difficult to directly evaporate HMF or distill DMSO from the reaction solution. Moreover, the distillation of DMSO results in a highly concentrated HMF solution that at the high temperature forms humins and other polymers due to the high reactivity of HMF. Therefore, trace amounts of DMSO can always be present in commercial HMF feedstock. Despite not a lot of attention has been given so far on its presence in HMF, it may have a strong influence on the catalyst activity, since sulfur is a well-known metal catalyst poison.[86–89]

The presence of trace DMSO amounts in HMF feedstock can have a striking effect on the aromatic hydrogenation activity, and thus is able to change the product selectivity. Interesting results for instance were obtained while optimizing HMF conversion to DMTHF using Ru/C catalyst.[70] A dual catalytic behavior was found during the screening of various high purity HMF feedstocks (>97%) from commercial suppliers. The key reaction product was either DMTHF with a yield of >70% or DMF with a yield of >90%. It has been shown that such a difference was caused by the presence of trace DMSO amounts in the HMF feedstock (e.g., 1.0 and 0.7 mol.% of HMF for Sigma Aldrich and Acros Organics samples, respectively; in our hands, HMF purchased from J&K Scientific, Alfa Aesar and Avantium is DMSO free). For DMSO free feedstocks DMTHF was the primary reaction product, in contrast to DMSO poisoned HMF, where the only conversion product was DMF under otherwise similar conditions. To elucidate the effect of DMSO impurity on the catalyst properties, Ru/C catalysts recovered after conversion of pure (J&K) and DMSO-contaminated (Sigma) HMF were analyzed. According to CO chemisorption analysis, the number of accessible Ru sites decreased by more than tenfold in the Ru/C Sigma sample compared to the Ru/C J&K spent catalyst. SEM-EDX analysis and CO chemisorption experiments confirmed higher sulfur concentration in Ru/C after using Sigma HMF sample compared to Ru/C after DMSO free HMF or nonused Ru/C. EDX analysis showed that sulfur was distributed in close proximity of Ru within this sample, meaning that it was strongly associated with the Ru particles of the catalyst after the reaction. XPS analysis qualitatively revealed the presence of disulfide or thiol groups exclusively for the contaminated Sigma sample tentatively indicating the reduction of DMSO under the applied reaction conditions. In addition, the effect of DMSO on HMF hydroconversion was studied by deliberately adding known aliquots of DMSO to the non-contaminated commercial HMF feedstock (Figure 4, a).

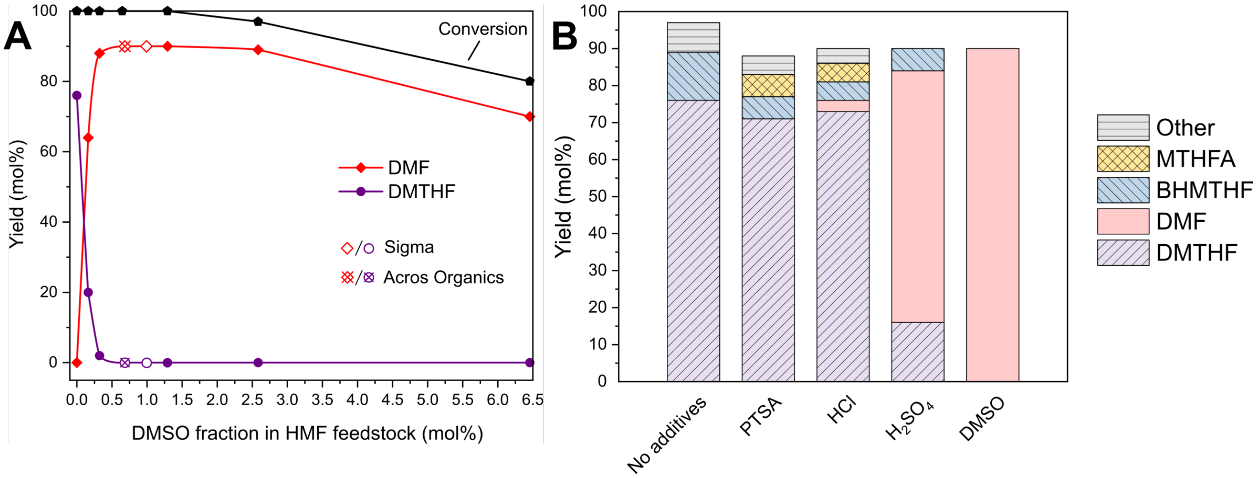


Figure 4. Influence of DMSO (a) and potential HMF impurities (b) addition on the yields of the products from J&K HMF conversion. Standard reaction conditions: 0.5 g HMF; 0.1 g Ru/C; 40.0 mL 1,4-dioxane; 50 bar H_2 at RT; T = 453 K; average ramp rate = 5 K min^{-1}; reaction time = 4 h, 800 rpm rotation speed. 20 μmol of potential HMF impurity was added. Reprinted with permission from Ref [[70]]. Copyright 2021, American Chemical Society.

