ChemSusChem

Review
doi.org/10.1002/cssc.202501282

Chemistry Europe
European Chemical
Societies Publishing

www.chemsuschem.org

Effect of Lignin, Humins, and Biomass-Derived Acids on Kinetics of Catalytic Hydroxymethylfurfural Production during Saccharide Dehydration Reactions

Ana Jakob, Blaž Likozar, and Miha Grilc*

Hemicelluloses, the most prevalent components of waste lignocellulosic biomass, can be efficiently converted through the hydrolysis of polysaccharides and subsequent dehydration of individual sugar units into value-added furanics. Over the past two decades, the hydroxymethylfurfural (HMF) biobased compound has demonstrated immense potential for its utilization capacity. However, the low process efficiency of the HMF production on an industrial scale has been restricting its valorization. Experimental kinetic studies are thus useful to elucidate underlying reaction mechanisms, enabling process optimization, and assessing biorefinery techno-economic operation. This review aims to present, analyze, and examine the validated characteristic activity of homogeneously, and heterogeneously catalyzed sugar dehydration, namely glucose, fructose, and xylose, as well as real wood and agricultural streams. Kinetic studies demonstrated the trend of strong temperature sensitivity for both HMF and humin formation and feedstock-dependent selectivity. Systematic testing with complex mixtures, controlled material samples, and model chemical intermediates contributes to unraveling the impact of feedstock complexity on HMF synthesis by identifying unwanted interactions and regulating the influence of impurities. Therefore, the principles of these elusive pathways are evaluated, discussing the possibilities of limiting undesired side products. Comparing the relevance of HMF, an overview is concluded with the acknowledged challenges of feedstock, impacting HMF selectivity.

1. Introduction

A rapid increase of the world population, growing demand of energy consumption, and accelerating carbon footprints are resulting in global warming and depletion of natural resources. In search for a suitable alternative, biomass can efficiently replace nonrenewable feedstock, although the application and viability of biofuel and biobased chemicals itself can be challenging due to not fully optimized and costly infrastructure and technologies.[1,2] Therefore, the development of efficient processes and cost-effective feedstock utilization up to date remains essential, prior to the widespread use of biomass.[3]

Generally, lignocellulosic biomass contains 25%–35% hemicellulose, 40%–50% cellulose, and 15%–20% lignin, denoted in **Table 1**.[4] Its complexity currently demands fraction isolation/separation for efficient production of targeted final products. Different physical/mechanical (milling, comminution, steam explosion, hydrothermolysis), chemical (acid, base hydrolysis, pyrolysis, organosolv), and biochemical (enzyme-hydrolysis) pretreatment methods can be employed to alter its structure and composition.[5] The proportion of individual biomass fractions is conditioned by its origin and can differ among the sources (plant residue, wood waste, and so on), which can be a vital parameter for the selection of suitable pretreatment and/or later product selectivity.[6]

After lignocellulose biomass fractionation, isolation, and hydrolysis of polysaccharides obtained from the (hemi)cellulose portion of biomass, several monomeric sugar units are available for further conversion. Pentoses present in hemicellulose fraction of biomass are, via dehydration reaction, converted into furfural, whereas hexoses (present in cellulose and hemicellulose) can be dehydrated into 5-hydroxymethylfurfural (5-HMF). 5-HMF can be also further rehydrated into levulinic acid (LA) and formic acid (FA), as demonstrated in **Figure 1**.[7] Common starting feedstocks for sugar dehydration into 5-HMF are biomass derived glucose and fructose. Using glucose as a reactant can appear to be more challenging, since it usually requires an additional step of isomerization. However, its lower cost makes glucose more industrially relevant feedstock for further conversion.[8] Acid-catalyzed dehydration is up till now the most studied route for the dehydration of sugars into 5-HMF.[9] In addition to the reaction of rehydration, 5-HMF yield and selectivity can be reduced due to the side reactions via (cross)polymerization of 5-HMF and sugars, resulting in humin formation, an undesirable furanic polymer.[8,10] Humins are identified as complex carbonaceous, heterogeneous, polydisperse compounds, and they can be classified as insoluble humins

---

A. Jakob, B. Likozar, M. Grilc
Department of Catalysis and Chemical Reaction Engineering
National Institute of Chemistry
Hajdrihova 19, Ljubljana 1000, Slovenia
E-mail: miha.grilc@ki.si

A. Jakob, M. Grilc
University of Nova Gorica
Vipavska 13, Nova Gorica 5000, Slovenia

Table 1. Variability of the feedstock of lignocellulosic biomass.

Feedstock	Celluloses [%]	Hemicelluloses [%]	Lignin [%]	References
Sugarcane bagasse	44	29	20	[145]
Corncob	30	37	33	[90]
Rice husk	28	28	24	[145]
Corncob	50	31	15	[145]
Maple wood	41	18	24	[146]
Corn stover	33	23	16	[146]
Soft wood (pine)	31	19	29	[147]
Switchgrass	34	26	16	[147]

(solid humins) and soluble humins (humin precursors).[11,12] Due to their complexity and difficult analytical determination, their precise molecular structure still remains relatively unknown.

With suitable analytical techniques such as solid-state nuclear magnetic resonance (NMR) and Fourier transform infrared (FTIR), researchers have been able to partially identify the structure of humins.[11,13] Studies mostly agree that humins are polymerized furanics, connected through aliphatic linkages with additional carboxyl, hydroxyl, and carbonyl groups.[14] Humin formation is not only responsible for greatly reduced 5-HMF and furfural yields but also can contribute to reactor plugging and catalyst poisoning/deactivation.[15,16] Reactor clogging during biomass valorization and sugar dehydration commonly occurs due to excessive humin formation; however, it can be particularly facilitated when using real biomass feedstock. Uncontrolled humin formation and/or utilization of not fully fractionated lignocellulosic biomass can result in excessive polymerization and solid formation.[17] As this issue can be particularly challenging, several mitigation strategies, such as enzymatic pretreatment and the use of suitable polar solvents, can be employed as viable solutions.[18] In addition, reactor design, in combination with careful solvent selection, can further contribute to mitigating humin formation and reducing the potential risk of reactor clogging. For instance, biphasic continuous-flow reactors have been reported in the literature as a promising approach to limit humin formation.[19,20]

Considering the aforementioned challenges, reaction conditions, catalyst, and starting sugar concentration must be carefully selected to minimize off-path reactions of humin formation.

Several studies have been investigating various factors that influence the 5-HMF production, including properties of different homogeneous and heterogeneous catalysts,[7] solvent,[9] feedstock composition, and heating systems.[21] The addition of polar aprotic solvents (such as dimethyl sulfoxide [DMSO], tetrahydrofuran [THF], methyl isobutyl ketone [MIBK]) to aqueous medium has so far shown superior performance, limiting side reactions, and achieving high 5-HMF yields.[7] Improved 5-HMF selectivity was also demonstrated in ionic liquids as a reaction media.[22] With acid-catalyzed dehydration of fructose performed in DMSO, Morales et al. and Sajid et al. achieved $\approx$90% molar yield of 5-HMF.[23,24] The benefits of H_2O/THF medium for lignocellulosic biomass conversion were presented by Li et al.,[25] with the role of THF as a cosolvent in a monophasic and/or biphasic system. Nikolla et al. reported 57% yield of 5-HMF from glucose feedstock in a THF-water biphasic system.[26] Good performance of a MIBK/water biphasic system was reported by Roman-Leshkov et al., where continuous, in situ extraction of 5-HMF resulted in 55% yield from fructose feedstock.[7,27]

The selection of catalysts is another critical factor that can greatly influence 5-HMF selectivity. Therefore, various types of homogeneous and heterogeneous acid catalysts have been investigated, trying to elucidate the role of Brønsted and Lewis acidity on saccharide conversion. As homogenous catalysts,

Ana Jakob is a researcher at the National Institute of Chemistry, Slovenia. She specializes in biomass valorization, focusing on the catalytic and noncatalytic conversion of sugars and hemicellulose into platform chemicals such as furfural, HMF, and LA, integrating experimental research with kinetic modeling and process optimization.

Blaž Likozar is a head of the Department of Catalysis and Chemical Reaction Engineering at the National Institute of Chemistry (NIC), Ljubljana, Slovenia. He is leading the research programme Chemical Reaction Engineering, as well as numerous research projects (15 H2020/40HorizonEurope alone). His expertise lies (among others) in heterogeneous catalysis materials, modeling, simulation, and optimization of thermodynamics, transport phenomena, and reaction kinetics. He has authored $>$400 articles, was cited $>$15 000 times, having a h-index of 66. He is also involved in many industrial projects.

Miha Grilc is a senior researcher at the National Institute of Chemistry and a lecturer at University of Nova Gorica. He works on catalytic biorefining processes, focusing on reaction engineering and electrification of multiphase reactors and microkinetic modeling of corresponding phenomena including reaction kinetics, sorption kinetics, transport phenomena, thermodynamics, and fluid dynamics.

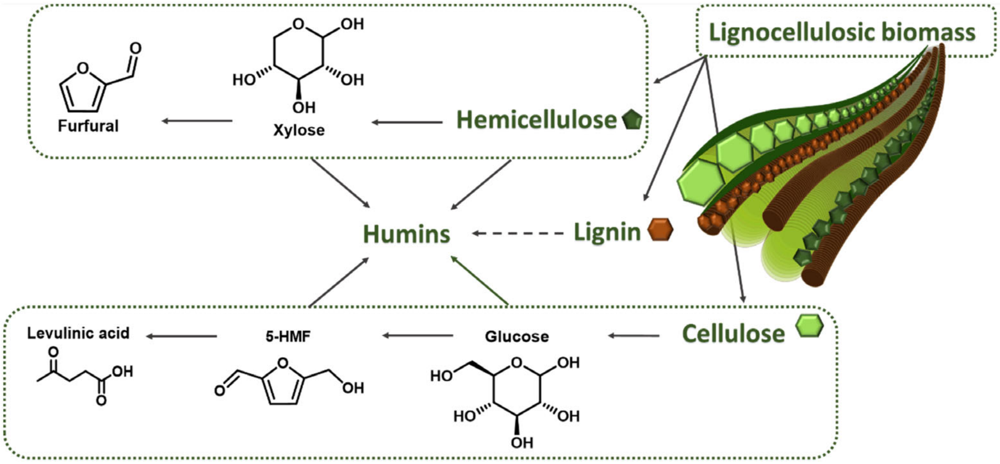


Figure 1. Formation of humin and polymerization byproducts during biomass valorization. (5-HMF~5-hydroxymethylfurfural). Adapted with permission.[12] Copyright 2013, John Wiley and Sons.

mineral (HCl, H_2SO_4) and organic acids (acetic, formic, lactic and so on) are widely used Brønsted acids, facilitating hydrolysis and dehydration, while metal chlorides ($AlCr_3$, $CrCl_2$, $SnCl_4$) as Lewis acids contribute to the glucose-fructose isomerization.[28,29] Due to the easier catalyst separation, recyclability, and nontoxicity, heterogeneous catalysts are often preferred over homogeneous. Heterogeneous catalysts can also overcome some challenges associated with the application of biocatalysts, such as higher cost and lower activity.[10] Commonly used solid acid catalysts for 5-HMF production are ion-exchange resins, namely Amberlyst-15 and Dowex-50, different types of zeolites, functionalized carbons and silica, metal oxides, and phosphates.[10]

So far, studies have mainly focused on the sugar dehydration reaction starting from sugar model compounds, fructose, and glucose, respectively. With the implementation of the real lignocellulosic biomass mixtures, the reaction itself becomes much more challenging to control, due to its complexity. To this end, information obtained through kinetic studies may be critical for further development of the process. By identifying key intermediates and rate-determining steps, they essentially provide valuable information for process optimization and efficient catalyst design.[30] Researchers perform reaction kinetic studies using different principles, such as power-law and/or first order kinetic modeling. Various studies focus on kinetics of homogenously catalyzed dehydration reactions. Alternatively, the studies conducting kinetic modeling of heterogeneous systems provide crucial information of liquid and surface phase reactions.[31,32] Although many conducted studies are limited to the kinetics of sugar model compounds, transferring, modifying, and studying the kinetic models for real biomass streams gives important information about the effect of several factors impacting the reaction. Therefore, this review aims to examine and assess the most relevant kinetic studies in order provide information about the optimal reaction conditions and catalyst selection for the lignocellulosic biomass conversion into 5-HMF. Knowing, humins are an unavoidable side product of sugar dehydration reaction, the goal is to provide information on humin formation and its efficient inhibition. Focusing on more effective feedstock utilization, the impact of lignin on the selectivity and kinetics of catalytic dehydration reaction will be discussed.

2. Mechanism of Carbohydrate Dehydration Reaction

Once glucose monomers become available, following the hydrolysis of (hemi)cellulose, different mechanisms and pathways are possible for the further conversion toward 5-HMF.[33] Based on theoretical studies, both acyclic and cyclic pathways of dehydration have been proposed. Staring with glucose as a substrate, researchers are concise that dehydration proceeds dominantly through the cyclic pathway, **Figure 2**.[28] Solvent system and catalyst selection can highly influence the reaction pathway itself.

Dehydration of glucose into 5-HMF over Brønsted acid catalyst can proceed solely through cyclic intermediates with negligible contribution of isomerization to fructose.[34] According to density-functional theory (DFT) calculations, Yang et al. reported glucose protonation as a rate-limiting step, followed by dehydration into protonated intermediates, which are able of further dehydration into 5-HMF. Similarly, Rodriguez et al. proposed a direct conversion of glucose to 5-HMF catalyzed by Brønsted acids, with results supported by a combination of experimental (13C NMR carbon mapping and kinetic isotope effects) and molecular dynamics simulation techniques.[35] In the presence of Lewis acid catalyst, glucose conversion proceeds via glucose-fructose isomerization. An important contribution to the understanding of underlying isomerization mechanism was presented by Román-Leshkov et al.[36] Authors have suggested two pathways of isomerization based on the nature of the selected catalyst. In the case of Lewis acid, isomerization proceeds through intramolecular hydride shift, but when basic catalyst is used, this step proceeds via proton transfer.[37] Alternatively, when using

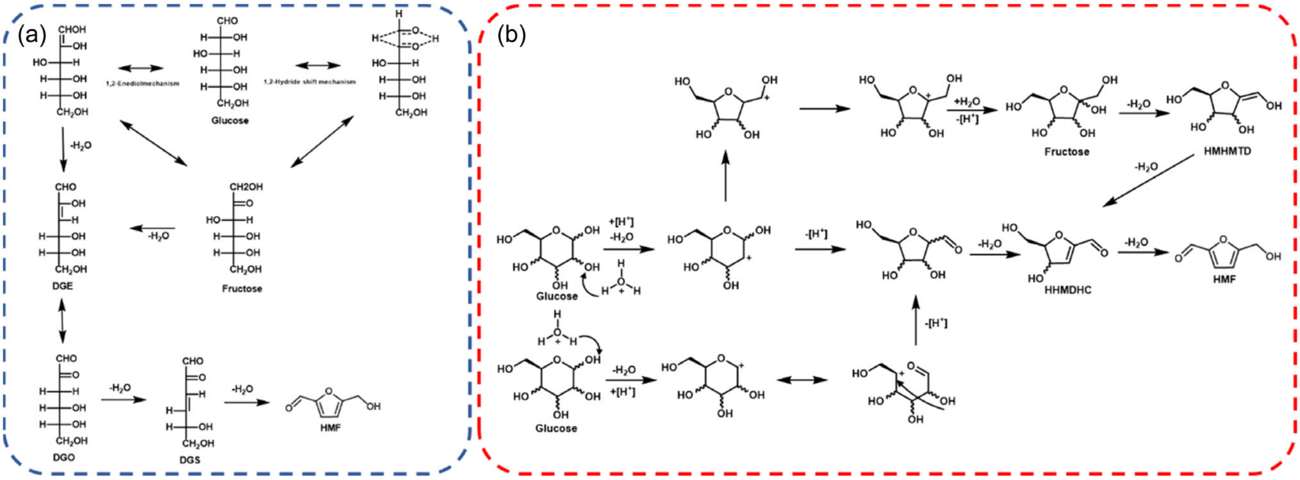


Figure 2. a) Acyclic and b) cyclic reaction mechanism of glucose and fructose dehydration. Abbreviations: DGE~3-deoxyglucos-2-ene, DGO~3-deoxyglucosone, DGS~3,4-deoxyglucosene, HMHMTD~2-(hydroxymethyl)-5-(hydroxylmethylene)-tetrahydrofuran-3,4-diol, HHMDHC~4-hydroxy-5-(hydroxymethyl)-4,5-dihydrofuran-2-carbaldehyde. Adapted with permission.[28] Copyright 2020, Elsevier; [35] Copyright 2023, American Chemical Society; [41] Copyright 2020, The Royal Society of Chemistry.

aqueous solution of LiBr, not only Li+ but also Br− ions significantly contributed to isomerization through the mechanism of proton transfer (as a weak Lewis base).[38] Choudhary et al. described the mechanism, denoted in Figure 7, where the Brønsted base is responsible for deprotonation, which later enables the second step of intramolecular hydride shift catalyzed by Lewis acid.[39] Thus, a synergy of Lewis acidity and Brønsted basicity (—OH) is required for glucose-fructose isomerization in aqueous media. After isomerization, hemiacetal of fructose in cyclic ketofuranose form can be dehydrated into 5-HMF in three consecutive steps, which involves two intermediates 2-(hydroxymethyl)-5-(hydroxylmethylene)-tetrahydrofuran-3,4-diol (HMHMTD) and 4-hydroxy-5-(hydroxymethyl)-4,5-dihydrofuran-2-carbaldehyde (HHMDHC), depicted in Figure 2.[28,40] Alternatively, fructose can undergo dehydration via acyclic path. This has been studied mostly to explain the formation of some side products, such as furfural.[41,42] Open configuration of fructose can undergo three steps of dehydration, with rate limiting step of 1,2-endiol isomerization.[40] Although according to the experimental studies conducted in D2O and with deuterated glucose or C_{13}-labeled fructose, the cyclic pathway is considered more plausible, especially in aqueous media.[36,41] Furfural was also later suggested to form through the cyclic pathway, predominantly in weak basic media.[34,43] The formation of degradation side products during saccharide dehydration reaction are almost unavoidable, partially due to the unstable nature of 5-HMF. Reaction can proceed with rehydration of 5-HMF to levulinic and FA or 5-HMF can undergo poly-condensation, leading to humin formation. Horvat et al. was first to propose the mechanism of both mentioned reactions, where LA can be formed through an intermediate of 2,5-dioxo-3-hexenal.[44] With C_{13} labeling and in situ NMR experiments, researchers were later able to identify the exact mechanism of rehydration, where the C1 carbon in 5-HMF forms FA, whereas the C6 carbon of 5-HMF correlates with the C_5 carbon in LA.[45]