The HMF conversion was only impacted for the high DMSO contents (above 1.5 mol% of HMF) likely due to the full blockage of active Ru sites. However, even minute amounts of DMSO, *viz*. 0.15 mol% of HMF, shift the selectivity from DMTHF to DMF. In this case, presence of DMSO thus hindered the furanic ring hydrogenation due to specific Ru site poisoning. This poison effect on selectivity was also observed in the hydroconversion of BHMF in presence of DMSO. Lastly, other potential HMF impurities such as p-toluenesulfonic acid, sulfuric acid, and hydrochloric acid were tested in HMF hydroconversion using DMSO-free feedstock (Figure 4, b). The addition of p-toluenesulfonic and hydrochloric acid led to only a slight increase in MTHFA yield at the expense of DMTHF. H_2SO_4 addition showed a similar but less marked effect on HMF hydroconversion selectivity compared to DMSO at equal concentrations. This effect was attributed to the strong adsorption of sulfate anions leading to Ru sites blocking rather than to the poisoning sulfur-ruthenium interaction.

A similar effect of DMSO addition on product selectivity was found by Li et al. in their study of one-pot fructose conversion towards DMTHF over Pd/C catalyst.[90] The addition of trace DMSO amount into the water-EtOEt biphasic system provoked the selectivity shift towards DMF (57.4% yield) and 2,5-HD (27.6% yield) instead of DMTHF (46.1% yield) at 130 °C after 4 h. 2,5-HD was likely formed from the DMF ring-opening reaction catalyzed by sulfuric acid present in the reaction mixture. Further increase in the DMSO loading led to another selectivity shift: MF and HMF were primarily obtained from fructose with a 34.5% and 20.4% yield, respectively. In both cases when DMSO was present in the reaction mixture, formation of DMTHF was prohibited. Authors believed that large quantities of DMSO stabilized the carbonyl groups of HMF, and thus products with aldehyde groups were mainly obtained (MF and HMF). However, DMSO added in low concentration mainly acts as a poisoning agent of Pd suppressing the double bond reduction and thus hampering DMTHF formation. The strong catalyst deactivation induced by DMSO can be caused by both sulfur and carbon deposition. Very recently, another group has reported the presence of DMSO in commercial HMF feedstock while investigating its hydroconversion to BHMF over Ni/SiO_2 catalysts.[91] The commercial sample supplied by Sigma Aldrich contained 0.5 wt% of DMSO, which is consistent with a previously discussed report.[70] Authors decided to dope the reaction feed with additional DMSO, while using 15 wt% Ni/SiO_2 catalyst. While no shift in selectivity was discussed, the recent results, similarly as with Ru/C, indicates a rate deactivation effect of DMSO when its concentration increased from 0.5 wt% to 8.5 wt%. The HMF conversion dropped to 56% after 6 hours at the highest amount of DMSO (8.5 wt%) compared to 98% conversion at 0.5 wt% DMSO concentration.

The presence of sulfur in the spent catalyst from the HMF hydrogenation in presence of DMSO (8.5 wt%) was shown by ICP analysis while HAADF-STEM with EDX mapping confirmed the location of sulfur in the vicinity of Ni particles. These results indicated that some of the catalyst deactivation likely originated from sulfur-nickel interaction. However, Raman spectroscopy experiments revealed that Ni/SiO_2 sample exposed to 8.5 wt% DMSO concentration underwent the highest degree of graphitization. The latter can lead to shell covering of active sites by carbonaceous species, thus being another reason of the catalytic activity loss.

HMF impurities can be adsorbed on the catalyst surface, thus reducing the HMF surface coverage and decreasing its conversion. The recent publication of Kim et al. shed some light on the stability of mesoporous Cu–Al_2O_3 catalyst for HMF to BHMF hydroconversion in presence of potential HMF impurities.[92] The effects of DMSO and H_2O as feedstock impurities on the catalytic performance were investigated. Preliminary batch reactor tests with DMSO addition showed that its effect on the hydrogenation activity of the Cu–Al_2O_3 catalyst was limited. Increasing the DMSO/HMF molar ratio from 0.8 to 3.3 had a minor effect on the BHMF yield, which was in the range of 97–99%. The latter only changed to a value of 89% at the DMSO to HMF molar ratio of 6.5 compared to 99% yield without deliberately adding DMSO . However, it is not clear whether HMF contained DMSO from the beginning since there is no information about its origin. It may be that low amounts of DMSO, being present in the HMF feedstock, already had an impact on the product selectivity, while further addition of DMSO only lowered the BHMF yield (and thus conversion rate) due to competitive adsorption of DMSO and HMF. The mesoporous Cu–Al_2O_3 catalyst turned out to be more sensitive to H_2O compared to DMSO likely due to stronger H_2O adsorption onto the catalyst surface. When the H_2O to HMF molar ratio changed from 0.6 to 3.2 and 7.2, the BHMF yield dropped from 97.0% to 92.4% and 68.1%, respectively, while the BHMF selectivity was constant at 96%. In addition, experiments with continuous hydroconversion of HMF were conducted using the feed containing various concentrations of H_2O. The average HMF conversion over > 50 hours slightly dropped from 98% to 94% and 91%, for 1 wt% and 3 wt% of H_2O content, respectively. However, there was no observable change in BHMF selectivity at any water content, indicating that HMF conversion decreased from a reduced surface coverage of HMF by water adsorption rather than from water-induced Cu–Al_2O_3 deactivation. Nevertheless, the product selectivity shift towards BHMF due to trace DMSO content in the feedstock could also take place.

These findings clearly indicate the utmost importance of bio-based HMF purity, with the presence of DMSO in particular. Remarkably, in 46% of the discussed manuscripts dealing with HMF transformation to BHMF, BHMTHF or DMTHF, no information concerning HMF purity is available, while in 15% of the cases even the supplier is not mentioned (see Table 1 in Supporting Information). However, given the impact of tiny amounts of e.g., DMSO on the catalytic outcome, this information is crucial for comparing experimental results from different scientific reports since most commonly HMF is used as received without further purification. In terms of product selectivity, we believe that DMSO mainly hampers the furan ring hydrogenation, thus having a particularly strong impact on the production of BHMTHF and DMTHF. In this regard, the commercial HMF likely containing DMSO was used in 19 manuscripts and for more than a half of them it could lead to erroneous conclusions about the catalyst performance.

HMF is mainly synthesized by the acid-catalyzed dehydration of monosaccharides in the aqueous or water-containing biphasic medium.[1] Thus, mineral acids such as HCl, H_2SO_4 and H_3PO_4 are frequently used to promote feedstock dehydration due to their low cost and high activity. Even minor amounts of these inorganic acids can deactivate catalysis used in the further HMF upgrading. Alamillo et al. suggested treatment of the HMF feedstock with a basic ion-exchange resin (Amberlite IRA–400(OH)) prior to reaction to neutralize the acidic impurities that could be present from dehydration of monosaccharides in acidic solutions.[55] After the treatment, the resin was removed by filtration, and the hydroconversion of HMF was carried out using Ru-containing catalysts. The feedstock treatment with resin led to a pH increase from slightly acidic (pH 5) to neutral (pH 6–7) and an increase of over 20% in the selectivity to BHMTHF at the expense of polyols. Consequently, BHMTHF selectivity can decrease due to the presence of minor acid impurities, likely assisting ring opening to form linear polyols after hydrogenation steps. HMF may contain two types of acids, organic acids that can be considered as side-product such as levulinic acid and formic acid, or residual acid catalyst from the HMF synthesis step. Levulinic and sulfuric acids were therefore added to the reaction mixture, that had been pretreated with a basic ion-exchange resin, to investigate and isolate the effects of these two acids on the HMF hydroconversion. The addition of levulinic acid (levulinic acid to HMF weight ratio = 1 : 4) led to a decrease in BHMTHF yield by 17% and an increase in the selectivity to triols and tetrols. In contrast, the addition of H_2SO_4 (H_2SO_4 to HMF weight ratio = 1 : 6, which was 3 times lower than the amount used in literature for the fructose dehydration[5]) resulted in a strong decrease of BHMTHF selectivity from 76% to 9% accompanied by an increase in selectivity to polyols and unidentified products. The enhanced production of polyols and unknown products was attributed to either HMF or BHMF acid-catalyzed degradation reactions.