3. Mechanism of Humin Formation and its Inhibition

The mechanism of humin formation can be attributed to different substrates during dehydration reaction, including sugars, furanics (5-HMF or furfural), or their intermediates. Sumerskii et al. studied formation of humin-like substances (HLS) under industrial conditions of wood hydrolysis (0.5% H_2SO_4, 2 h, 175–180 °C).[15] Authors proposed poly-condensation of 5-HMF via formation of carbocation. Protonation of either the aldehyde or alcohol group enabled the formation of ether or/and (hemi)acetal derived oligomers. In hydrothermal acidic media, the possibility of LA or monosaccharide integration into humin formation was not excluded. Considering the presence of lignin authors also suggested the possibility of lignohumic complex formation. Based on analytic techniques (gas chromatography-mass spectrometry (MS) and 13C-NMR), it was suggested that HLS are comprised of 60% furanic rings and 20% aliphatic linkers.[15] Acidic properties of humins are suggestive of possible incorporation of LA into the humin structure. Whitaker et al. have confirmed the latter by cation exchange titration of produced humins.[46] Horvat et al. proposed the involvement of a highly reactive intermediate (2,5-dioxo-6- hydroxy-hexanal) DHH in the formation of 5-HMF-derived humins, **Figure 3**.[47] Patil et al. proposed the aldol addition/condensation between 5-HMF and DHH as a primary route for humin formation.[14] Condensation reactions and/or nucleophilic attack of 5-HMF, with the possible participation of LA, was later also confirmed by attenuated total reflectance-FTIR spectroscopy, scanning electron microscopy, and dynamic light scattering.[48] Comparisons between glucose, fructose, and 5-HMF humin formation revealed that the direct conversion of sugars into humins does not seem to be as significant in relation to 5-HMF.[49] This contradicts the proposed mechanisms of most kinetic studies, which include direct formation of humins and FA from either fructose or glucose. Alternatively, the direct

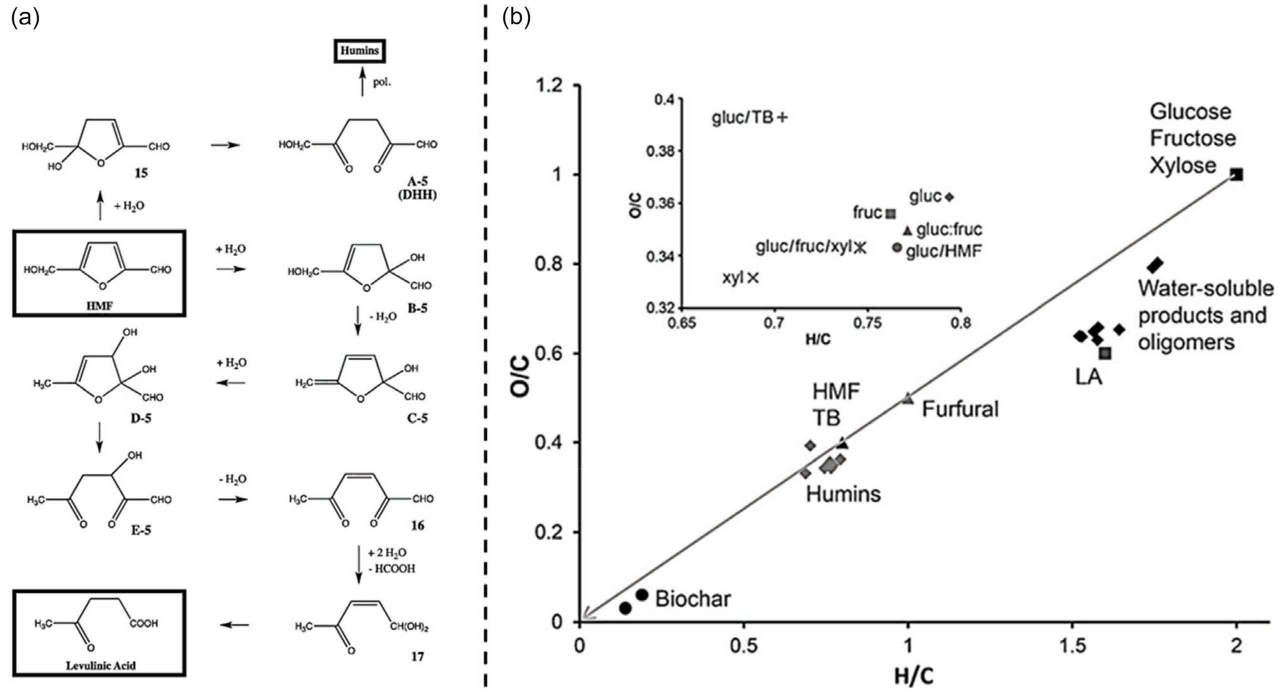


Figure 3. a) Mechanism of humin formation (DHH-2,5-dioxo-6-hydroxy-hexanal). Reprinted with permission.[14] Copyright 2011, John Wiley and Sons. b) A van Krevelen plot, with the changes in H/C and O/C ratio during acid-catalyzed dehydration of sugars (HMF~5-hydroxymethylfurfural, TB ~1,2,4-Trihydroxybenzen, LA~levulinic acid). Adapted with permission.[12] Copyright 2013, John Wiley and Sons.

degradation of saccharides (fructose/glucose) was suggested to be due to the stoichiometric excess of detected FA in comparison to LA during dehydration reactions, as shown in **Table 2**. Fu et al. proposed the formation of oligomeric species, described as humin precursors, via 5-HMF and LA cross-polymerization and self-5-HMF condensation.[50] Authors have also utilized electrospray ionization-MS to explore the additional path of direct saccharide degradation to FA and humins. Van Zandvoort et al. later reported that humins can be formed through additional reaction pathways.[12] The presented Van Krevelen plot demonstrated participation of sugars, intermediates, and furanics in humin formation (Figure 3). Alternatively, additional experiments and analytics (2D solid-state NMR and infrared spectroscopy, and gel permeation chromatography) confirmed that humins are mostly derived by 5-HMF.[11,13] Oppositely, Maruani et al. proposed that the appearance of water-soluble glucose oligomers under acidic hydrothermal conditions during dehydration reaction could contribute to humin formation.[51] In addition, Meier et al. demonstrated that the elimination of pentose's/hexose's hydroxyl groups on carbon atoms 2, 3, and 5 can prevent the formation of furfural/5-HMF and also inhibit formation of humins.[52] Despite all these efforts, the consensus on the mechanism of humin formation has not been reached. However, it can be observed that the mechanism of humin formation is strongly influenced by both the catalyst type and the reactor system used in the studies. For example, in hydrothermal liquid water (HLW) systems where no acid catalysts were applied, the formation of sugar-degradation-derived FA was not observed; therefore, the hypothesis that humins originate primarily from HMF appears plausible. In contrast, when either solid acid or homogeneous acid catalysts were introduced, the data indicate significant degradation of both sugars and furanics. This is supported by the stoichiometric excess of FA reported in most kinetic studies. Incorporation of LA into humins is considered unlikely, as its concentration typically does not decrease over time. Therefore, there are most likely multiple possible mechanisms of humin formation, depending on the specific reaction systems utilized.

Due to inefficient 5-HMF production that can appear because of the excess humin formation, researchers are striving to maximize its inhibition. Humin formation can be extensively limited by changing the solvent system, either by the addition of an organic solvent to the aqueous medium or its total replacement. Tang et al. investigated the effect of THF addition on the kinetics of glucose dehydration over $AlCl_3$.[53] The reported reaction rates demonstrated suppression of 5-HMF-derived humin formation and 5-HMF rehydration. Illuminating the importance of solvent systems, Fu et al. studied solvent effects on the degradative condensation of fructose.[54] Each individual solvent revealed the promotion of different side products. THF and dioxane lead to excessive formation of FA, while MIBK facilitated formation of acetic acid. A significant amount of LA was formed in gamma valero-lactone (GVL) and N-methyl-2-pyrrolidone, whereas DMSO specifically promoted formation of 5-HMF.[54] Furthermore, Kimura et al. demonstrated the influence of reaction media (DMSO, water, and methanol) on the product distribution of non-catalytic dehydration of fructose. DMSO led to the formation of 5-HMF as the final product formed via two distinct intermediates with the highest reaction rate constant. Water resulted in the

Table 2. Homogenously catalyzed monosaccharide dehydration.

Feedstock	T [°C]	Catalyst	Solvent	Activation energy [kJ mol^{-1}]	Reaction network	References
Fructose	*140–180*	*H_2SO_4* *(0.005–1M)*	*water*	$Ea_1 = 123$ $Ea_2 = 92$ $Ea_3 = 148$ $Ea_4 = 119$	*Fructose à HMF* *HMF à Levulinic and formic acid* *Fructose à humins* *HMF à humins*	[76]
Glucose	*140–200*	*H_2SO_4* *(0.005–1M)*	*water*	$Ea_1 = 152$ $Ea_2 = 111$ $Ea_3 = 165$ $Ea_4 = 111$	*Glucose à HMF* *HMF à Levulinic and formic acid* *Glucose à humins* *HMF à humins*	[148]
Fructose/Glucose	*117–155*	*H_2SO_4* *(0.005–0.45 M)*	*Water/MIBK*	$Ea_1 = 156$ $Ea_2 = 181$ $Ea_3 = 177$ $Ea_4 = 133$ $Ea_5 = 142$ $Ea_6 = 147$ $Ea_7 = 97$ $Ea_8 = 108$ $Ea_9 = 104$	*Glucose à HMF* *Glucose à humins* *Glucose à humins and formic acid* *Fructose à HMF* *Fructose à humins* *Fructose à humins and formic acid* *HMF à Levulinic and formic acid* *HMF à humins* *HMF à humins and formic acid*	[67]
Fructose	*90–130*	*HCl* *(0.05−0.25M)*	*water*	$Ea_1 =$ n.a. $Ea_2 = 88$ $Ea_3 = 135$ $Ea_4 = 136$ $Ea_5 = 91$ $Ea_6 = 115$ $Ea_7 = 77$ $Ea_8 = 114$	*Glucose à Fructose* *Fructose à HMF* *Glucose à humins* *Fructose à humins* *HMF à Levulinic and formic acid* *Glucose à Anhydroglucose* *Glucose à Glucose dimer* *Glucose à HMF*	[74]
Fructose	*70–150*	*HCl* *(pH 0.7–1.6)*	*water*	$Ea_1 = 126$ $Ea_2 = 97$ $Ea_3 = 135$ $Ea_4 = 62$ $Ea_5 = 130$	*Fructose à HMF* *HMF à Levulinic and formic acid* *Fructose à humins* *HMF à humins* *Fructose à humins and formic acid*	[75]
Glucose	*140–180*	*HCl* *(0.1M)*	*water*	$Ea_1 = 160$ $Ea_2 = 95$ $Ea_3 = 51$ $Ea_4 = 142$	*Glucose à HMF* *HMF à levulinic and formic acid* *Glucose à humins* *HMF à humins*	[77]
Fructose	*210–270*	*HCl* *(pH = 1.5)* *supercritical water*	*water*	$Ea_1 = 161$ $Ea_2 = 132$ $Ea_3 = 96$ $Ea_4 = 113$ $Ea_5 = 104$ $Ea_6 = 102$ $Ea_7 = 115$	*Fructose à HMF* *Fructose à furfural* *HMF à levulinic and formic acid* *Formic acid à degradation products 1* *LA à degradation products 2* *Fructose à humins* *HMF à humins*	[87]
Fructose	*100–130*	*pTSA* *(1.0 M)*	*DMSO*	$Ea_1 = 34$ $Ea_2 = 25$	*Fructose à HMF* *HMF à Levulinic and formic acid*	[24]
Fructose	*100–130*	*Oxalic acid* *(1.0 M)*	*DMSO*	$Ea_1 = 97$ $Ea_2 = 78$	*Fructose à HMF* *HMF à Levulinic and formic acid*	[24]
Glucose	*180–220*	*High-temperature liquid water*	*water*	$Ea_1 = 108$ $Ea_2 = 136$ $Ea_3 = 89$ $Ea_4 = 109$ $Ea_5 = 31$	*Glucose à HMF* *Glucose à humins* *HMF à LA* *HMF à humins* *LA à degradation products*	[88]
Fructose	*180–220*	*High-temperature liquid water*	*water*	$Ea_{1(no\ catalyst)} = 127$ $Ea_{1(formic\ acid)} = 112$ $Ea_{1(acetic\ acid)} = 126$	*Fructose à HMF*	[79]
Glucose	*130–170*	*Formic acid* *(10–64 wt%)*	*water*	$Ea_1 = 132$ $Ea_2 = 91$ $Ea_3 = 106$ $Ea_4 = 113$	*Glucose à HMF* *HMF à Levulinic and formic acid* *Glucose à humins* *HMF à humins*	[80]

Table 2. Continued.

Feedstock	T [°C]	Catalyst	Solvent	Activation energy [kJ mol^{-1}]	Reaction network	References
Glucose	*180–220*	*Formic acid (5–20 wt%)*	*water*	$Ea_1 = 153$ $Ea_2 = 107$ $Ea_3 = 117$ $Ea_4 = 127$ $Ea_5 = 110$	*Glucose à intermediate* *HMF à Levulinic and formic acid* *Glucose à humins* *HMF à humins* *Intermediate à HMF*	[81]
Fructose/glucose	*130–190*	*High-temperature liquid water*	*water*	$Ea_1 = 139$ $Ea_2 = 98$ $Ea_3 = 106$ $Ea_4 = 108$ $Ea_5 = 120$ $Ea_6 = 78$ $Ea_7 = 85$	*Fructose à HMF* *Fructose à Glucose* *HMF à humins* *Glucose à Fructose* *Fructose à humins* *Glucose à humins* *Glucose à HMF*	[85]
Glucose/Fructose/ Mannose/HMF	*110–140*	*HCl (5–120 mM)*	*water*	$Ea_1 = 175$ $Ea_2 = 58$ $Ea_3 = 127$ $Ea_4 = 133$ $Ea_5 = 97$ $Ea_6 = 64$ $Ea_7 = 129$ $Ea_8 = 160$ $Ea_9 = 51$	*Mannose à HMF* *Mannose à humins* *Fructose à HMF* *Fructose à humins* *HMF à Levulinic and formic acid* *HMF à humins* *Fructose à Fromic acid and humins* *Glucose à HMF* *Glucose à humins*	[149]
Glucose/Fructose/ Mannose/HMF	*110–140*	*$CrCl_3$ (5–17 mM)*	*water*	$Ea_1 = 100$ $Ea_2 = 91$ $Ea_3 = 80$ $Ea_4 = 114$ $Ea_5 = 68$ $Ea_6 = 71$ $Ea_7 = 56$	*Glucose à Fructose* *Fructose à Mannose* *Mannose à Glucose* *Fructose à humins* *Mannose à humins* *Glucose à humins* *HMF à humins*	[149]
Glucose	*140–200*	*HCl (0.01–0.1 M)*	*water*	$Ea_1 = 17$ $Ea_2 = 58$ $Ea_3 = 127$ $Ea_4 = 133$ $Ea_5 = 64$ $Ea_6 = 129$ $Ea_7 = 92$ $Ea_8 = 139$ $Ea_9 = 180$ $Ea_9 = 183$	*Mannose à HMF* *Mannose à humins* *Fructose à HMF* *Fructose à humins* *HMF à humins* *Fructose à Fromic acid and humins* *HMF à Levulinic and formic acid* *Glucose à HMF* *Glucose à Formic acid* *Glucose à humins*	[93]
Glucose/Fructose/ Mannose/HMF	*140–200*	*$CrCl_3$ (1.7 mM)*	*water*	$Ea_1 = 73$ $Ea_2 = 75$ $Ea_3 = 80$ $Ea_4 = 71$ $Ea_5 = 110$ $Ea_6 = 73$ $Ea_7 = 55$	*Glucose à Fructose* *Fructose à Mannose* *Mannose à Glucose* *Fructose à humins* *Mannose à humins* *Glucose à humins* *HMF à humins*	[93]

formation of levulinic and FA together with a small amount of 2,4-benzenetriol. Methanol promoted the formation of anhydrofructoses.[55]

Cheng et al. provided an important contribution by assessing the solubility of humins in various solvents.[11] The solubility of humins was found to be in good correlation with the solvent donor number, where THF and DMSO resulted in the highest concentration of solubilized humins. Vasudevan et al. studied glucose solvation, using force-field molecular simulation.[56] It was proposed that even a small amount of cosolvent (DMSO, dimethylformamide, THF) added to the aqueous system can stabilize glucose molecules via stronger water-glucose interactions. Importantly, Mellmer et al. addressed high 5-HMF yields and selectivity in polar aprotic solvent systems, mainly attributing them to increased rates of glucose dehydration.[57] The relative change in stabilization of acidic protons in comparison to protonated transition state enhances the reaction rate of dehydration, especially when using strong Brønsted acid catalysts, including solid acids such as zeolite and heteropoly-acids, as illustrated in **Figure 4**.[57]