The presence of mineral acids can also affect the HMF catalytic transfer hydrogenation (CTH) process. For instance, a poisoning effect of H_2SO_4 on Ru/C catalyst was observed by Gilkey et al. in the hydrodeoxygenation of DMF via CTH in 2-propanol.[93] It is believed that the efficient ring-opening of furans to linear molecules requires a combination of metal and acid sites. However, severe suppression of metal chemistry was observed when having both Ru/C and H_2SO_4 in the reaction system. When no H_2SO_4 was added to the reaction mixture, full DMF conversion was achieved having DMTHF, 2-hexanol (HOL), and 2,5-hexanediol (2,5-HDO) as the main products in yields of 33%, 22%, and 53%, respectively. Increasing the acid concentration led to a decrease in conversion and selectivity towards 2,5-HDO and HOL. When the concentration of 0.72 M H_2SO_4 was tested, both DMF conversion and DMTHF yield dropped significantly resulting in a 40% HMF conversion and 10% DMTHF yield under otherwise identical conditions. Moreover, 2-hexanol formation was not observed, providing the evidence of inhibition of Ru hydrogenation activity. Once the concentration of the H_2SO_4 reached 1.78 M, neither DMTHF nor HOL was formed during the reaction stating complete suppression of the Ru catalytic activity. In addition, experiments with water addition showed that H_2O played a negligible role in obstructing Ru's hydrogenation ability, likely only affecting the equilibrium between DMTHF and 2,5-HDO. Specific inorganic salts can also be considered to be HMF impurities since they are commonly used to accelerate monosaccharides conversion to HMF, or as agent to fortify extraction in two-phasic conditions.[94–99] The effect of various sulfate salts addition on the conversion was also investigated by the same research group (Figure 5, a). A comparable decrease in DMF conversion was observed when replacing H_2SO_4 with a sulfate salt in the identical concentration soluble in 2-propanol, e.g. $ZnSO_4$ or $MgSO_4$. However, only partial loss of metal activity was observed in the presence of the sulfate salts, since DMTHF and HOL were still produced in contrast to using sulfuric acid. This was ascribed to the incomplete blocking of metal sites by adsorbed sulfate. Switching to Na_2SO_4 (which is insoluble in 2-propanol) led to no appreciable change in product distribution after reaction, probably due to the lack of sulfate ions in the solution. However, the addition of an equimolar concentration of $NaHSO_4$ resulted in very similar product distribution to that of H_2SO_4, indicating that protons somehow are involved blocking Ru sites.