Additionally, an exceptional 5-HMF yield and selectivity of ≈90% have been recorded, specifically when using DMSO as reaction media. The superior performance of 5-HMF formation in DMSO is in the literature described by various mechanisms.[58] Amarasekara et al. suggested that DMSO promotes dehydration reactions by stabilizing fructose molecules in the furanose isomer

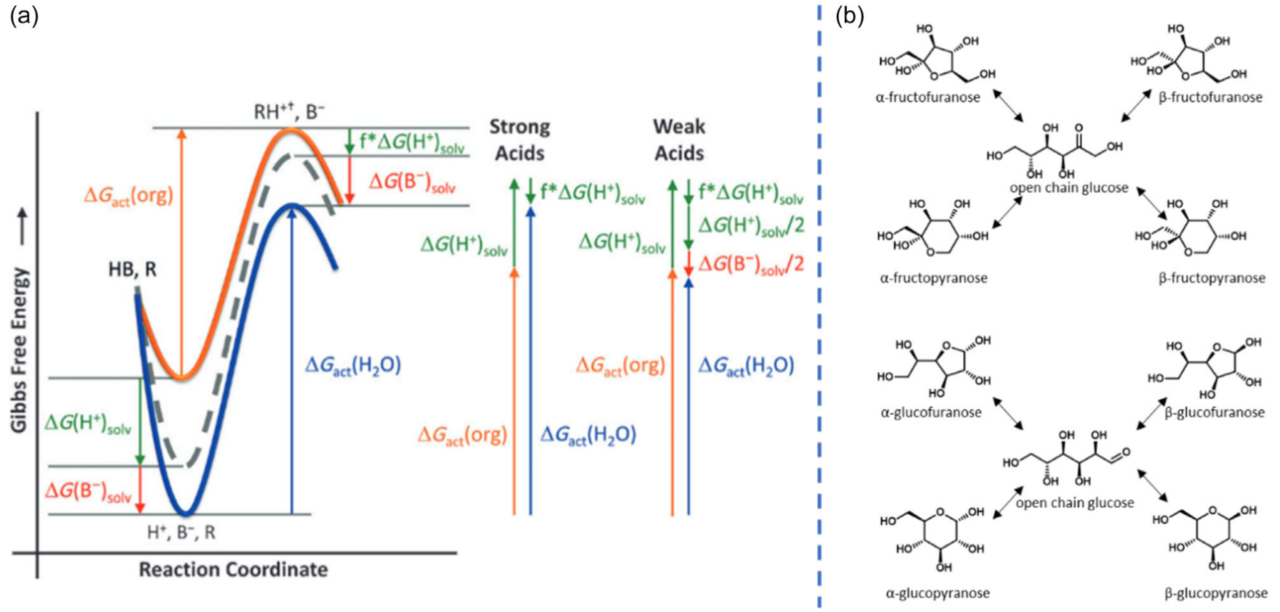


Figure 4. a) Comparison of Gibbs free energy for Brønsted acid-catalyzed reaction in water and organic solvents. ΔGact/solv activation and solvation free energy barrier. Reprinted with permission.[57] Copyright 2014, Wiley. b) Isomeric forms of glucose and fructose.

form, leading to dehydration through a cyclic intermediate.[59] Additionally, DMSO was also found to stabilize the hydronium ion in the vicinity of fructose but destabilizes it in the close proximity of 5-HMF, resulting in an increased dehydration rate and reduced humin formation.[60] Whitaker et al. similarly discussed the impact of DMSO on the sugar dehydration reaction mechanism.[46] Authors have refuted the possibility of catalytic activity of DMSO's degradation species and suggested that the main reason for higher 5-HMF yields and selectivity lies in the stabilization of both molecules, fructose and 5-HMF, respectively.

Pedersen et al. conducted dehydration reactions from glucose/fructose mixtures in an acetone-water solvent system, which, similarly to DMSO, demonstrated an effect of 5-HMF stabilization.[61] Furthermore, acetone was reported to suppress 5-HMF rehydration and facilitate 5-HMF formation, which could be attributed to not only to the modification of the reaction pathway and/or water being a product of dehydration reaction but also to the distribution of monosaccharide isomer (fructofuranose).[62] Glucose and fructose are known to exist in α or β pyranose and furanose forms, where α-furanose appears to be readily converted to 5-HMF (Figure 4). Both solvation effects and stability of specific isomers are temperature-dependent,[62] as such, β-furanose isomer dominates at higher temperatures and polar aprotic solvent environment, making it favorable for 5-HMF formation.[63]

To improve 5-HMF yield and inhibit humin formation, organic solvents can also be added to the aqueous medium in order to form a biphasic system. Biphasic system enables increased 5-HMF yields due to transpiring in situ extraction. Once 5-HMF is formed, it is extracted to the organic phase where reactions leading to undesirable products, namely levulinic and FA and humins, are suppressed, as shown in **Figure 5**. Román-Leshkov et al. investigated biphasic systems for fructose to 5-HMF conversion.[27] The addition of MIBK as a water-immiscible organic solvent resulted in increased 5-HMF selectivity. This was later improved further by the addition of water and organic phase modifiers; DMSO/polyvinylpyrrolidone and 2-butan. Additionally, methyl propyl ketone appeared to be a suitable solvent for the biphasic dehydration of glucose due to the higher partition coefficient of 5-HMF compared to MIBK, resulting in higher yields.[64] The overall efficiency of these biphasic systems can be predefined by numerous different parameters. Lin et al. have demonstrated that the free solvation energy of the product in organic solvent may be of the greatest importance, followed by the parameters such as solubility of the product, free solvation energy of the organic solvent in water, and the degradation of the furanic in selected organic solvents.[65] Recently, Rodriguez et al. have demonstrated a superior behavior of water-saturated MIBK solvent systems for the direct dehydration of glucose.[35] It was found that solvents with ketone functionality allow easier protonation of specific fructose —OH groups, resulting in a better 5-HMF selectivity.

For particular organic solvents, such as THF, the addition of salt (NaCl) is needed to induce the biphasic system. In specific NaCl-H_2O/THF system, the addition of NaCl not only suppressed isomerization and glucose formation but also facilitated FA and humin formation from fructose and 5-HMF rehydration. Importantly, fructose to 5-HMF dehydration was significantly enhanced.[53] The introduction of Cl^- ions through NaCl addition also enhances the intermediate stabilization during 5-HMF formation, increasing its overall yield. However, $CaCl_2$ seems to be less efficient with a lower increase in partition coefficient and potential glucose complexation, leading to slower 5-HMF formation.[58] Hu et al. demonstrated that the addition of NaCl can inhibit

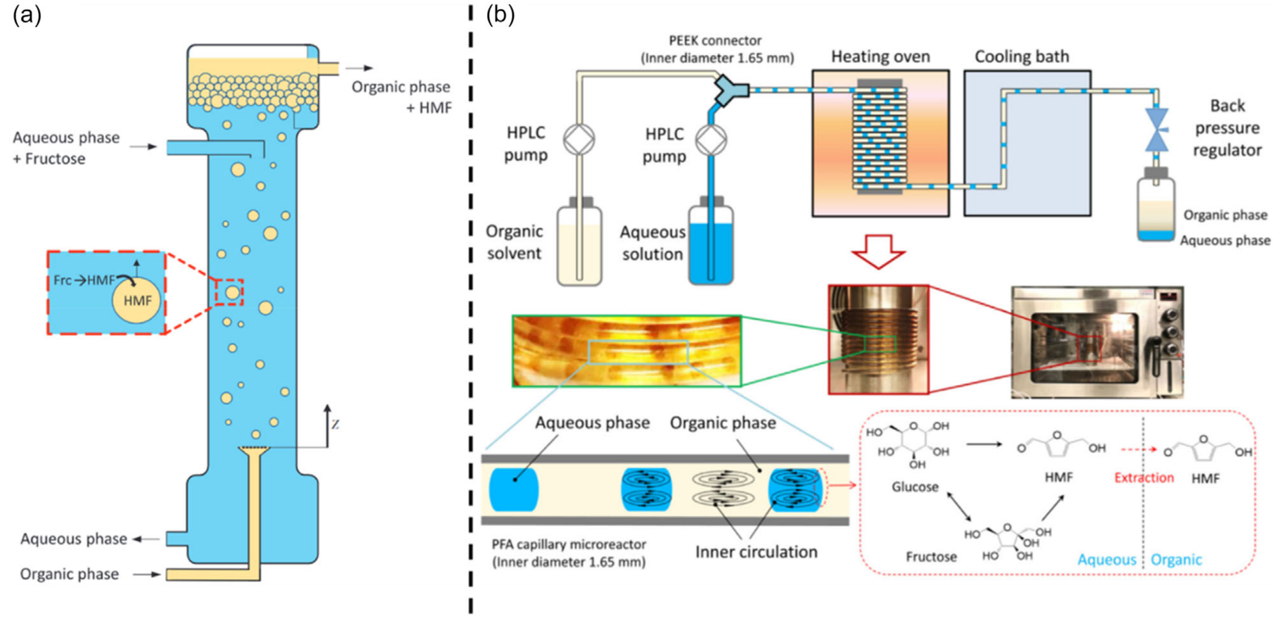


Figure 5. Hexose dehydration in biphasic system a) tubular reactor (PFA-Perfluoroalkoxy alkane) Reprinted with permission.[67] Copyright 2019, John Wiley and Sons and b) slug flow capillary microreactor. (Frc ~ fructose, HMF~5-hydroxymethylfurfural). Reprinted with permission.[20] Copyright 2020, Elsevier.

humin formation by preventing C—C cleavage of fructose, through hydrogen bonding interactions between Cl^- ions and fructose molecules. However, NaCl can also promote fructose aggregation by altering the ratio of fructose anomers present in solution, leading to the soluble humin formation.[66]

Fu et al. studied the suppression of unwanted oligomeric side products (humin precursors) in a triphasic system containing H_2O–CO_2, THF–CO_2, and CO_2. THF was found to be responsible for the inhibition of cross/self-condensation of 5-HMF and LA, while CO_2 suppressed the sugar oligomer formation.[50]

To achieve higher conversion and yields, researchers also tried to implement a simultaneous-isomerization-and-reactive-extraction process for 5-HMF production where, in order to increase 5-HMF yield, enzymatically formed ketoses are extracted into acidic ionic liquid (IL) medium where formed 5-HMF is then further extracted into an additional organic phase (THF).[18] When performing reaction kinetic modeling for biphasic systems, several factors should be carefully considered such as miscibility of selected solvents, their partition coefficients along with extraction rates. Guo et al. first developed a kinetic model for fructose/glucose dehydration by using sulfuric acid as a catalyst in aqueous media and later expanded it further using a biphasic system containing MIBK and water.[67]

Initial feedstock or substrate loading has been reported to affect the formation of 5-HMF, levulinic and FA, and humins differently. Humin formation tends to have a higher reaction order due to it being apolymerization type of reaction.[68] Although Patil et al. reported humin formation from 5-HMF as a first-order reaction according to an experimental kinetic modeling study.[14] Van Zandvoort et al. ascribed the difference between glucose and fructose humin formation to higher yields of 5-HMF formed from fructose.[12] Another study has found that glucose concentration had no significant impact on the humin formation. Oppositely, temperature and to some extend also acid concentration had a more pronounced effect on the amount of humins formed via acid-catalyzed dehydration of glucose. Tsilomelekis et al. have studied the impact of temperature and acid concentration on the growth kinetics, where increasing temperature and/or acid concentration resulted in higher growth rates.[48] Fructose concentration showed no effect on the growth rate of humins (zero order), while the opposite was observed for the initial concentration of 5-HMF, where increased starting concentration of 5-HMF resulted in higher growth rate.[69] Bounoukta et al. developed two different models for glucose dehydration over p-toluene sulfonic acid (pTSA)/Ca carbon catalyst, where second order humin formation was found to better describe obtained experimental data.[70] Reviewing kinetic studies on saccharide dehydration, different reaction orders for humin formation have been reported. Most studies model humin formation as a first-order reaction, primarily for reasons of simplicity.

4. Reaction Kinetics for Dehydration of Model Compounds

Kinetic studies are of significant importance and provide valuable information that can contribute to the process optimization and rational catalyst design. Traditionally, kinetic studies are based on fitting experimental data to obtain apparent rate constants.[71] Reaction kinetics can be studied using different modeling approaches. Macrokinetic studies, using power-law approach appear to be most prevalent, due to its simplicity for industrial purposes. Within the reaction rate equation, the reaction rate constant describes the temperature dependance, while exponents represent the reaction orders in relation to the concentration of observed species.[30] The experimental data regression using power-law approach also allows an easy incorporation of heat and mass transfer phenomena, although the obtained data are only transferable within a limited range of reaction conditions. Regression analysis of experimental data suggests that reactions of sugar dehydration tend to follow first order kinetics. Researchers, therefore, often assume first order kinetics in their set of differential equations for saccharide conversion into 5-HMF. The temperature dependance of reaction rate constants is commonly expressed by Arrhenius equation regardless of type of model used. On the contrary, microkinetic modeling developed during the last two decades avoids any prior assumptions and includes all of the elementary steps of the reaction.[30,72] First, principle data obtained from DFT calculations can be applied within the transition theory to determine the reaction rates. Kinetic experimental data is later being fitted to obtained model data to confirm and validate the established microkinetic model.[30,71] Despite all the advantages offered by microkinetic modeling, this approach is rather scarce among the kinetic studies of lignocellulosic biomass conversion into 5-HMF, due to its complexity.

4.1. Kinetic Studies Using Homogenous Acid Catalysis

Homogenous catalysis so far remains one of the most used and industrially applicable methods for furanic production. In addition to their nonrecyclable nature, they are difficult to separate from the desirable products. Homogeneous catalysts can also pose an environmental risk due to often being highly corrosive.[73] Nonetheless, its continued use on the industrial scale lays in its high activity and low costs.[7] For the acid-catalyzed dehydration of sugars, mineral acids such as sulfuric and hydrochloric acids are usually used, as well as some organic acids and metal chlorides, which are listed in Table 2.

4.1.1. Mineral and Organic Acids

The literature has so far mostly focused on the mechanisms and kinetics of homogeneously catalyzed reactions with fructose and glucose, commonly selected as model compounds. Reaction networks for kinetic modeling usually consist of multiple, consecutive steps including sugar dehydration, followed by 5-HMF rehydration, and optional pathways of degradation and/or humin formation. When glucose is used as a substrate, an additional isomerization step may also occur. A comprehensive reaction mechanism with seven parameters was proposed by Garcés et al. while studying an aqueous phase conversion of glucose and fructose to 5-HMF and LA over HCl.[74] The model included the equilibrium reaction of glucose-derived intermediate formation, such as isomerization to fructose, dimerization, and anhydro-glucose formation.[74] Swift et al. proposed additional steps of open chain configuration when studying the conversion of fructose. The proposed mechanism for the dehydration of fructose to 5-HMF also involves the formation of an additional reversible intermediate (tautomer).[75] The tautomerization of fructose strongly affects the reaction kinetics, so it is important to include it in the developed kinetic models to avoid underestimation of the fructose dehydration rate. Pedersen et al. established a kinetic model, with a reaction pathway for conversion of high fructose corn sirup (glucose and fructose mixture) under HCl, with the hypothesis that sugars are the main source for humin formation.[61] Higher calculated activation energies ($228\,\mathrm{kJ\,mol^{-1}}$) for glucose-derived humins, indicate that the reaction is more favorable at higher temperatures. Although a direct comparison of the kinetic studies can be challenging due to the different reaction conditions, catalysts, and feedstock concentrations, some trends were observed in the calculated activation energies and reaction rate constants. Fructose dehydration to 5-HMF usually proceeds the fastest with the highest reaction rate constant and a relatively high activation energy ($120–135\,\mathrm{kJ\,mol^{-1}}$), as shown in Table 2. When using glucose as a starting feedstock, slightly higher activation energies and significantly lower reaction rate constants can be observed, suggesting higher reactivity of fructose.[67,76,77] Sugar-derived humin formation commonly results in the highest activation energy, indicating the thermosensitivity of the reaction. Alternatively, rehydration of 5-HMF into organic acids had the lowest activation energies. Similarly to the addition of NaCl in biphasic systems, the difference in kinetics of H_2SO_4 and HCl catalyzed sugar dehydration can also appear due to the stabilization of transition state by Cl^- ions during 5-HMF formation.[62]

Fachri et al. presented a kinetic model for fructose dehydration to 5-HMF catalyzed by sulfuric acid. The developed model considered reactions of 5-HMF rehydration to levulinic and FA, and humin formation from both fructose and 5-HMF.[76] Based on the calculated reaction order using power-law approach modeling, it was proposed that varying the initial concentration of fructose had a negligible effect on its conversion or yield of formed 5-HMF. Changing reaction conditions, such as increasing reaction temperature and acid concentration, result in higher reaction rates, whereas more diluted acid concentrations can also lead to higher 5-HMF yields which consequently limits humin formation.[76] In biphasic reaction systems, the final 5-HMF yield is not affected by acid concentration, but the latter highly impacts the reaction rate. By biphasic system utilization, formed 5-HMF is extracted into the organic phase, preventing 5-HMF degradation.[67] Furthermore, studying the kinetics of sulfuric acid-catalyzed sugar dehydration Van Putten et al. explained the importance of hydroxyl group orientation in relation to reactivity of different ketoses.[78] Among fructose, sorbose, and tagatose, the latter was the most reactive with significantly lower activation energy ($89\,\mathrm{kJ\,mol^{-1}}$) and higher reaction rate constant in comparison with sorbose ($138\,\mathrm{kJ\,mol^{-1}}$) and fructose ($124\,\mathrm{kJ\,mol^{-1}}$). Different reactivity is proposed to be a function of hydroxyl group orientation at C4 and C5 position, illustrated in **Figure 6**. Based on the orientation of the hydroxyl (—OH) groups, different cation intermediates are formed. The intermediate with the most stable structure was found to have its dipole moment aligned in the same direction as that of the product (HMF).The orientation of hydroxyl groups does not have the same effect on the reactivity

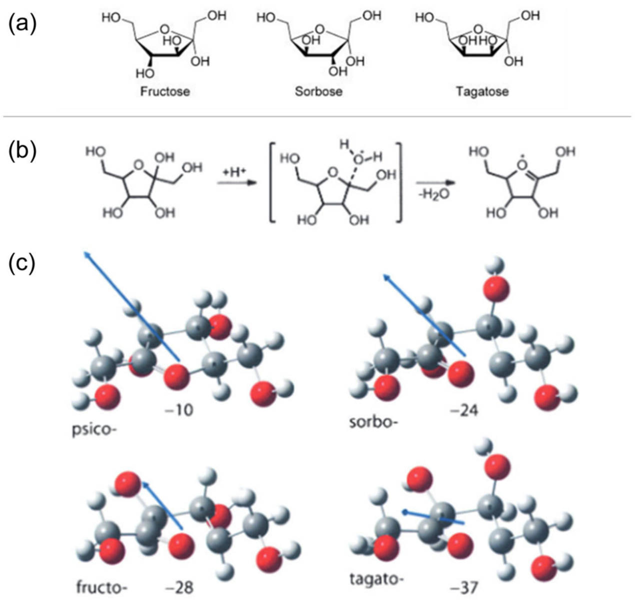


Figure 6. a) Ketoses, with different orientations of hydroxyl groups at the C4 and C5 positions; b) dehydration mechanism of the furanose form; and c) intermediate cation structures of four furanoses, with the orientation of their dipole moments. Reprinted with permission.[77] Copyright 2013, John Wiley and Sons.

of aldoses, which was found to result in lower 5-HMF selectivity and reaction rates.[78]

Considering the small difference between activation energy denoted in Table 2, multiple pathways of side product formation could occur along with the desired 5-HMF. Compared to mineral acids, organic acids are less corrosive, homogenous catalyst alternatives that provide Brønsted acidity necessary for sugar dehydration reactions.[7] While studying fructose conversion in high-temperature liquid water, Li et al. discussed the influence of formic and acetic acid. The latter showed no effect on lowering the activation energy (126 kJ mol^{-1}), while the decrease of activation energy was more pronounced with FA (112 kJ mol^{-1}).[79] Dussan et al. and Kupiainen et al. studied the conversion of glucose (and different saccharides) using FA as a catalyst.[80] Reaction of glucose dehydration in both cases demonstrated the highest and rehydration of 5-HMF in the lowest activation energy.[80,81] Seemala et al. reported lignocellulose biomass conversion using LA as an acid catalyst.[82] Considering the carbohydrate dehydration reaction pathway, formic and LA can be formed via rehydration of 5-HMF. Therefore, in situ formed organic acids (levulinic and FA) could act as an acid catalyst and influence the reported reaction kinetics. Guo et al. proposed to include the dissociation of levulinic and FA in the kinetic models when dilute acid catalyst is used or high amounts of these acid are formed.[67] On the contrary, Whitaker et al. studied the conversion of fructose in DMSO and water, the authors found no significant effect of organic acid (formic and LA 10 mol%) on the fructose conversion to 5-HMF.[46] Sajid et al. focused on the kinetics of fructose conversion in DMSO and water, studying the catalytic activity of five different organic acids: pTSA, oxalic acid maleic acid, succinic acid, and malonic acid.[24] Based on the calculated reaction rate constants, the dehydration reaction was reported to be the fastest in all five organic acid systems, followed by significantly slower 5-HMF rehydration and humin formation. The reaction rate constants of fructose dehydration in water appeared to be as followed: pTSA $>$ oxalic acid $>$ maleic acid $>$ malonic acid $>$ succinic acid. Changing the reaction media to DMSO resulted in significantly higher reaction rate constants and lower activation energies for dehydration reactions and fructose derived humin formation (34 and 25 kJ mol^{-1}) catalyzed by pTSA. The kinetic paramters differ significantly from all previously mentioned, which can imply the

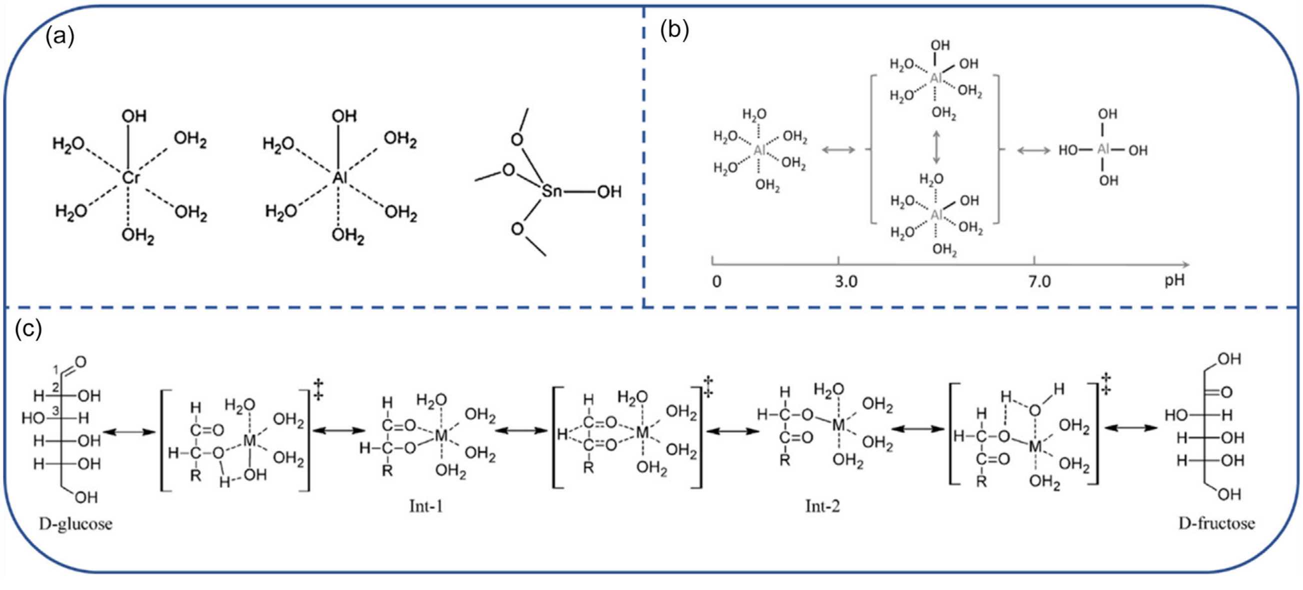


Figure 7. Scheme of active sites involved in aldose-ketose isomerization in aqueous media a) $CrCl_3$, Reprinted with permission.[39] Copyright 2013, John Wiley and Sons, b) $AlCl_3$, Reprinted with permission.[20] Copyright 2020, Elsevier, and c) Sn-beta zeolite (Int-1~intermediat 1, Int-2~intermediate 2). Reprinted with permission.[39] Copyright 2013, John Wiley and Sons.

difficulty of reaction kinetics comparison due to the difference in each individual reaction system and conditions.

4.1.2. Catalysis through Subcritical Water

When water is heated between 175 and 275 °C, the concentration of H^+ and OH^- ions are increased, and therefore, can contribute to acid-catalyzed dehydration reactions.[83] High 5-HMF yields of 47% and 30% have been achieved in aqueous environments at 175 °C starting from fructose and glucose, respectively.[84] Recently Jakob et al. studied dehydration of different carbohydrates (glucose, fructose, and xylose) under hydrothermal conditions (130–190 °C) with and without added catalysts.[85] The results additionally confirmed high 5-HMF yields, when fructose was applied as a feedstock (52%), while glucose dehydration lead to considerably lower 5-HMF yields (33%). Elevated temperatures and pressures have also been reported to result in additional side reactions, and substantial formation of trihydroxy benzene, 1,6-anhydroglucose, erythrose, glyceraldehyde and so on.[86] Jing et al. proposed a reaction mechanism, addressing decomposition products formation from all compounds involved including glucose, 5-HMF, and LA in the temperature range of 180–220 °C.[87,88] Studies conducted in aqueous media at elevated temperatures (above 180 °C), tend to report and include degradation of LA to their kinetic model.[87,88] Calculated kinetic parameters of studies conducted in subcritical water can be highly affected by the change in reaction conditions.[89] Yu et al. discussed the effect of initial glucose concentration on its conversion in hot-compressed water (175–275 °C).[83] The initial glucose concentration turned out to be of significant importance in the underlying reaction mechanism. Increased initial sugar loading resulted in dehydration as a primary route of glucose decomposition, because H^+ ions overruled the effect of OH^-. Contrarily, lower initial concentrations were more susceptible to the effect of OH^- ions. The latter led to facilitated isomerization and aldehyde formation.[83] The developed kinetic models thus far usually do not specify the difference between the catalytic contribution of subcritical water, and the present H^+ and OH^- ions or the effect of solely thermal degradation of saccharides. Although, this additional catalytic performance should be acknowledged since it can highly impact the calculated kinetic parameters.

4.1.3. Metal Chlorides

Metal chlorides offer Lewis acidity which facilitates glucose-fructose isomerization which typically can improve 5-HMF yield and selectivity in various solvent systems. Metal chlorides can be identified as either water sensitive or water compatible based on their hydrolysis constant, where water sensitive metal chlorides result in higher constant values.[90] Hydrolyzed metal ions in water can result in both Lewis and Brønsted acidity (hydronium ion) that can catalyze both isomerization and dehydration reactions.[91] Different metal chlorides have been investigated in aqueous glucose conversion reactions where smaller metal ion radium was correlated with increased reaction rates. Authors explained this phenomenon by stronger effective surface charge density of smaller metal ions, making them harder Lewis acid, leading to more pronounced attraction of glucose. Catalytic activity of water-sensitive and water-compatible metal chlorides followed the trend of $LaCl_3 < DyCl_3 < YbCl_3$ and $InCl_3 < GaCl_3 < AlCl_3$, respectively.[91] Comparing homogenously $CrCl_3$, $AlCl_3$ and heterogeneously Sn-beta catalyzed glucose isomerization, the latter was found to be the most active. In terms of activity of homogenous catalyst, $AlCl_3$ resulted in significantly higher reaction rate than $CrCl_3$, which could be as aforementioned due to the acid hardness.[39] Higher activation energies of water-compatible metal salts were accompanied with lower reaction rates, whereas activation energies for glucose conversion calculated for water-sensitive salts showed no specific trends in relation to reaction rates. Starting with fructose as a feedstock, the same authors suggested the involvement of Lewis acid sites in fructose dehydration to 5-HMF. When comparing fructose conversion conducted with HCl, $AlCl_3$, and $YbCl_3$, the latter two resulted in higher reaction rates but lower 5-HMF selectivity. These findings imply that Lewis acidity can facilitate humin formation, resulting in lower 5-HMF selectivity. A kinetic study of Brønsted/Lewis acid-catalyzed glucose dehydration was conducted using maleic acid and HCl, along with $AlCl_3$ providing Lewis acidity.[92] The role of pH has been shown to influence the strength of the Lewis acidity of different metal halides in aqueous environments.[91] A combination of HCl and $AlCl_3$ (pH = 1.20) resulted in the highest glucose-fructose isomerization reaction rate and increased humin formation. When maleic acid alone (pH = 1.85) or in combination with $AlCl_3$ (pH = 1.44) was utilized, humin formation was suppressed and resulted in the lowest reaction rate constant. The authors describe this phenomenon to be related to the possible favorable intermediate formation between 5-HMF/fructose and maleic acid.[92] Similarly, Guo et al. reported the influence of pH changes introduced by HCl on $AlCl_3$ hydrolysis and its catalytic activity, allowing enhanced glucose isomerization in the pH range of 2–4 by $Al(OH)_2$ species, **Figure 7**.[20] Chen et al. presented a model of glucose dehydration accounting for tandem Lewis ($CrCl_3$) and Bronsted (HCl) catalytic species, by using hierarchical approach, where authors integrate three submodels of Lewis and Bronsted acid-catalyzed reaction as well as so called catalyst speciation model.[93]

In addition to metal chlorides, organic bases can also facilitate sugar isomerization reactions, where the catalytic performance of trimethylamine was found to be comparable to other Lewis acid catalyst.[94] Additionally, solvent was again found as important variable, effecting the tautomeric form of hexoses and consequentially navigating the reaction pathway.[95]

4.2. Kinetic Studies Using Different Solid Acid Catalysis

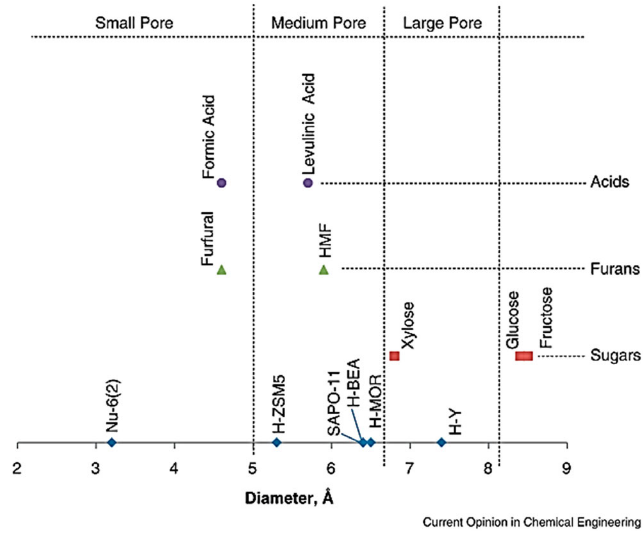
Other widely used catalytic systems for conversion of saccharides to 5-HMF are heterogeneous solid acid catalysis. These catalysts are easily recyclable, and their use simplifies final product separation and offers possible basicity and acidity modulation.[96,97]

Commonly used solid acid catalysts include alumina silicates, zeolites, heteropolyacids, functionalized carbon catalysts, and ion exchange resins.[40,98] Ion exchange resins, such as Amberlyst-15, with the presence of sulfonic groups ($\text{—}SO_3H$) exhibit Brønsted acidity, necessary for dehydration reactions. Modulated with different metals can serve as efficient catalysts for saccharide conversion.[99] Zeolites are porous, solid acid alumino-sillicate catalysts, possessing Brønsted and Lewis acid sites. Different zeolite topologies (e.g., MFI, BEA, MOR) can result in different pore size and structure. The acid ratio can be influenced with particular pretreatments (calcinations), while metal doping can increase Lewis acidity.[100]

In addition to catalyst acidity and porosity, it is particularly important to balance the hydrophobicity and hydrophilicity of the catalyst based on the selected solvent and its polarity when using a solid acid catalyst. In the case of a highly hydrophilic catalyst surface, a polar solvent such as water can block the acid sites and decrease catalytic activity.[101] Increasing the hydrophobicity of the catalyst can also enhance catalyst stability and improve the selectivity toward HMF.[102] However, it is important to note that some degree of hydrophobicity is necessary for the adsorption of sugars and can influence the overall product distribution.[103] Therefore, it is important to balance the interplay of solvent polarity and catalyst hydrophobicity. The disadvantage of both zeolite and Amberlyst-15 catalysts is their instability in aqueous media at elevated temperatures, leading to leaching and fouling under these conditions.[104–107]

Swift et al. studied the conversion of fructose and glucose to 5-HMF over H-BEA zeolites.[108] The reaction network implemented for the kinetic model contained five reaction rate constants, including the equilibrium of glucose-fructose isomerization. This study is one of the only studies that considers both heterogeneous and homogeneous contribution while also accounting for the ratio between Lewis and Brønsted acid sites of the catalyst. The resulting turnover frequency (TOF) of H-BEA was lower compared to when homogenous HCl catalyst was used. Authors also demonstrated that the high activation energy of glucose-fructose isomerization over H-beta zeolite (145 kJ mol^{-1}) can be significantly lowered by impregnation of the zeolite with Sn (89 kJ mol^{-1}).[85,108,109] Similarly, Jakob et al. studied the conversion of glucose and fructose under hydrothermal reaction conditions with the addition of H-BEA zeolite.[85] Authors have concluded that the addition of the specific catalyst (H-BEA 28) especially facilitates the glucose-fructose isomerization and 5-HMF rehydration toward LA, consequently resulting in decreased 5-HMF yields.[85] Carniti et al. used niobium phosphate as a catalyst for fructose dehydration in a continuous flow reactor, where they obtained an activation energy of 66 kJ mol^{-1} in the temperature range from 90 to 110 °C.[110]