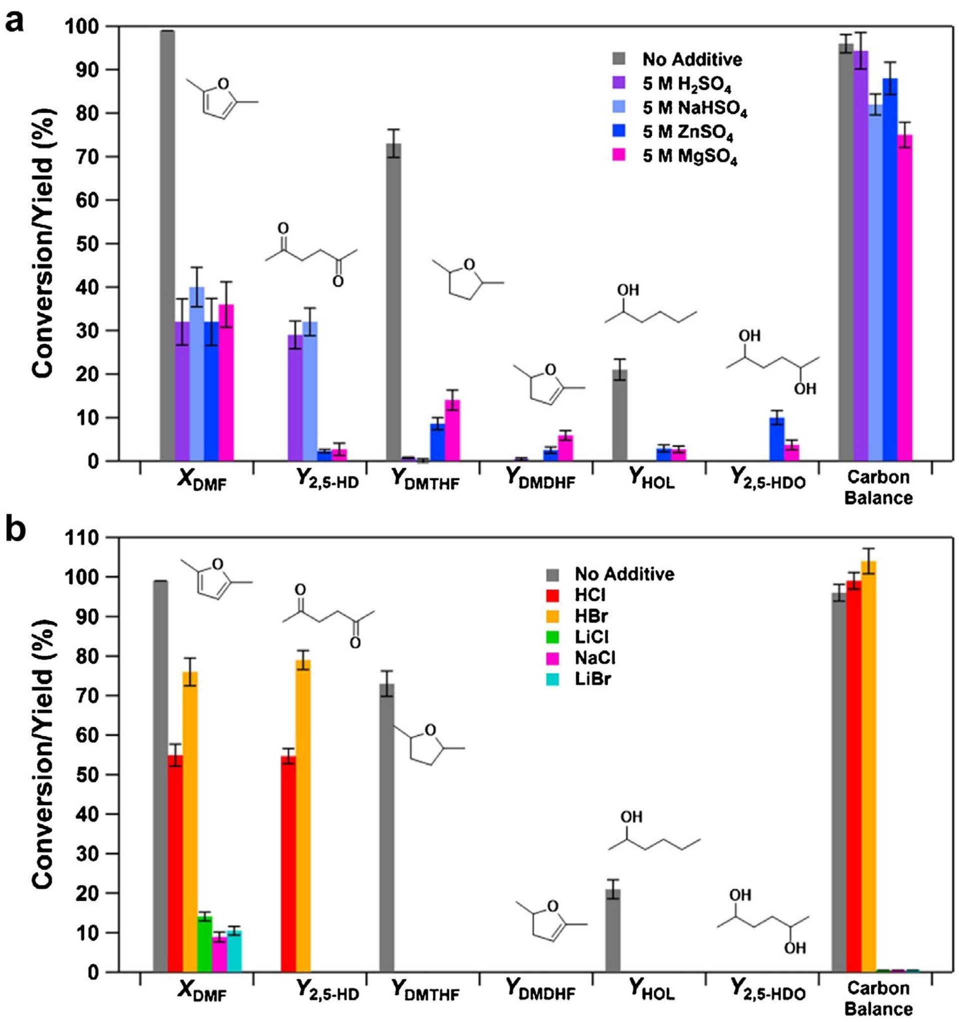


Figure 5. Effect of acids and salts (a) and hydrohalic acids and halide based salts (b) addition on DMF conversion and product distribution Conditions: 1 wt% DMF in 14 mL 2-propanol with 0.5 mL of 5 M acid or salt (in water), T = 80 °C, t = 2 h, m_{cat} = 80 mg reduced Ru/C, $P(N_2)$ = 20.7 bar. Reprinted with permission from Ref [[93]]. Copyright 2017, Elsevier.

Halides showed similar suppression of Ru's ring hydrogenation activity, evidenced by the minimal formation of DMF hydrogenation products in their presence (Figure 5, b). The addition of mineral acids e.g. HCl, HBr, or HI led to a full blockage of hydrogenation and hydrogenolysis chemistry of Ru, leading to the sole production of 2,5-HD. Halide salts were more severe in deactivating Ru sites compared to sulfates at similar concentrations, likely due to their stronger binding ability to Ru. The poisoning nature of sulfate and halide anions interaction with Ru sites was supported by the lack of catalyst deactivation when replacing mineral acids with a solid acid, i.e., Nafion, because the tethered sulfonic groups cannot adsorb the Ru sites on carbon due to their compartmentalization. Ex-situ pre-treatment of Ru/C catalysts by sulfuric acid or sulfate salts at room temperature for 2 h resulted in total catalyst deactivation indicating that sulfuric acid or sulfate salt is able to irreversibly block or remove the active sites on Ru/C. However, 2,5-HD could still be converted (>99%) over these catalysts although with a significantly lower carbon balance.

This suggested that Ru sites responsible for hydrogenation were poisoned significantly but not completely. Ex-situ XPS analysis and CO chemisorption experiments revealed that the availability of Ru sites strongly decreased after both sulfate salt and acid pre-treatments. Authors suggested two mechanisms of Ru deactivation: proton-mediated water removal from RuO_2 sites with subsequent covalent sulfate bonding, and CTH-mediated reduction of Ru followed by non-covalent sulfate-Ru interaction. When acids are used, both mechanisms can occur, resulting in a more pronounced loss in activity. This was consistent with experimental data, when increasing the concentration of H_2SO_4 resulted in a more pronounced Ru deactivation. On the other hand, the deactivation in presence of salts can only proceed via the second mechanism due to the lack of protons, thus leading to a milder loss in activity.

The carbon-supported Ru catalysts thus proved to be very sensitive to minor amounts of H_2SO_4. In contrast, Ru catalysts supported on metal oxides, such as ZrO_2, can be stable in the presence of the same impurity due to preferential sulfate adsorption onto the support surface which protects Ru active sites from deactivation. Ftouni et al. showed that minor amounts of H_2SO_4 (i.e., 0.025–0.1 wt% with respect to the total feed weight) significantly inhibited the hydroconversion of levulinic acid (LA) to γ-valerolactone (GVL) over Ru/C catalyst, with GVL yield nearly decreasing to zero.[100] Authors proposed to use Ru/ZrO_2 as a catalyst prone to sulfur-induced deactivation. The GVL yields over Ru/ZrO_2 catalyst with and without trace H_2SO_4 impurities were 96% and 91%, respectively. However, H_2SO_4 concentration of 1.0 wt% resulted in almost complete deactivation of Ru/ZrO_2 catalyst, giving very low LA conversion and GVL yield. The obtained results suggested that the ZrO_2 support acted as a sulfate scavenger of finite capacity. The scavenging function of the ZrO_2 support was proved by a set of experiments using a physical mixture of Ru/C and ZrO_2 with 0.1 wt% H_2SO_4. The GVL yield obtained with physical mixture of Ru/C and ZrO_2 was similar to that obtained with Ru/ZrO_2 and superior to that obtained with Ru/C alone. This indicates that the scavenging process occurred much faster than reactions leading to Ru poisoning. Moreover, authors proposed a suitable regeneration method of Ru/ZrO_2 catalyst through a hot water wash followed by mild drying, which provided good stability after five reuse cycles in the presence of H_2SO_4.

Finally, side-products obtained from carbohydrates dehydrogenation to HMF can also become impurities changing the further HMF hydroconversion process. For instance, increasing the temperature of fructose conversion to obtain higher HMF yields can lead to the degradation of HMF, visible as a deep brown color.[101] The by-products could be soluble polymers and humins formed from condensation between HMF molecules or cross-polymerization between HMF and fructose. Remarkably, the acid-catalyzed dehydrogenation of fructose to HMF was shown to produce more humins than that of glucose or xylose due to a higher HMF concentration in the solution.[102] This data is consistent with other report stating the humin formation to be first order in HMF.[103] Humins generally grow as spherical particles having the increasing diameter as the reaction proceeds.[104,105]Most commonly, they have an olygomeric furan structure with alcohol, acid, ketone, and aldehyde functional groups. The mechanism of humins formation includes aldol condensation, and/or etherification reactions along with the direct HMF addition to the primary particles.[106] In this regards, the HMF concentration in the solution is an important parameter that needs to be cautiously considered for the selective HMF hydroconversion. Generally, the HMF concentrations less than 5 wt.% are applied in catalytic studies (see Tables 1-3). Adopting too high concentrations can lead to a lower catalytic performance due to enhanced humins formation, thus leading to smaller amounts of HMF available for the target transformation. These effects can be even more pronounced at high temperatures or in the presence of acids and catalysts with acidic properties since the reactions of aldol condensation and etherification are acid-catalyzed. Being present as minor compounds in the HMF feedstock or formed during the reaction, humins can also influence the catalyst performance and thus the HMF hydroconversion process.

While studying the HMF hydroconversion over transition metal catalysts, Iriondo et al. found that the presence of humins can impact product selectivity.[107] Two types of HMF feedstocks were tested, one feedstock containing humins was obtained from fructose dehydration containing around 0.7 wt% of HMF in 1-butanol, while the pure one was prepared using 0.7 wt% of commercial HMF (likely containing DMSO based on the origin tracing) diluted in 1-butanol. It should be noted that that the procedure of fructose to HMF conversion is not described in detail, thus it is not clear whether DMSO was used as a co-solvent. Moreover, the commercial HMF was purchased from Sigma Aldrich, which was reported to contain DMSO impurities.[70,91] In the case of their purest commercial HMF, a 43.0% DMF selectivity was obtained over CuZr catalyst after 2 h at 200 °C 5 bar H_2 in a continuous bench-scale fixed bed reactor, whereas 11.0% selectivity was obtained using the self-made crude HMF feedstock at similar conversion and otherwise similar reaction conditions. Authors believed that lower DMF selectivity was related to the presence of impurities (mainly 5-methyl furfural and furfural) in the HMF feedstock produced from fructose dehydrogenation, even though not being detected with the used equipment. Perhaps, a selectivity shift could occur while using the commercial HMF that may contain DMSO, thus enhancing the selectivity towards DMF. However, it is not clear from the experimental data what were other reaction products formed during HMF conversion besides DMF. Recently, the addition of crude and purified humin samples was found to influence the catalytic hydrogenation of levulinic acid to γ-valerolactone over Ru-containing catalysts.[108] The industrial humins were produced by fructose conversion in methanol, while the purified ones were obtained by solvent washing of a crude sample to remove residual monomeric HMF and 5-methoxymethylfurfural. The addition of 1 wt% crude humin sample (relative to the total weight of the mixture) led to a significant decline of the total GVL and 4-hydroxypentanoic acid (4-HPA) yield at short reaction time in water medium (Figure 6). In the case of purified humins, similar but less marked effect was observed. Such difference was explained by the presence of low molecular weight impurities in the crude humin sample compared to purified humin sample that contained only oligomeric humins. Remarkably, reactions in dioxane at 150 °C in presence of 0.5 wt% purified humins provided a more significant effect on product yields at short reaction times compared to the addition of the same amount of purified humins in water. This was explained by the humins solubility, being higher in dioxane compared to in water. Nevertheless, in all cases the overall GVL plus 4-HPA yield did not change significantly after 300 minutes of conversion stating that humins had a limited effect on LA conversion.