An important contribution for a more in-depth understanding of kinetics of fructose dehydration was introduced by Moreau et al.[42] The dehydration of fructose to 5-HMF was conducted using an H-mordenite type of zeolite in a biphasic MIBK/water solvent system. H-mordenite catalysts with different Si/Al ratios were tested at a reaction temperature of 165 °C. Both the highest fructose conversion and 5-HMF selectivity, along with the highest initial rate constant of 7.6×106 mol s^{-1} was achieved with a Si/Al ratio of 11. A pseudo first-order approach was introduced for the kinetic modeling with a two-step reaction scheme: 1) dehydration of 5-HMF and 2) 5-HMF rehydration to formic and LA, where reported activation energies were 141 and 64 kJ mol^{-1}, respectively.[42] A kinetic study conducted by Lourvanij et al. contributed valuable information on how different catalyst properties impact reaction rates and product selectivity.[111] Among the important catalyst parameters, such as catalyst acidity and catalyst morphology, pore size and its geometry play an important role during saccharide dehydration. To investigate how the pore size of solid porous aluminosillicate catalysts affects selectivity and reaction rates, four different types of micro- and mesoporous catalysts were selected with similar acidity: HY-zeolite (FAU topology), aluminum-pillared montmorillonite (APM), MCM-20, and MCM-41. The authors established a kinetic model based on 13 parameters. Activation energies for three of the studied catalysts (HY-zeolite, APM, and MCM-40) followed the trend that more energy is needed for either fructose or glucose (fructose produced by isomerization of glucose) dehydration (134–218 kJ mol^{-1}), whereas, the reaction of 5-HMF rehydration activation energy resulted in a significantly lower value (54–80 kJ mol^{-1}). Based on the kinetic modeling results and reaction rate constants, the study suggests that the mechanism for the formation of 5-HMF via the glucose-fructose isomerization pathway is more likely to occur in relation to direct glucose conversion to 5-HMF. Comparing the forward rate constants (reaction rate constant of individual reactions per acidity on the catalyst), they concluded that the dehydration of fructose and glucose was fastest when the catalyst pore diameter was around 10 Å, due to the size of the hydrated sugar molecule. Furthermore, reaction rate constants for 5-HMF rehydration and bond cleavage were, in all the studied cases, higher compared to dehydration reactions. The developed model also included coke formation which suggested the formation of coke and insoluble humins can be facilitated when using microporous materials.[111] Similar conclusions were presented by Kruger et al. where furan selectivity can be severely dependent on the catalyst pore diameter, with regards to the size of sugars/furanics molecules as shown in **Figure 8**.[97] Catalyst can be characterized as microporous, with the pore size <20 Å, mesoporos 20–500 Å, and macroporous >500 Å. As pore sizes of some catalysts are close or smaller than the size of sugar molecules, internal diffusion can become an important factor with these porous materials. Alternatively, it has been suggested that larger pores might facilitate humin and oligomer formation. Along with the impact of catalyst structure, acidic properties are also considered of vital importance when it comes to the conversion of sugars. By introducing metal ions onto alumino-sillicate catalysts, it is possible to increase Lewis acidity and thus, facilitate this isomerization step. The study conducted by Wei et al. exemplified that an increase in Lewis acidity can lead to faster dehydration of glucose when using 8 wt% Cr/HZSM-5 (MFI topology) catalyst instead of undoped HZSM-5.[112] With the addition of Cr, the reaction rate constant for glucose dehydration significantly increased and the Ea decreased, whereas the decrease in the Ea for 5-HMF



Current Opinion in Chemical Engineering

Figure 8. Catalyst pore size comparison. Reprinted with permission.[96] Copyright 2012, Elsevier.

rehydration was not as significant. However, the authors mentioned that an excessive increase of Lewis acidity in the case of higher Cr loading (16% Cr/HZSM-5) resulted in facilitated cross-polymerization, and therefore, increased humin formation.[112]

The topology and acidity of zeolite can greatly impact catalytic activity and product distribution. While some acidity is necessary, too acidic catalyst can lead to high activity and conversion but low selectivity toward the desired products by facilitating humin formation. In addition, the type of acid sites appears to be crucial, as the right balance between Lewis and Brønsted acid sites is required to achieve high yields of furanics and LA. While conventional zeolites may face challenges due to their microporosity and pore sizes, as discussed above, researchers have explored the advantages of using hierarchical zeolites for sugar dehydration. Different pretreatments, such as dealumination, desilication, including steam and/or acid treatment, can modify the pore structure and acidity. Introduction of mesoporosity facilitates easier molecular diffusion and higher reaction rates. Using this approach, Xiang et al. were able to achieve higher HMF yields.[113]

Ramli et al. has in the study of dehydration of glucose to LA over Fe/HY zeolite included additional kinetic parameter of reaction rate constants for humin formation.[114] Introduction of Fe metal ion to the HY-zeolite catalyst surface increased the Lewis acidity, and therefore, promoted glucose-fructose isomerization, which provided higher yields of the final product (LA).[100] Similarly to Cr doped HZSM-5, increased loading of Fe resulted in higher Lewis acidity, causing excess humin and side product formation. The addition of Fe to the catalyst modified the pore diameter (increased mesopore and decreased micropore volume). Authors proposed a theory where a larger mesoporous size in an aqueous environment can lead to formation of H_3O^+ ions. This significantly increases the effective acidity within the pore microenvironment and can therefore, promote unwanted side reactions of humin formation.[100,114] A kinetic model was presented proposing that the reaction rate of 5-HMF decomposition to LA and humins is higher than its formation, which would explain the low 5-HMF concentration that was achieved.[114] Recently, a study using Fe/HY zeolite as a heterogeneous catalyst for a dehydration reaction discussed the impact of porosity on catalyst deactivation by humin deposits.[115] The time needed to deactivate the catalyst was increasing with increased porosity up to an optimal value (0.2). Further increase in the catalyst porosity resulted in glucose and 5-HMF diffusion into the center of the particle and earlier catalyst deactivation, which steadily decreased 5-HMF yield and selectivity. Due to the thermossensitivity, higher temperatures lead to higher humin yield and faster catalyst deactivation. By adjusting acidic properties and porosity, it is possible to limit humin formation. Marzo et al. studied the stability of niobic acid catalysts in which high acid density resulted in fast catalyst deactivation due to deposition of humins, where catalyst ion doping decreased the acidity and increased long term catalyst activity.[16]

Li et al. proposed that humin formation and rehydration to LA can be promoted by medium-to-strong Lewis acidity,[116] while high amounts of Brønsted acid can facilitate aldol addition/condensation. Therefore, it can be noted that both total acidity and the L/B acid ratio can significantly impact the reaction mechanism as well as the distribution of the final products. Li et al. demonstrated that fructose conversion and its isomerization can increase with decreasing Si/Al ratio of HZSM-5. 5-HMF yield primarily increased but started decreasing after Si/Al ratio of 25, although further decrease appeared to be beneficial for the formation of LA.[117] Acid strength can therefore be a key factor determining the reaction rate, selectivity, and product distribution. Both strong Bronsted and Lewis acid sites can contribute to increased reaction rate and conversion. Strong Lewis acids are known to facilitate sugar isomerization, while strong Bronsted sites promote dehydration. However, both can also negatively impact product selectivity and stability, particularly in the case of sugar dehydration. Therefore, catalyst optimization is crucial, and methods for tuning catalyst acidity include controlling both the density and strength of acid sites. Strategies for achieving this include adjusting the Si/Al ratio, performing cation exchange, and applying postsynthetic treatments, such as dealumination or desilication. For example, decreasing the Si/Al ratio increases the total acid site density by introducing more Al; however, this can also increase Lewis acidity and consequently influence the overall acid strength due to the formation of extraframework aluminum.

Additionally, it was found that leaching species of zeolite have negligible activity for fructose dehydration, they can play a major role in humin formation via dehydrative condensation of 5-HMF and fructose. Overall, it is proposed that a higher Si/Al ratio can lead to the formation of smaller humin oligomers, while a lower Si/Al ratio results in larger oligomers.[117]

Despite the efforts of humin formation regulation, they are often an inevitable side product of sugar dehydration reactions, therefore, there is still a need for catalyst regeneration. Common methods refer to calcination and catalyst washing, but authors have also discussed regeneration of catalyst under mild oxidation condition at low temperature of 70 °C, using Fenton's chemistry.[118] A technique showed promising results especially in removing the humin deposits, but unfortunately prior present acids sides could not be fully recovered. The data of kinetic parameters and reaction network studied is presented in **Table 3**.

5. From Model Compounds to Real Biomass Feedstock Kinetics

5.1. Homogenous Catalysis

The transition from simple sugar model compounds toward realistic biomass streams can be particularly challenging. In 1945, Saeman et al. studied biomass hydrolysis along with glucose decomposition and established the first systematic kinetic model.[119] A two-step reaction mechanism included cellulose hydrolysis with glucose decomposition as the second step. Increased acid concentration and temperature resulted in a relatively higher rate of hydrolysis compared to glucose decomposition. Girisuta et al. studied acid-catalyzed hydrolysis of microcrystalline cellulose to LA and established a kinetic model using a power-law approach.[120] Hydrolysis of cellulose- and glucose-derived humin formation required the largest activation energies (175 and 165 kJ mol^{-1}, respectively), meaning these reactions will be facilitated at increased reaction temperatures. Based on the calculated kinetic parameters, authors proposed that lower temperatures and higher acid concentrations are favorable for 5-HMF rehydration, resulting in higher selectivity toward LA. Authors later transferred their established kinetic model by introducing specific correction factors to a real biomass sample containing water hyacinth plant. Hemicellulose conversion to C5 sugars was found to proceed with a higher rate compared to cellulose decomposition to C6 sugars.[121] The study also demonstrated a higher rate of pure cellulose conversion in comparison to the conversion of the real biomass cellulose. This could be attributed to either different stages of cellulose crystallinity and/or the presence of lignin matrix in the real biomass sample. Two kinetic studies conducted by Rivas et al. also showed the same trend of higher pentose reactivity in comparison to hexoses, which correlated with higher values of reaction rate constants.[122,123] The evaluation of the kinetic parameters for the conversion of 5-HMF and furfural showed the higher stability of furfural. Rehydration and 5-HMF-derived humin formation resulted in higher reaction rates in comparison to furfural. A study conducted by Girisuta et al. demonstrated a relatively high reaction rate of C6 oligomer conversion which was significantly affected by acid concentration, namely more acidic media lead to higher glucose yields.[124] The highest rate constants and lowest activation energy was attributed to the 5-HMF rehydration reaction. Shen et al. studied the conversion of cellulose under hydrochloric acid catalysis and proposed the reaction of glucose dehydration to 5-HMF to be the rate controlling step due to the lowest absolute reaction rate.[125] Qing et al. studied $SnCl_4$ catalyzed conversion of corncob where the activation energy for glucose dehydration into 5-HMF appeared to be significantly lower compared to other homogenous catalysts (HCl, H_2SO_4) denoted in **Table 4**.[126]

Instead of relying on commonly used dilute acid pretreatment to hydrolyze biomass streams, hydrothermal pretreatment can be applied for hemicellulose or cellulose decomposition to avoid the use of highly corrosive acids. Dos Santos Rocha et al. presented a kinetic model for the degradation of sugarcane straw, separately developing a kinetic model for the conversion of hemicellulose to C5 sugars and furfural, and cellulose to C6 sugars and 5-HMF.[127] The experiments were carried out in a temperature range of 185–210 °C. The conversion of hemicellulose to monomers tended not to be particularly temperature dependent, whereas, the hydrolysis of xylooligomers to monomers (220 kJ mol^{-1}) and their degradation to byproducts (146 kJ mol^{-1}) were strongly favored at higher temperatures. On the contrary, the hydrolysis step of cellulose required higher temperatures than that of hemicellulose. The activation energies showed a strong instability of 5-HMF at higher temperatures (266 kJ mol^{-1}), whereas, the temperature-dependent degradation of furfural was not as prominent.

As another environmentally friendly option, ionic liquids can be applied as a solvent for one pot biomass conversion toward value-added products. Good solubility of the cellulose fraction in ionic liquids can ensure homogenous conditions, avoiding mass transfer limitations. Vanoye et al. performed hydrolysis of lignocellulosic biomass starting form cellobiose as a cellulose model compound.[128] The developed kinetic model was successfully applied to the conversion of pure cellulosic feedstock, while the predicted optimal conditions were not transferable to the conversion of raw biomass (Miscanthus grass). An important observation was also that the real biomass sample did not completely dissolve into IL, so the reaction proceeded under heterogeneous conditions. Therefore, additional modifications and correction factors should be introduced to achieve a good fit for crude biomass samples.

The presence of various compounds/impurities can affect the utilization of lignocellulosic biomass, and additional steps are usually required for process optimization. Similarly, as in the reactions conducted with the model compounds the by Girisuta et al.[120] and Rivas et al.,[123] difficulty in achieving higher 5-HMF yields can be attributed to the high activation energy of direct sugar humin formation ($\approx$160 kJ mol^{-1}) and favorable rehydration reaction at lower temperatures and highly acidic media.

5.2. Solid Acid Catalysis

The use of solid catalysts for a one pot conversion of lignocellulosic biomass material is not often reported in the literature. One of the main reasons lies in the solid state of the substrate/starting feedstock (cellulose), consequently creating heterogeneous reaction system, where the efficiency of solid catalyst can be highly compromised by the limits of the mass transfer. In order for cellulose to undergo catalytic conversion, it must dissolve in water.

Table 3. Heterogeneously catalyzed monosaccharide dehydration to 5-HMF.

Feedstock	T [°C]	Catalyst	Solvent	Activation energy [kJ mol^{-1}]	Reaction network	References
Glucose (1 g)	120–200	10% Fe/HY zeolite (1 g)	water	$Ea_1 = 64$ $Ea_2 = 76$ $Ea_3 = 61$ $Ea_4 = 70$	Glucose à HMF Glucose à humins HMF à LA HMF à humins	[114]
Glucose (1 mmol)	180	pTSa-Ca/AC Ca/AC, pTSA/AC (40 mg)	MIBK/H_2O	No data	Glucose à Fructose Glucose à Levoglucosan Fructose à HMF Levoglucosan à HMF HMF à Levulinic and formic acid Glucose à humins Glucose + HMF à humins HMF à humins	[70]
Glucose (1 g)	160–200	HZSM-5 (0.75 g)	water	$Ea_1 = 87$ $Ea_2 = 58$	Glucose à HMF HMF à Levulinic and formic acid	[112]
Glucose (1 g)	160–200	Cr/HZSM-5 (0.75 g)	water	$Ea_1 = 69$ $Ea_2 = 54$	Glucose à HMF HMF à Levulinic and formic acid	[112]
Fructose/glucose (10 wt%)	110 –140	H-BEA-25 (0.25 g, 125 g L^{-1})	water	$Ea_1 = 142$ $Ea_2 = 111$ $Ea_3 = 145$ $Ea_4 = 79$ $Ea_5 = 133$	Fructose à HMF HMF à Levulinic and formic acid HMF à humins Fructose à humins and formic acid Fructose ßà Glucose	[108]
Fructose (≈0.3 M)	90 –110	Niobium phosphate (3–4 g)	water	$Ea_1 = 66$	Fructose à HMF	[110]
Glucose (2% m/v)	125 –145	Niobium phosphate (3:1 glucose vs catalyst)	water	$Ea_1 = 132$ $Ea_2 = 86$ $Ea_3 = 25$ $Ea_4 = 134$ $Ea_5 = 162$ $Ea_6 = 133$	Glucose à humins Glucose à Fructose Fructose à HMF Fructose à humins HMF à Levulinic and formic acid HMF à humins	[150]
Fructose (3.5 g)	165	H-form mordenite (1 g)	MIBK/water	$Ea_1 = 141$ $Ea_2 = 64$	Fructose à HMF HMF à Levulinic and formic acid	[42]
Glucose 2% wt (0.74M)	130–190	HY-zeolite (5 g)	water	$Ea_1 = 178$ $Ea_2 = 205$ $Ea_3 = 53$	Glucose à HMF Fructose à HMF HMF à Levulinic and formic acid	[111]
Glucose 2% wt (0.74M)	130–190	APM and MCM-41 (5 g)	water	$Ea_1 = 209$ $Ea_2 = 187$ $Ea_3 = 77$	Glucose à HMF Fructose à HMF HMF à Levulinic and formic acid	[111]
Glucose 2% wt (0.74M)	130 –190	APM and MCM-41 (5 g)	water	$Ea_1 = 216$ $Ea_2 = 132$ $Ea_3 = 54$	Glucose à HMF Fructose à HMF HMF à Levulinic and formic acid	[111]
Glucose (0.1 g)	160–175	Dual-functional carbon-based solid acid catalyst (DFCSA-P,N,Al) (0.05 g)	water	$Ea_1 = 162$ $Ea_2 = 86$ $Ea_3 = 126$ $Ea_4 = 153$ $Ea_5 = 172$	Glucose à intermediate Intermediate and HMF à humins Intermediate à HMF HMF à LA LA à humins	[151]
Fructose/glucose (0.5 g)	130–190	H-BEA (0.5 g)	water	$Ea_1 = 10$ $Ea_2 = 151$ $Ea_3 = 140$ $Ea_4 = 136$ $Ea_5 = 97$ $Ea_6 = 21$ $Ea_7 = 17$ $Ea_8 = 60$	Fructose à HMF Fructose à Glucose HMF à humins Glucose à Fructose Fructose à humins Glucose à humins Glucose à HMF HMF à Levulinic and formic acid	[85]

This can be achieved by decrystallization and/or depolymerisaiton using alkai pretreatment. Gromov et al. recently published a study with a kinetic model of multistep hydrolysis-dehydration of cellulose as a starting material over solid sulfonated carbon catalyst. They reported cellulose solubilization and glucose-fructose isomerization as the main rate limiting steps in 5-HMF formation, without significant LA formation.[129] Jiang et al. have proven that acid sites present on the solid catalyst surface can donate a proton to a solid cellulose particle, resulting in protonated species that can dissolve and degrade in water.[130] Since cellulose is a macromolecule, it can also undergo free radical degradation reaction. MCM-41, modified by sulfuric acid facilitates cellulose

Table 4. Homogeneously catalyzed cellulose and real biomass samples.