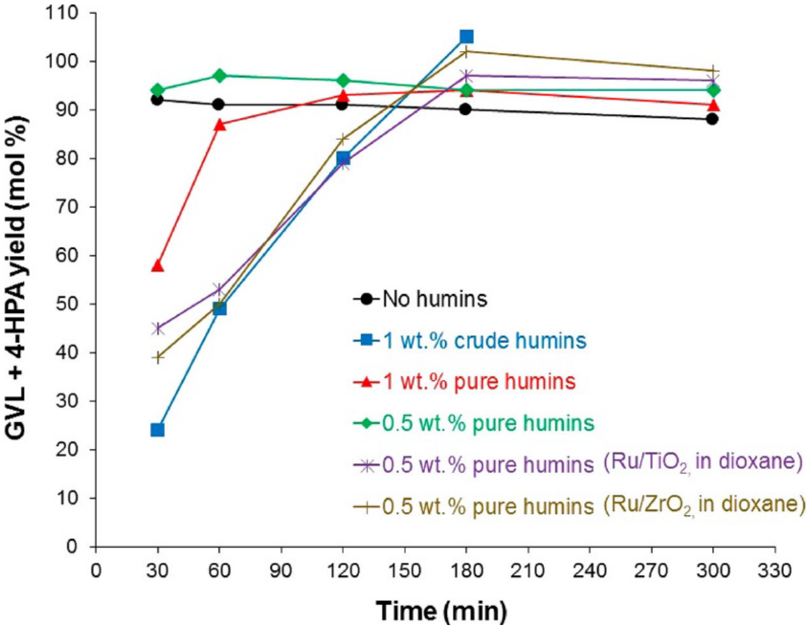


Figure 6. Influence of humins on LA hydrogenation activity. Combined GVL and 4-HPA yields are given as a function of time in a batch setup using 1 wt% Ru/TiO_2 catalyst in water in the presence of crude and purified industrial humins at different wt% intakes. Conditions: LA/Ru wt ratio of 400, 90 °C (water), 150 °C (dioxane), and 50 bar H_2. Reprinted with permission from Ref [[108]]. Copyright 2020, American Chemical Society.

Surprisingly, even purified HMF can undergo degradation during its storage. Ananikov et al. have found that a 97–99% pure HMF is susceptible to rapid aging and decomposition while being stored in an oil form. HMF was synthesized from fructose in [BMIm]Cl ionic liquid with H_2SO_4 as a catalyst. Firstly, HMF was isolated as an oil (97-99% purity), dried and stored at room temperature. After two weeks of storage, HMF dimer was formed with almost 50% yield which was confirmed by X-Ray and NMR analysis. In addition, several higher molecular weight compounds with three to ten furan cores were formed which was revealed by HPLC-ESI-MS study. This process was accompanied by the color change of the sample from light yellow to dark brown. Secondly, under optimized reaction conditions, >99% pure HMF was obtained in the form of yellow crystals. In contrast to the behavior of oily HMF, the crystalline HMF did not decompose and remained pure, as confirmed by NMR and MS analysis, after the storage for 1 month at room temperature. Authors suggested that the aggregation of HMF in solution led to the formation of a self-organized hydrogen-bonded network which favored the dimerization and further oligomerization. Moreover, this process is readily facilitated at high concentrations of HMF or in the presence of acidic impurities. Finally, the synthesis of valuable pharmaceutical product Ranitidine was carried out from various HMF feedstocks to evaluate their performance. An overall yield of 65% was obtained starting from both fresh and stored for one month crystalline HMF. In contrast, only a 15% yield of Ranitidine was obtained using one-month-old oily 5-HMF. It is worth to mention that the formed HMF dimers and oligomers exhibited similar reactivity compared to HMF and readily participated in the same reactions resulting in lower target product yield. Therefore, a special attention should be paid to the presence of HMF oligomers (primarily by means of physical appearance) while working with commercially supplied HMF feedstocks.

Summary and Outlook

In this review, we have critically highlighted the latest developments on the catalytic hydroconversion of HMF towards various valuable chemicals, and noted where possible some caution in the conclusions due to new insights. The key messages and strategies of selective HMF transformation into BHMF, BHMTF and DMTHF as well as the catalytic insights concerning the multifunctional/cascade catalytic systems are summarized below. The insight in effects due to presence of impurities are in particularly highlighted as ignorance of those could give erroneous results and wrong (general) conclusions with respect to structure/activity relationships, as well as this is essential to get an handle on (expensive) purification steps prior to HMF upgrading.