Feedstock	T [°C]	Catalyst	Activation energy [kJ mol^{-1}]	Reaction network	References
Woody biomass (Douglas-fir)	*170–190*	H_2SO_4	$Ea_1 = 180$ $Ea_2 = 138$	*Cellulose à Glucose* *Glucose à degradation products*	[119]
Cellulose	*150–200*	*1.7 wt%* H_2SO_4	$Ea_1 = 152$ $Ea_2 = 152$ $Ea_3 = 111$ $Ea_4 = 165$ $Ea_5 = 111$ $Ea_6 = 175$	*Cellulose à glucose* *Glucose à HMF* *HMF à Levulinic and formic acid* *Glucose à humins* *HMF à humins* *Cellulose à humins*	[120]
P. pinaster wood	*130–250*	H_2SO_4	*Glucose:* $Ea_1 = 113$ $Ea_2 = 138$ $Ea_3 = 72$ $Ea_4 = 166$ *Galactose:* $Ea_1 = 100$ $Ea_2 = 148$ $Ea_3 = 72$ $Ea_4 = 158$ *Mannose:* $Ea_1 = 103$ $Ea_2 = 156$ $Ea_3 = 72$ $Ea_4 = 180$ *Xylose:* $Ea_1 = 78$ $Ea_2 = 158$ $Ea_3 = 129$ $Ea_4 = 79$ *Arabinose:* $Ea_1 =$ *n.a.* $Ea_2 = 141$ $Ea_3 = 116$ $Ea_4 = 79$	*C6 oligosaccharides à hexoses* *Hexoses à HMF* *HMF à Levulinic and formic acid* *Hexoses à humins* *C5 oligosaccharides à pentoses* *Pentoses à furfural* *Pentoses à humins* *Furfural àhumins*	[123]
Sugar cane bagasse	*150–200*	H_2SO_4	$Ea_1 = 145$ $Ea_2 = 152$ $Ea_3 = 102$ $Ea_4 = 161$	*Glucan à Glucose* *Glucose à HMF* *HMF à Levulinic and formic acid* *Glucose à humins*	[124]
Microcrystalline cellulose	*160–200*	*HCl*	$Ea_1 = 96$ $Ea_2 = 137$ $Ea_3 = 144$ $Ea_4 =$ *n.a.* $Ea_5 = 147$ $Ea_6 = 59$	*Cellulose à Glucose* *Glucose à HMF* *HMFà Levulinic and formic acid* *Glucose à humins* *HMF à humins* *Levulinic and formic acids à degradation products*	[125]
Corncobs	*160–200*	$SnCl_4$	$Ea_1 = 48$ $Ea_2 = 46$ $Ea_3 = 57$ $Ea_4 = 76$ $Ea_5 = 67$	*Cellulose à Glucose* *Glucose à HMF* *HMFà Levulinic and formic acid* *Glucose à humins* *HMF à humins*	[126]
Sugarcane straw	*180–210*	*Hydrothermal treatment*	$Ea_1 = 105$ $Ea_2 = 216$ $Ea_3 = 106$ $Ea_4 = 181$ $Ea_5 = 119$ $Ea_6 = 266$	*Cellulose à Glucose* *Cellulose à oligomers of glucose* *Oligomers of glucose à Glucose* *Glucose à HMF* *Glucose à degradation products* *HMF à degradation products*	[127]
Sugarcane straw	*180–210*	*Hydrothermal treatment*	$Ea_1 = 63$ $Ea_2 = 109$ $Ea_3 = 220$ $Ea_4 = 123$ $Ea_5 = 146$ $Ea_6 = 120$	*Hemicellulose à Monomers* *Hemicellulose à Xylo-oligomers* *Xylo-oligomers à Monomers* *Monomers à Furfural* *Monomers à degradation products* *Furfural à degradation products*	[127]
Cellobiose	*80–150*	*Methanesulfonic acid (in IL)*	$Ea_1 = 111$ $Ea_2 = 102$	*Cellobiose à Glucose* *Glucose à degradation products*	[128]

degradation at increased temperatures. Using sulfonated MCM-41, authors observed a fast decrease in the cellulose concentration at the start of the reaction due to the degradation of the amorphous cellulose fraction. Their developed kinetic model also provides reaction rate constants and activation energies, where degradation of 5-HMF demonstrated the highest activation energy and reaction rates. The use of solid acid catalyst can be challenging due to possible deactivation and humin deposition.[115] To avoid these difficulties, the reaction media can be a crucial factor in suppressing undesired product formation. When studying realistic stream mixtures, it is important to consider their complex structure with possible presence of metal ions, which can be a defining factor for catalyst selection. Authors have reported the change in acidity of zeolite catalyst. Based on metal-exchange studies, metal ions can be responsible for catalyst deactivation due to their possibility to exchange with the Brønsted acid sites.[131]

5.2.1. Effect of Lignin

The structure of lignocellulosic biomass is an important aspect when conducting reactions with real biomass samples, where the protective lignin layer can affect the surface accessibility of cellulose and hemicellulose.[9] Based on a study on glucose decomposition, Xiang et al. established a complex reaction network and discussed the effect of acid soluble lignin (ASL) on the degradation process.[132,133] It has been proven that ASL in acid medium facilitates glucose conversion by formation of ALS-glucose or ALS-oligomer complexes.[133] A comprehensive kinetic study conducted by Yan et al. revealed the impact of cellulose crystallinity, in situ formed ASL-glucose complex, and humins on the reaction kinetics.[134] Cellulose crystallinity significantly impacted the reaction rate of hydrolysis at lower temperatures (140–160 °C), whereas this tended to diminish with an increase in temperature. In situ formed ASL-glucose complex and humins demonstrated a greater influence on the reaction kinetics at higher temperatures. Generation of the ALS-glucose complex was facilitated by higher hydronium ion concentration in water medium, which negatively impacted 5-HMF yield. The third parameter of 5-HMF-derived humin formation was negligible at lower temperature below 160 °C, whereas the increase in temperature resulted in lower 5-HMF and LA yields.[134]

Raw lignocellulosic biomass is comprised of both C5 and C6 sugars, therefore, the understanding of possible lignin interference and its impact on conversion of both hexoses and pentoses is crucial for process optimization and catalyst design to achieve maximum yields. When studying acid-catalyzed conversion of model compounds (xylose/ xylan) along with a real biomass sample, Yemisß et al. obtained higher furfural yield in straw biomass compared to pure model compound.[135] Interestingly, the study conducted by Daorattanachai et al. contrarily showed that the presence of Kraft lignin negatively impacted furfural yields from xylose and xylan.[136] The opposite has been proven for hexoses where lignin could promote glucose-fructose isomerization. It was proposed that the isomerization reaction could be promoted by organic acids originating from lignin under conditions of hot-compressed water. Although, the study does not mention possible contribution of in situ formed organic acids. The impact of lignin on sugar conversion was studied at different acid concentrations where at concentration $\geq$0.5 M H_3PO_4, the presence of lignin increased 5-HMF yields.[136] This indicates a possible lignin neutralization capacity which was studied later by Lamminpää et al., where authors presented the impact of kraft lignin on xylose conversion.[137] Lignin has shown to significantly impact the pH of the reaction media. Authors demonstrated the inhibition effect of lignin on xylose conversion and furfural yield which was more pronounced when using sulfuric acid in comparison to FA. The variance was ascribed to different acid strength and dissociation ability. The neutralizing capacity could also originate from cations (potassium, sodium, magnesium) present in biomass. The changes in pH could not fully explain the inhibition of xylose conversion. It has been suggested that there are additional pathways existing during xylose dehydration inhibition.[137] Gomes et al. investigated the production of furanics from sugarcane bagasse and reported lower 5-HMF and furfural yield when real biomass was used as a feedstock.[138] Authors have associated the inhibitory effect of lignin with a barrier-like effect of lignin as a macromolecule and/or possible catalyst ($ZnCl_2$/HCl, $AlCl_3$/HCl)-lignin interaction resulting in catalytic deactivation and lower activity. Alternatively, Jongerius et al. studied the presence of lignin and lignin model compounds as catalyst stabilizers. Authors reported that lignin could prevent recrystallization of alumina support to boehmite in Pt/γ-Al_2O_3 and consequently avoid the loss of Lewis acidity and sintering of metal particles.[139]

It was reported that higher lignin concentrations in the biomass stream can decrease furfural yield, along with an increase in degradation rate.[17] Alternatively, the addition of lignin model compounds to saccharide mixtures had no significant effect on either furfural or xylose degradation. Dussan et al. proposed the mechanism for xylose/furfural degradation in the presence of lignin. The authors proposed two possible pathways for lignin facilitated xylose/furfural degradation, which resulted in lower furfural yields. The first reaction pathway can be described by aldol condensation between a lignin carbonyl group and furfural. Another explanation for the low furfural selectivity can be due to the electrophilic behavior of xylose intermediates reacting with the lignin carbocation formed under the acidic conditions. The results in the study also proposed no significant effect of lignin on glucose dehydration to 5-HMF or its degradation.

On the contrary, an efficient method for feedstock purification was implemented by Liu et al. when studying the conversion of biomass hydrolysate containing high glucose concentrations into 5-HMF.[140] With the addition of activated charcoal (50 wt%), they were able to remove inhibitors, such as lignin and furanics, leading to higher yields of 5-HMF. Additionally, Binder et al. reported no negative effect of lignin and other macromolecules on the 5-HMF yield using N,N-dimethylacetamide-LiCl (10%) with ionic liquid as a reaction media for conversion of corn stover.[141] Similarly, no interference of lignin present in the biomass was observed when authors used GVL as a solvent. Other advantages of using solvents, like GVL, are its ability to dissolve lignin and huminic species that are formed during dehydration.[142]

It has been proven that lignin can react and form complexes with both C5 and C6 sugars, when biomass conversion is conducted under hydrothermal acidic catalysis. This can consequently lead to lower selectivity and yields of 5-HMF and furfural, respectively.[133,137] Oppositely, positive effects of lignin on glucose-fructose isomerization have also been demonstrated in the literature. However, considering lignin's ability of neutralization, using acid catalyst in low concentrations can lead to neutralization and decreased acid concentration, affecting catalyst activity.[136,137]

Acknowledging the challenges of real biomass conversion, strategies such as advanced process intensification and staged pretreatments could greatly benefit the design of a fully integrated biorefinery to maximize the process efficiency.[143]

6. Summary and Outlook

Lignocellulosic biomass is an abundant raw material, which makes it suitable feedstock for an industrial production of 5-HMF. Efficient conversion requires different pretreatment steps, hydrolysis of polysaccharides, and dehydration of individual sugar units. Kinetic studies are thus of significant importance, contributing to process optimization and better understanding of underlying reaction mechanisms. This review presents and examines kinetic studies of homogeneously and heterogeneously catalyzed dehydration of individual sugars, namely fructose and glucose, as well as real lignocellulosic biomass feedstocks. Despite the availability of comprehensive literature, comparison of catalyst performance can be limited due to the lack of standardized normalization metrics. To improve data comparability, it would be beneficial to report results as yield per unit surface area, TOF or turnover number. This would allow more direct data comparison. However, the use of these metrics also requires several assumptions, including the accurate determination of acid sites and their accessibility, and does not account for differences in reaction conditions or systems used.

The biomass composition has shown to be one of the most critical factors in 5-HMF production. Accordingly, kinetic studies with more complex mixtures and real biomass samples are great contributors to help unravel the impact of stream complexity on 5-HMF production and identify possible unwanted interactions. Studying these systems revealed the effect of hemicelluloses and lignin presence on the reaction kinetics and 5-HMF yield. The major problems for inefficient lignocellulosic biomass utilization are still attributed to excessive humin formation. Therefore, the principles and pathways of humin formation along with the possibilities of limitation and inhibition of these undesired side products were discussed. Based on the kinetic studies reported in the literature, a suitable combination of reaction conditions, catalyst and solvent selection can considerably limit humin formation. Additionally, polar aprotic solvents and biphasic system were reported to be efficient in achieving high 5-HMF yield. Several studies of sugar dehydration were carried out in HLW water, which indicates a possible increased catalytic performance at higher temperatures, potentially impacting the reported kinetic parameters. However, HLW can also be seen as an efficient, environmentally friendly, and scalable option for industrial-scale sugar dehydration reactions. On the contrary, homogeneous catalysts (mineral and organic acids, metal chlorides) can be efficiently utilized for the dehydration of sugars into 5-HMF, but they are known to be corrosive. In contrast, more environmentally friendly heterogeneous catalysts can, through manipulation of Lewis and Brønsted acidity as well as porosity, significantly improve 5-HMF yields. Solid acid catalysts can also be a feasible option due to their recyclability, yet they are also known to suffer from poor stability. Regarding the mechanism of humin formation, researchers suggested that 5-HMF plays a key role in the condensation and/or cross/self-polymerization reaction. However, there is still no consensus in the existing literature on the involvement of partially dehydrated sugars or rehydration byproducts in the structure of humins. In contrast, most kinetic studies consider the formation of humins and/or by-products directly from sugars (glucose and fructose). Furthermore, lignin and humins have been found to significantly influence and/or modify the reaction kinetics. Therefore, several correction factors had to be employed for a better fit of the model when using real biomass streams. Therefore, future research should focus on the possibility of solvent and catalyst-dependent reaction mechanisms of humin formation and explore the impact of complex biomass streams. This would help to develop more accurate kinetic models and allow a better description of real biomass feedstock reactivity, as this remains a critical challenge.

Acknowledgements

The authors would like to appreciatively acknowledge the financial support of the EU Framework Program for Research and Innovation Horizon 2020 under grant agreement no. 887226 (BioSPRINT) and the Slovenian Research Agency (Programme P2-0152).

Conflict of Interest

The authors declare no conflict of interest.

Keywords: carbohydrate dehydration · catalysis · humins · hydroxymethylfurfural · kinetic modelling · lignocellulosic biomass

[1] C. Thoma, J. Konnerth, W. Sailer-Kronlachner, P. Solt, T. Rosenau, H. W. G. van Herwijnen, Current Situation of the Challenging Scale-Up Development of Hydroxymethylfurfural Production, *ChemSusChem* **2020**, *13*, 3544.
[2] S. Chakraborty, V. Aggarwal, D. Mukherjee, K. Andras, Biomass to biofuel: a review on production technology, *Asia-Pac. J. Chem. Eng.* **2012**, *7*, S254.
[3] N. Tripathi, C. D. Hills, R. S. Singh, C. J. Atkinson, Biomass waste utilisation in low-carbon products: harnessing a major potential resource, *NPJ Clim. Atmos. Sci.* **2019**, *2*, https://doi.org/10.1038/s41612-019-0093-5.
[4] D. M. Alonso, J. Q. Bond, J. A. Dumesic, Catalytic conversion of biomass to biofuels, *Green Chem.* **2010**, *12*, 1493.
[5] N. Mosier, C. Wyman, B. Dale, R. Elander, Y. Y. Lee, M. Holtzapple, M. Ladisch, Features of promising technologies for pretreatment of lignocellulosic biomass, *Bioresour. Technol.* **2005**, *96*, 673.
[6] S. Behera, R. Arora, N. Nandhagopal, S. Kumar, Importance of chemical pretreatment for bioconversion of lignocellulosic biomass, *Renewable Sustainable Energy Rev.* **2014**, *36*, 91.
[7] I. K. M. Yu, D. C. W. Tsang, Conversion of biomass to hydroxymethylfurfural: A review of catalytic systems and underlying mechanisms, *Bioresour Technol* **2017**, *238*, 716.
[8] T. Wang, M. W. Nolte, B. H. Shanks, Catalytic dehydration of C6 carbohydrates for the production of hydroxymethylfurfural (HMF) as a versatile platform chemical, *Green Chem.* **2014**, *16*, 548.
[9] S. Kang, J. Fu, G. Zhang, From lignocellulosic biomass to levulinic acid: A review on acid-catalyzed hydrolysis, *Renewable Sustainable Energy Rev.* **2018**, *94*, 340.
[10] X. Zhang, K. Wilson, A. F. Lee, Heterogeneously Catalyzed Hydrothermal Processing of C5–C6 Sugars, *Chem Rev* **2016**, *116*, 12328.
[11] Z. Cheng, J. L. Everhart, G. Tsilomelekis, V. Nikolakis, B. Saha, D. G. Vlachos, Structural analysis of humins formed in the Brønsted acid catalyzed dehydration of fructose, *Green Chem.* **2018**, *20*, 997.
[12] I. Van Zandvoort, Y. Wang, C. B. Rasrendra, E. R. H. Van Eck, P. C. A. Bruijnincx, H. J. Heeres, B. M. Weckhuysen, Formation, molecular structure, and morphology of humins in biomass conversion: Influence of feedstock and processing conditions, *ChemSusChem* **2013**, *6*, 1745.
[13] I. Van Zandvoort, E. J. Koers, M. Weingarth, P. C. A. Bruijnincx, M. Baldus, B. M. Weckhuysen, Structural characterization of 13C-enriched humins and alkali-treated 13C humins by 2D solid-state NMR, *Green Chem.* **2015**, *17*, 4383.
[14] S. K. R. Patil, C. R. F. Lund, Formation and growth of humins via aldol addition and condensation during acid-catalyzed conversion of 5-hydroxymethylfurfural, *Energy Fuels* **2011**, *25*, 4745.

[15] I. V. Sumerskii, S. M. Krutov, M. Y. Zarubin, Humin-Like substances formed under the conditions of industrial hydrolysis of wood, *Russ. J. Appl. Chem.* **2010**, *83*, 320.

[16] M. Marzo, A. Gervasini, P. Carniti, Improving stability of Nb2O5 catalyst in fructose dehydration reaction in water solvent by ion-doping, *Catal. Today* **2012**, *192*, 89.

[17] K. Dussan, B. Girisuta, M. Lopes, J. J. Leahy, M. H. B. Hayes, Effects of Soluble Lignin on the Formic Acid-Catalyzed Formation of Furfural: A Case Study for the Upgrading of Hemicellulose, *ChemSusChem* **2016**, *9*, 492.

[18] S. Alipour, High yield 5-(hydroxymethyl)furfural production from biomass sugars under facile reaction conditions: A hybrid enzyme- and chemocatalytic technology, *Green Chem.* **2016**, *18*, 4990.

[19] S. Souzanchi, L. Nazari, K. T. Venkateswara Rao, Z. Yuan, Z. Tan, C. Charles Xu, Catalytic dehydration of glucose to 5-HMF using heterogeneous solid catalysts in a biphasic continuous-flow tubular reactor, *J. Ind. Eng. Chem.* **2021**, *101*, 214.

[20] W. Guo, H. J. Heeres, J. Yue, Continuous synthesis of 5-hydroxymethylfurfural from glucose using a combination of AlCl3 and HCl as catalyst in a biphasic slug flow capillary microreactor, *Chem. Eng. J.* **2020**, *381*, https://doi.org/10.1016/j.cej.2019.122754.

[21] Y. Zhao, K. Lu, H. Xu, L. Zhu, S. Wang, A critical review of recent advances in the production of furfural and 5-hydroxymethylfurfural from lignocellulosic biomass through homogeneous catalytic hydrothermal conversion, *Renewable Sustainable Energy Rev.* **2021**, *139*, 110706.

[22] M. Dashtban, A. Gilbert, P. Fatehi, Recent advancements in the production of hydroxymethylfurfural, *RSC Adv.* **2014**, *4*, 2037.

[23] G. Morales, J. A. Melero, M. Paniagua, J. Iglesias, B. Hernández, M. Sanz, Sulfonic acid heterogeneous catalysts for dehydration of C6-monosaccharides to 5-hydroxymethylfurfural in dimethyl sulfoxide, *Cuihua Xuebao/Chin. J. Catal.* **2014**, *35*, 644.

[24] M. Sajid, Y. Bai, D. Liu, X. Zhao, Organic acid catalyzed production of platform chemical 5-hydroxymethylfurfural from fructose: Process comparison and evaluation based on kinetic modeling, *Arab. J. Chem.* **2020**, *13*, 7430.

[25] J. Li, W. Zhang, S. Xu, C. Hu, The Roles of H2O/Tetrahydrofuran System in Lignocellulose Valorization, *Front. Chem.* **2020**, *8*, https://doi.org/10.3389/fchem.2020.00070.

[26] E. Nikolla, Y. Román-Leshkov, M. Moliner, M. E. Davis, 'One-Pot' Synthesis of 5-(Hydroxymethyl)furfural from Carbohydrates using Tin-Beta Zeolite, *ACS Catal.* **2011**, *1*, 408.

[27] Y. Román-Leshkov, J. N. Chheda, J. A. Dumesic, Phase Modifiers Promote Efficient Production of Hydroxymethylfurfural from Fructose, *Science* **2006**, *312*, 1933.

[28] L. Hu, Z. Wu, Y. Jiang, X. Wang, A. He, J. Song, J. Xu, S. Zhou, Y. Zhao, J. Xu, Recent advances in catalytic and autocatalytic production of biomass-derived 5-hydroxymethylfurfural, *Renewable Sustainable Energy Rev.* **2020**, *134*, 110317.

[29] L. Zhu, X. Fu, Y. Hu, C. Hu, Controlling the Reaction Networks for Efficient Conversion of Glucose into 5-Hydroxymethylfurfural, *ChemSusChem* **2020**, *13*, 4812.

[30] A. H. Motagamwala, J. A. Dumesic, Microkinetic Modeling: A Tool for Rational Catalyst Design, *Chem Rev.* **2021**, *121*, 1049.

[31] B. Pomeroy, M. Grilc, S. Gyergyek, B. Likozar, Catalyst structure-based hydroxymethylfurfural (HMF) hydrogenation mechanisms, activity and selectivity over Ni, *Chem. Eng. J.* **2021**, *412*, 127553.

[32] R. Šivec, M. Huš, B. Likozar, M. Grilc, Furfural hydrogenation over Cu, Ni, Pd, Pt, Re, Rh and Ru catalysts: Ab initio modelling of adsorption, desorption and reaction micro-kinetics, *Chem. Eng. J.* **2022**, *436*, https://doi.org/10.1016/j.cej.2022.135070.

[33] Y. B. Huang, Y. Fu, Hydrolysis of cellulose to glucose by solid acid catalysts, *Green Chem.* **2013**, *15*, 1095.

[34] L. Yang, G. Tsilomelekis, S. Caratzoulas, D. G. Vlachos, Mechanism of Brønsted Acid-Catalyzed Glucose Dehydration, *ChemSusChem* **2015**, *8*, 1334.

[35] N. Rodriguez Quiroz, T.-H. Chen, S. Caratzoulas, D. G. Vlachos, Direct Brønsted Acid-Catalyzed Dehydration of Glucose to HMF in Methyl Isobutyl Ketone, *ACS Catal.* **2023**, *13*, 14221.

[36] Y. Román-Leshkov, M. Moliner, J. A. Labinger, M. E. Davis, Mechanism of glucose isomerization using a solid lewis acid catalyst in water, *Angew. Chem., – Int. Ed.* **2010**, *49*, 8954.

[37] E. A. Pidko, V. Degirmenci, R. A. Van Santen, E. J. M. Hensen, Coordination properties of ionic liquid-mediated chromium(II) and copper(II) chlorides and their complexes with glucose, *Inorg. Chem.* **2010**, *49*, 10081.

[38] C. G. Yoo, N. Li, M. Swannell, X. Pan, Isomerization of glucose to fructose catalyzed by lithium bromide in water, *Green Chem.* **2017**, *19*, 4402.

[39] V. Choudhary, A. B. Pinar, R. F. Lobo, D. G. Vlachos, S. I. Sandler, Comparison of homogeneous and heterogeneous catalysts for glucose-to-fructose isomerization in aqueous media, *ChemSusChem* **2013**, *6*, 2369.

[40] R. J. Van Putten, J. C. Van Der Waal, E. De Jong, C. B. Rasrendra, H. J. Heeres, J. G. De Vries, Hydroxymethylfurfural, a versatile platform chemical made from renewable resources, *Chem. Rev.* **2013**, *113*, 1499.

[41] T. Istasse, A. Richel, Mechanistic aspects of saccharide dehydration to furan derivatives for reaction media design, *RSC Adv.* **2020**, *10*, 23720.

[42] C. Moreau, R. Durand, S. Razigade, J. Duhamet, P. Faugeras, P. Rivalier, R. Pierre, G. Avignon, Dehydration of fructose to 5-hydroxymethylfurfural over H-mordenites, *Appl. Catal. A* **1996**, *145*, 211.

[43] M. Asakawa, A. Shrotri, H. Kobayashi, A. Fukuoka, "Solvent basicity controlled deformylation for the formation of furfural from glucose and fructose, *Green Chem.* **2019**, 6146.

[44] J. Horvat, B. Klaić, B. Metelko, V. Šunjić, Mechanism of levulinic acid formation, *Tetrahedron Lett.* **1985**, *26*, 2111.

[45] J. Zhang, E. Weitz, An in Situ NMR Study of the Mechanism for the Catalytic Conversion of Fructose to 5-Hydroxymethylfurfural and then to Levulinic Acid Using 13 C Labeled, *ACS Catal.* **2012**, *2*, 1211–1218.

[46] M. R. Whitaker, A. Parulkar, P. Ranadive, R. Joshi, N. A. Brunelli, Examining Acid Formation During the Selective Dehydration of Fructose to 5-Hydroxymethylfurfural in Dimethyl Sulfoxide and Water, *ChemSusChem* **2019**, *12*, 2211.

[47] J. Horvat, B. Klaic, B. Metelko, V. Sunjic, Mechanism of levulinic acid formation in acid catalyzed hydrolysis of 2-(hydroxymethyl)furan and 5-(hydroxymethyl)-2-furancarboxaldehyde., *Croat. Chem. Acta* **1986**, *59*, 429.

[48] G. Tsilomelekis, M. J. Orella, Z. Lin, Z. Cheng, W. Zheng, V. Nikolakis, D. G. Vlachos, Molecular structure, morphology and growth mechanisms and rates of 5-hydroxymethyl furfural (HMF) derived humins, *Green Chem.* **2016**, *18*, 1983.

[49] S. K. R. Patil, J. Heltzel, C. R. F. Lund, Comparison of structural features of humins formed catalytically from glucose, fructose, and 5-hydroxymethylfurfuraldehyde, *Energy Fuels* **2012**, *26*, 5281.

[50] X. Fu, J. Dai, X. Guo, J. Tang, L. Zhu, C. Hu, Suppression of oligomer formation in glucose dehydration by CO2 and tetrahydrofuran, *Green Chem.* **2017**, *19*, 3334.

[51] V. Maruani, S. Narayanin-Richenapin, E. Framery, B. Andrioletti, Acidic Hydrothermal Dehydration of d -Glucose into Humins: Identification and Characterization of Intermediates, *ACS Sustain. Chem. Eng.* **2018**, *6*, 13487.

[52] S. Meier, A. R. Hansen, P. R. Jensen, Probing the Role of Individual OH Sites in Carbohydrate Conversion Suggests Strategies for Increasing Product Selectivity and Avoiding Humins, *ACS Sustain. Chem. Eng.* **2023**, *11*, 1027.

[53] J. Tang, L. Zhu, X. Fu, J. Dai, X. Guo, C. Hu, Insights into the Kinetics and Reaction Network of Aluminum Chloride-Catalyzed Conversion of Glucose in NaCl-H2O/THF Biphasic System, *ACS Catal.* **2017**, *7*, 256.

[54] X. Fu, Y. Hu, Y. Zhang, Y. Zhang, D. Tang, L. Zhu, C. Hu, Solvent Effects on Degradative Condensation Side Reactions of Fructose in Its Initial Conversion to 5-Hydroxymethylfurfural, *ChemSusChem* **2019**, *13*, 501.

[55] H. Kimura, M. Nakahara, N. Matubayasi, Solvent effect on pathways and mechanisms for d-fructose conversion to 5-hydroxymethyl-2-furaldehyde: In situ 13C NMR study, *J. Phys. Chem. A* **2013**, *117*, 2102.

[56] V. Vasudevan, S. H. Mushrif, Insights into the solvation of glucose in water, dimethyl sulfoxide (DMSO), tetrahydrofuran (THF) and N,N-dimethylformamide (DMF) and its possible implications on the conversion of glucose to platform chemicals, *RSC Adv.* **2015**, *5*, 20756.

[57] M. A. Mellmer, C. Sener, J. M. R. Gallo, J. S. Luterbacher, D. M. Alonso, J. A. Dumesic, Solvent effects in acid-catalyzed biomass conversion reactions, *Angew. Chem., – Int. Ed.* **2014**, *53*, 11872.

[58] X. Cui, L. Zheng, Q. Li, Y. Guo, A remarkable bifunctional carbon-based solid acid catalyst derived from waste bio-tar for efficient synthesis of 5-hydroxymethylfurfural from glucose, *Chem. Eng. J.* **2023**, *474*, https://doi.org/10.1016/j.cej.2023.146006.

[59] A. S. Amarasekara, L. T. D. Williams, C. C. Ebede, Mechanism of the dehydration of d-fructose to 5-hydroxymethylfurfural in dimethyl sulfoxide at 150 °C: an NMR study, *Carbohydr. Res.* **2008**, *343*, 3021.

[60] J. C. Velasco Calderón, S. Jiang, S. H. Mushrif, Understanding the Effect of Solvent Environment on the Interaction of Hydronium Ion with Biomass Derived Species: A Molecular Dynamics and Metadynamics Investigation, *ChemPhysChem* **2021**, *22*, 2222.

[61] A. Toftgaard Pedersen, R. Ringborg, T. Grotkjær, S. Pedersen, J. M. Woodley, Synthesis of 5-hydroxymethylfurfural (HMF) by acid catalyzed dehydration of glucose-fructose mixtures, *Chem. Eng. J.* **2015**, *273*, 455.

[62] Y. Zhang, H. Zhu, Z. Ji, Y. Cheng, L. Zheng, L. Wang, X. Li, Experiments and Kinetic Modeling of Fructose Dehydration to 5-Hydroxymethylfurfural with Hydrochloric Acid in Acetone-Water Solvent, *Ind. Eng. Chem. Res.* **2022**, *61*, 13877.

[63] H. Kimura, M. Nakahara, N. Matubayasi, In situ kinetic study on hydrothermal transformation of d -glucose into 5-hydroxymethylfurfural through d -fructose with 13C NMR, *J. Phys. Chem. A* **2011**, *115*, 14013.

[64] F. Olivito, V. Algieri, M. A. Tallarida, A. Jiritano, P. Costanzo, L. Maiuolo, A. De Nino, High-yield synthesis of HMF from glucose and fructose by selective catalysis with water-tolerant rare earth metal triflates assisted by choline chloride, *Green Chem.* **2023**, *25*, 1679.

[65] Q. Lin, Q. Zhan, R. Li, S. Liao, J. Ren, F. Peng, L. Li, Solvent effect on xylose-to-furfural reaction in biphasic systems: Combined experiments with theoretical calculations, *Green Chem.* **2021**, *23*, 8510.

[66] W. Guo, Z. Zhang, J. Hacking, H. J. Heeres, J. Yue, Selective fructose dehydration to 5-hydroxymethylfurfural from a fructose-glucose mixture over a sulfuric acid catalyst in a biphasic system: Experimental study and kinetic modelling, *Chem. Eng. J.* **2021**, *409*, 128182.

[67] M. Aigner, D. Roth, J. Rußkamp, J. Klankermayer, A. Jupke, Model-based equipment design for the biphasic production of 5-hydroxymethylfurfural in a tubular reactor, *AIChE J.* **2020**, *66*, https://doi.org/10.1002/aic.16849.

[68] Z. Cheng, K. A. Goulas, N. Quiroz Rodriguez, B. Saha, D. G. Vlachos, Growth kinetics of humins studied: Via X-ray scattering, *Green Chem.* **2020**, *22*, 2301.

[69] C. E. Bounoukta, C. Megías-Sayago, F. Ammari, S. Ivanova, A. Monzon, M. A. Centeno, J. A. Odriozola, Dehydration of glucose to 5-Hydroxymethlyfurfural on bifunctional carbon catalysts, *Appl. Catal., B* **2021**, *286*, 119938.

[70] S. Rok, M. Grilc, M. Hus, B. Likozar, *Multiscale Modeling of (Hemi) cellulose Hydrolysis and Cascade Hydrotreatment of 5 – Hydroxymethylfurfural, Furfural, and Levulinic Acid* **2019**, https://doi.org/10.1021/acs.iecr.9b00898.

[71] A. Bjelić, M. Grilc, B. Likozar, Catalytic hydrogenation and hydrodeoxygenation of lignin-derived model compound eugenol over Ru/C: Intrinsic microkinetics and transport phenomena, *Chem. Eng. J.* **2018**, *333*, 240.

[72] R. Karinen, K. Vilonen, M. Niemelä, Biorefining: Heterogeneously catalyzed reactions of carbohydrates for the production of furfural and hydroxymethylfurfural, *ChemSusChem* **2011**, *4*, 1002.

[73] D. Garcés, E. Díaz, S. Ordóñez, Aqueous Phase Conversion of Hexoses into 5-Hydroxymethylfurfural and Levulinic Acid in the Presence of Hydrochloric Acid: Mechanism and Kinetics, *Ind. Eng. Chem. Res.* **2017**, *56*, 5221.

[74] T. D. Swift, C. Bagia, V. Choudhary, G. Peklaris, V. Nikolakis, D. G. Vlachos, Kinetics of homogeneous Brønsted acid catalyzed fructose dehydration and 5-hydroxymethyl furfural rehydration: A combined experimental and computational study, *ACS Catal.* **2014**, *4*, 259.

[75] B. A. Fachri, R. M. Abdilla, H. H. V. De Bovenkamp, C. B. Rasrendra, H. J. Heeres, Experimental and Kinetic Modeling Studies on the Sulfuric Acid Catalyzed Conversion of d -Fructose to 5-Hydroxymethylfurfural and Levulinic Acid in Water, *ACS Sustain. Chem. Eng.* **2015**, *3*, 3024.

[76] R. Weingarten, J. Cho, R. Xing, W. C. Conner, G. W. Huber, Kinetics and reaction engineering of levulinic acid production from aqueous glucose solutions, *ChemSusChem* **2012**, *5*, 1280.

[77] R. J. Van Putten, J. N. M. Soetedjo, E. A. Pidko, J. C. Van Der Waal, E. J. M. Hensen, E. De Jong, H. J. Heeres, Dehydration of different ketoses and aldoses to 5-hydroxymethylfurfural, *ChemSusChem* **2013**, *6*, 1681.

[78] Y. Li, X. Lu, L. Yuan, X. Liu, Fructose decomposition kinetics in organic acids-enriched high temperature liquid water, *Biomass Bioenergy* **2009**, *33*, 1182.

[79] K. Dussan, B. Girisuta, M. Lopes, J. J. Leahy, M. H. B. Hayes, Conversion of Hemicellulose Sugars Catalyzed by Formic Acid: Kinetics of the Dehydration of D-Xylose, L-Arabinose, and D-Glucose, *ChemSusChem* **2015**, *8*, 1411.

[80] L. Kupiainen, J. Ahola, J. Tanskanen, Kinetics of glucose decomposition in formic acid, *Chem. Eng. Res. Des.* **2011**, *89*, 2706.

[81] B. Seemala, V. Haritos, A. Tanksale, Levulinic Acid as a Catalyst for the Production of 5-Hydroxymethylfurfural and Furfural from Lignocellulose Biomass, *ChemCatChem* **2016**, *8*, 640.

[82] B. Girisuta, L. P. B. M. Janssen, H. J. Heeres, GREEN CHEMICALS A Kinetic Study on the Conversion of Glucose to Levulinic Acid, *Chem. Eng. Res. Des.* **2006**, https://doi.org/10.1205/cherd05038.

[83] M. Möller, F. Harnisch, U. Schröder, Microwave-assisted hydrothermal degradation of fructose and glucose in subcritical water, *Biomass Bioenergy* **2012**, *39*, 389.

[84] Z. Yan, J. Lian, Y. Feng, M. Li, F. Long, R. Cheng, S. Shi, H. Guo, J. Lu, A mechanistic insight into glucose conversion in subcritical water: Complex reaction network and the effects of acid-base catalysis, *Fuel* **2021**, *289*, 119969.

[85] T. Dallas Swift, H. Nguyen, A. Anderko, V. Nikolakis, D. G. Vlachos, Tandem Lewis/Brønsted homogeneous acid catalysis: conversion of glucose to 5-hydoxymethylfurfural in an aqueous chromium(iii) chloride and hydrochloric acid solution, *Green Chem.* **2015**, *17*, 4725.