The key challenge in BHMF (primary product) synthesis lies in priority hydrogenation of the HMF aldehyde group, while avoiding furan ring hydrogenation and C–O hydrogenolysis of the hydroxyl groups. Moderate reaction temperatures and pressure, especially with noble metal catalysis, are sufficient to cease HMF hydrogenation selectively at the stage of BHMF. High BHMF selectivity was observed for all metal catalysts when using molecular hydrogen as a hydrogen source. However, the use of non-noble metals often requires higher reaction temperatures (>100 °C) to achieve BHMF yields similar to those in the case of noble metals at lower temperatures (<60 °C). Here, the researcher plays with the structural properties of the catalyst to create optimal structural properties that can promote for instance the adsorption and activation of the HMF carbonyl group, facilitating its selective hydrogenation. Besides catalyst properties and reaction conditions, the selective BHMF production depends also on the solvent properties, with high polarity and negative difference between donor and acceptor number being favorable for high BHMF yields at elevated temperatures and pressure. Catalyst tuning may be different depending on the reducing agent, *viz.* molecular hydrogen versus hydrogen donors. Lewis/Brønsted catalyst sites accelerate the etherification of BHMF with the alcohol solvent used in CTH, resulting in lower BHMF selectivity. Therefore, low catalyst acidity is preferential for BHMF production via CTH process.

More active hydrogenation catalysts are needed to hydrogenate the HMF furan ring, thus explaining the more frequent employment of noble metals, such as Pd and Ru, for the secondary BHMTHF product due to their furan ring configuration favorable for its saturation. Slightly increasing reaction temperature and H_2 pressure are advantageous to avoid side products from reactions other than hydrogenations. Too high temperatures, *viz.* 130°C and higher, should be avoided as they enable the high energy barrier cleavage of C–O bonds. The isoelectric point of the catalyst support or catalyst additive also needs to be taken into account, although it is not clear what is beneficial for selective production of BHMTHF.

The catalytic transformation of HMF to DMTHF requires a subsequent transformation of all HMF functional groups and thus is accompanied by numerous side reactions. Compared to BHMF and BHMTHF synthesis, higher temperatures (> 180 °C) and longer reaction times (>10 h) are most commonly applied. The presence of both metal and acid sites is required to reach the balance between the furan ring hydrogenation and C–O hydrogenolysis reactions, thus providing high DMTHF yields. Despite some promising results, the development of highly effective catalysts with finely tuned active sites is still challenging but highly desirable.

Among mentioned chemicals, DMTHF synthesis from HMF is the most challenging due to high requirements to the catalyst properties which is necessary to selectively produce DMTHF while avoiding the formation of numerous side products. Further research should be focused on DMTHF production from HMF, that can be considered as a mature platform chemical, rather than from carbohydrate feedstock in a one-pot conversion process. Strongly different reaction conditions and catalyst properties to achieve high sole yields of HMF and DMTHF in combination with numerous side reactions make a one-pot synthesis approach very difficult to perform. The mechanism of DMTHF formation also needs more detailed investigation since at this moment there is no clear agreement on its formation from HMF.

The utilization of tunable multifunctional catalytic systems is a novel approach towards the selective production of biomass-derived chemicals. The strategy of changing only the reaction conditions and the catalyst synthesis procedure is more efficient to obtain concrete HMF derivatives from both catalyst potential and economical points of view. It is worth mentioning that most of those catalytic systems are based on non-noble metals such as Ni or Cu, which is crucial for the design of economically competitive processes. Currently, such multifunctional catalytic systems are scarcely studied, though deserving attention and further development.

The effect of biomass-derived HMF purity is crucial in the aspect of its further catalytic upgrading since even trace amounts of impurity can drastically change HMF conversion and product selectivity. Therefore, more attention should be paid to the (mentioning of) substrate origin and purity to avoid erroneous conclusions about catalyst properties and its performance. In this regard, HMF separation techniques have to be developed to isolate various impurities including DMSO, levulinic acid, formic acid, inorganic acids and salts, humins, and water since they can strongly influence the catalyst performance during the following catalytic hydroconversion process.. Devising catalysts prone to such poisoning agents would help to selectively obtain desired products when the presence of such impurities is inevitable. However, selective catalyst poisoning by low amounts of mentioned impurities has a big potential for shaping the selectivity control of HMF hydroconversion, though requiring careful examination. Lastly, the balance between high substrate concentration and the formation of side products from HMF should be ensured to maximize the hydroconversion efficiency.

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