[86] S. Kunnikuruvan, N. N. Nair, Mechanistic Insights into the Brønsted Acid-Catalyzed Dehydration of β-d-Glucose to 5-Hydroxymethylfurfural under Ambient and Subcritical Conditions, *ACS Catal* **2019**, *9*, 7250.

[87] Q. Jing, X. Lü, Kinetics of Non-catalyzed Decomposition of Glucose in High-temperature Liquid Water, *Chin J Chem Eng* **2008**, *16*, 890.

[88] A. Jakob, B. Likozar, M. Grilc, Aqueous conversion of monosaccharides to furans: were we wrong all along to use catalysts?, *Green Chem.* **2022**, https://doi.org/10.1039/d2gc02736d.

[89] T. Wang, J. A. Glasper, B. H. Shanks, Kinetics of glucose dehydration catalyzed by homogeneous Lewis acidic metal salts in water, *Appl. Catal., A* **2015**, *498*, 214.

[90] L. Zhang, G. Xi, J. Zhang, H. Yu, X. Wang, Efficient catalytic system for the direct transformation of lignocellulosic biomass to furfural and 5-hydroxymethylfurfural, *Bioresour. Technol.* **2017**, *224*, 656.

[91] X. Zhang, B. B. Hewetson, N. S. Mosier, Kinetics of maleic acid and aluminum chloride catalyzed dehydration and degradation of glucose, *Energy Fuels* **2015**, *29*, 2387.

[92] J. M. Carraher, C. N. Fleitman, J. P. Tessonnier, Kinetic and mechanistic study of glucose isomerization using homogeneous organic brønsted base catalysts in water, *ACS Catal.* **2015**, *5*, 3162.

[93] Y. Yu, H. Wu, Kinetics and mechanism of glucose decomposition in hot-compressed water: Effect of initial glucose concentration, *Ind. Eng. Chem. Res.* **2011**, *50*, 10500.

[94] P. Drabo, M. Fischer, M. Emondts, J. Hamm, M. Engelke, M. Simonis, L. Qi, S. L. Scott, R. Palkovits, I. Delidovich, Solvent effects on catalytic activity and selectivity in amine-catalyzed D-fructose isomerization, *J. Catal.* **2023**, *418*, 13.

[95] B. R. Caes, R. E. Teixeira, K. G. Knapp, R. T. Raines, Biomass to Furanics: Renewable Routes to Chemicals and Fuels, *ACS Sustain. Chem. Eng.* **2015**, *3*, 2591.

[96] J. S. Kruger, V. Nikolakis, D. G. Vlachos, Carbohydrate dehydration using porous catalysts, *Curr. Opin. Chem. Eng.* **2012**, *1*, 312.

[97] B. Agarwal, K. Kailasam, R. S. Sangwan, S. Elumalai, Traversing the history of solid catalysts for heterogeneous synthesis of 5-hydroxymethylfurfural from carbohydrate sugars: A review, *Renewable Sustainable Energy Rev.* **2018**, *82*, 2408.

[98] S. Xu, C. Yin, D. Pan, F. Hu, Y. Wu, Y. Miao, L. Gao, G. Xiao, Efficient conversion of glucose into 5-hydroxymethylfurfural using a bifunctional Fe 3+ modified Amberlyst-15 catalyst, *Sustainable Energy Fuels* **2019**, *3*, 390.

[99] N. A. S. Ramli, N. A. S. Amin, Fe/HY zeolite as an effective catalyst for levulinic acid production from glucose: Characterization and catalytic performance, *Appl. Catal., B* **2015**, *163*, 487.

[100] S. B. Kim, S. J. You, Y. T. Kim, S. M. Lee, H. Lee, K. Park, E. D. Park, Dehydration of D-xylose into furfural over H-zeolites, *Korean J. Chem. Eng.* **2011**, *28*, 710.

[101] Y. Yin, Y. Qi, C. Ma, W. Li, S. Luo, S. Liu, Efficient conversion of cellulose to 5-hydroxymethylfurfural using a bifunctional hydrophobic SBA-15 catalyst: The effects of hydrophobicity, morphology and acidity, *Fuel Process. Technol.* **2023**, *245*, 107752.

[102] D. M. Sboiu, M. D. Márquez-Medina, M. Lara-Serrano, S. Morales-delaRosa, J. M. Campos-Martin, "Catalytic conversion into 5-hydroxymethylfurfural and furfural by heterogeneous sulfonic acid catalysis in a flowing acetone–water system, *Fuel* **2024**, *372*, 132200.

[103] J. S. Kruger, V. Nikolakis, D. G. Vlachos, Aqueous-phase fructose dehydration using Brønsted acid zeolites: Catalytic activity of dissolved aluminosilicate species, *Appl. Catal., A* **2014**, *469*, 116.

[104] R. L. Johnson, F. A. Perras, M. P. Hanrahan, M. Mellmer, T. F. Garrison, T. Kobayashi, J. A. Dumesic, M. Pruski, A. J. Rossini, B. H. Shanks, Condensed Phase Deactivation of Solid Brønsted Acids in the Dehydration of Fructose to Hydroxymethylfurfural, *ACS Catal.* **2019**, *9*, 11568.

[105] I. Sádaba, M. López Granados, A. Riisager, E. Taarning, Deactivation of solid catalysts in liquid media: the case of leaching of active sites in biomass conversion reactions, *Green Chem.* **2015**, *17*, 4133.
[106] J. S. Kruger, V. Choudhary, V. Nikolakis, D. G. Vlachos, Elucidating the roles of zeolite H-BEA in aqueous-phase fructose dehydration and HMF rehydration, *ACS Catal.* **2013**, *3*, 1279.
[107] T. D. Swift, H. Nguyen, Z. Erdman, J. S. Kruger, V. Nikolakis, D. G. Vlachos, Tandem Lewis acid/Brønsted acid-catalyzed conversion of carbohydrates to 5-hydroxymethylfurfural using zeolite beta, *J. Catal.* **2016**, *333*, 149.
[108] R. Bermejo-Deval, R. S. Assary, E. Nikolla, M. Moliner, Y. Román-Leshkov, S. J. Hwang, A. Palsdottir, D. Silverman, R. F. Lobo, L. A. Curtiss, M. E. Davis, Metalloenzyme-like catalyzed isomerizations of sugars by Lewis acid zeolites, *Proc. Natl. Acad. Sci. U S A* **2012**, *109*, 9727.
[109] P. Carniti, A. Gervasini, S. Biella, A. Auroux, Niobic acid and niobium phosphate as highly acidic viable catalysts in aqueous medium: Fructose dehydration reaction, *Catal Today* **2006**, *118*, 373.
[110] K. Lourvanij, G. L. Rorrer, Reaction rates for the partial dehydration of glucose to organic acids in solid-acid, molecular-sieving catalyst powders, *J. Chem. Technol. Biotechnol.* **1997**, *69*, 35.
[111] W. Wei, S. Wu, Experimental and kinetic study of glucose conversion to levulinic acid in aqueous medium over Cr/HZSM-5 catalyst, *Fuel* **2018**, *225*, 311.
[112] H. Xiang, S. Zainal, H. Jones, X. Ou, C. D'Agostino, J. Esteban, C. M. A. Parlett, X. Fan, Hierarchical zeolite catalysed fructose dehydration to 5-hydroxymethylfurfural within a biphasic solvent system under microwave irradiation, *RSC Sustainability* **2023**, *1*, 1530.
[113] N. A. S. Ramli, N. A. S. Amin, Kinetic study of glucose conversion to levulinic acid over Fe/HY zeolite catalyst, *Chem. Eng. J.* **2016**, *283*, 150.
[114] S. Liu, X. Wei, W. Sun, C. Wang, W. Li, L. Ma, Q. Liu, Coking Prediction in Catalytic Glucose Conversion to Levulinic Acid Using Improved Lattice Boltzmann Model, *Ind. Eng. Chem. Res.* **2020**, *59*, 17462.
[115] M. M. de J. Junior, S. A. Fernandes, E. Borges, B. E. L. Baêta, F. de Á. Rodrigues, "Kinetic study of the conversion of glucose to 5-hydroxymethylfurfural using niobium phosphate, *Mol. Catal.* **2022**, *518*, https://doi.org/10.1016/j.mcat.2021.112079.
[116] L. Li, Y. Hu, H. Li, P. Hu, Z. Xue, D. Wu, C. Hu, L. Zhu, Probing the formation of soluble humins in catalytic dehydration of fructose to 5-hydroxymethylfurfural over HZSM-5 catalyst, *Fuel* **2023**, *344*, https://doi.org/10.1016/j.fuel.2023.128133.
[117] I. Agirrezabal-Telleria, N. Miletić, P. L. Arias, Regeneration of surface acid sites via mild oxidation on dehydration catalysts, *Catal. Sci. Technol.* **2016**, *6*, 3367.
[118] J. F. Saeman, Kinetics of Wood Saccharification - Hydrolysis of Cellulose and Decomposition of Sugars in Dilute Acid at High Temperature, *Ind. Eng. Chem.* **1945**, *37*, 43.
[119] B. Girisuta, L. P. B. M. Janssen, H. J. Heeres, Kinetic study on the acid-catalyzed hydrolysis of cellulose to levulinic acid, *Ind. Eng. Chem. Res.* **2007**, *46*, 1696.
[120] B. Girisuta, B. Danon, R. Manurung, L. P. B. M. Janssen, H. J. Heeres, Experimental and kinetic modelling studies on the acid-catalysed hydrolysis of the water hyacinth plant to levulinic acid, *Bioresour. Technol.* **2008**, *99*, 8367.
[121] S. Rivas, M. J. González-Muñoz, C. Vila, V. Santos, J. C. Parajó, Manufacture of levulinic acid from pine wood hemicelluloses: A kinetic assessment, *Ind. Eng. Chem. Res.* **2013**, *52*, 3951.
[122] S. Rivas, M. J. González-Muñoz, V. Santos, J. C. Parajó, Acidic processing of hemicellulosic saccharides from pine wood: Product distribution and kinetic modeling, *Bioresour. Technol.* **2014**, *162*, 192.
[123] B. Girisuta, K. Dussan, D. Haverty, J. J. Leahy, M. H. B. Hayes, A kinetic study of acid catalysed hydrolysis of sugar cane bagasse to levulinic acid, *Chem. Eng. J.* **2013**, *217*, 61.
[124] J. Shen, C. E. Wyman, Hydrochloric Acid-Catalyzed Levulinic Acid Formation from Cellulose : Data and Kinetic Model to Maximize Yields, *AIChE* **2012**, *58*, 236.
[125] Q. Qing, Q. Guo, P. Wang, H. Qian, X. Gao, Y. Zhang, Kinetics study of levulinic acid production from corncobs by tin tetrachloride as catalyst, *Bioresour. Technol.* **2018**, *260*, 150.
[126] M. S. R. dos Santos Rocha, B. Pratto, R. de Sousa, R. M. R. G. Almeida, A. J. G. da Cruz, "A kinetic model for hydrothermal pretreatment of sugarcane straw, *Bioresour. Technol.* **2017**, *228*, 176.
[127] L. Vanoye, M. Fanselow, J. D. Holbrey, M. P. Atkins, K. R. Seddon, Kinetic model for the hydrolysis of lignocellulosic biomass in the ionic liquid, 1-ethyl-3-methyl-imidazolium chloride, *Green Chem.* **2009**, *11*, 390.
[128] N. V. Gromov, O. P. Taran, C. Aymonier, V. N. Parmon, Kinetic modeling of the multistep hydrolysis-dehydration of cellulose to platform molecules over a solid carbon acid catalyst in pure water, *React. Kinet., Mech. Catal.* **2020**, *130*, 669.
[129] C.-W. Jiang, X. Zhong, Z.-H. Luo, An improved kinetic model for cellulose hydrolysis to 5-hydroxymethylfurfural using the solid SO42−/Ti-MCM-41 catalyst, *RSC Adv.* **2014**, *4*, 15216.
[130] P. Bhaumik, A. K. Deepa, T. Kane, P. L. Dhepe, Value addition to lignocellulosics and biomass-derived sugars: An insight into solid acid-based catalytic methods, *J. Chem. Sci.* **2014**, *126*, 373.
[131] Q. Xiang, J. S. Kiim, Y. Y. Lee, A Comprehensive Kinetic Model for Dilute-Acid Hydrolysis of Cellulose, *Appl. Biochem. Biotechnol.* **2003**, *105*, 337.
[132] Q. Xiang, Y. Y. Lee, R. W. Torget, Kinetics of glucose decomposition during dilute-acid hydrolysis of lignocellulosic biomass, *Appl. Biochem. Biotechnol. - Part A: Enzyme Eng. Biotechnol.* **2004**, *115*, 1127.
[133] L. Yan, A. A. Greenwood, A. Hossain, B. Yang, A comprehensive mechanistic kinetic model for dilute acid hydrolysis of switchgrass cellulose to glucose, 5-HMF and levulinic acid, *RSC Adv.* **2014**, *4*, 23492.
[134] O. Yemiş, G. Mazza, Acid-catalyzed conversion of xylose, xylan and straw into furfural by microwave-assisted reaction, *Bioresour. Technol.* **2011**, *102*, 7371.
[135] P. Daorattanachai, N. Viriya-empikul, N. Laosiripojana, K. Faungnawakij, Effects of Kraft lignin on hydrolysis/dehydration of sugars, cellulosic and lignocellulosic biomass under hot compressed water, *Bioresour. Technol.* **2013**, *144*, 504.
[136] K. Lamminpää, J. Ahola, J. Tanskanen, Acid-catalysed xylose dehydration into furfural in the presence of kraft lignin, *Bioresour. Technol.* **2015**, *177*, 94.
[137] G. R. Gomes, D. S. Rampon, L. P. Ramos, Production of furan compounds from sugarcane bagasse using a catalytic system containing ZnCl2/HCl or AlCl3/HCl in a biphasic system, *J. Braz. Chem. Soc.* **2018**, *29*, 1115.
[138] A. L. Jongerius, J. R. Copeland, G. S. Foo, J. P. Hofmann, P. C. A. Bruijnincx, C. Sievers, B. M. Weckhuysen, Stability of Pt/γ-Al2O3 catalysts in lignin and lignin model compound solutions under liquid phase reforming reaction conditions, *ACS Catal.* **2013**, *3*, 464.
[139] L. Liu, H. Chang, H. Jameel, J.-Y. Park, S. Park, Catalytic Conversion of Biomass Hydrolysate into 5-Hydroxymethylfurfural, *Ind. Eng. Chem. Res.* **2017**, *56*, 14447.
[140] J. B. Binder, R. T. Raines, Simple chemical transformation of lignocellulosic biomass into furans for fuels and chemicals, *J. Am. Chem. Soc.* **2009**, *131*, 1979.
[141] D. M. Alonso, S. G. Wettstein, M. A. Mellmer, E. I. Gurbuz, J. A. Dumesic, Integrated conversion of hemicellulose and cellulose from lignocellulosic biomass, *Energy Environ. Sci.* **2013**, *6*, 76.
[142] J. Slak, B. Pomeroy, A. Kostyniuk, M. Grilc, *A review of bio-refining process intensification in catalytic conversion reactions, separations and purifications of hydroxymethylfurfural (HMF) and furfural* **2022**, *429*, https://doi.org/10.1016/j.cej.2021.132325.
[143] T. Runge, C. Zhang, Two-stage acid-catalyzed conversion of carbohydrates into levulinic acid, *Ind. Eng. Chem. Res.* **2012**, *51*, 3265.
[144] D. Jung, P. Körner, A. Kruse, Kinetic study on the impact of acidity and acid concentration on the formation of 5-hydroxymethylfurfural (HMF), humins, and levulinic acid in the hydrothermal conversion of fructose, *Biomass Convers. Biorefin.* **2019**, https://doi.org/10.1007/s13399-019-00507-0.
[145] A. Chareonlimkun, V. Champreda, A. Shotipruk, N. Laosiripojana, Catalytic conversion of sugarcane bagasse, rice husk and corncob in the presence of TiO2, ZrO2 and mixed-oxide TiO2-ZrO2 under hot compressed water (HCW) condition, *Bioresour. Technol.* **2010**, *101*, 4179.
[146] C. M. Cai, N. Nagane, R. Kumar, C. E. Wyman, Coupling metal halides with a co-solvent to produce furfural and 5-HMF at high yields directly from lignocellulosic biomass as an integrated biofuels strategy, *Green Chem.* **2014**, *16*, 3819.
[147] C. L. Williams, T. L. Westover, R. M. Emerson, J. S. Tumuluru, C. Li, Sources of Biomass Feedstock Variability and the Potential Impact on Biofuels Production, *Bioenergy Res.* **2016**, *9*, 1.
[148] F. S. Asghari, H. Yoshida, Kinetics of the decomposition of fructose catalyzed by hydrochloric acid in subcritical water: Formation of

5-hydroxymethylfurfural, levulinic, and formic acids, *Ind. Eng. Chem. Res.* **2007**, *46*, 7703.

[149] T. Y. Chen, Z. Cheng, P. Desir, B. Saha, D. G. Vlachos, Fast microflow kinetics and acid catalyst deactivation in glucose conversion to 5-hydroxymethylfurfural, *React. Chem. Eng.* **2021**, *6*, 152.

[150] S. Xiong, C. Luo, Z. Yu, N. Ji, L. Zhu, S. Wang, Dual Functional Carbon-based Solid Acid-Induced Hydrothermal Conversion of Biomass Saccharides: Catalyst Rational Design and Kinetic Analysis, *Green Chem.* **2021**, https://doi.org/10.1039/d1gc01968f.

[151] X. Li, K. Peng, X. Liu, Q. Xia, Y. Wang, Comprehensive Understanding of the Role of Brønsted and Lewis Acid Sites in Glucose Conversion into 5-Hydromethylfurfural, *ChemCatChem* **2017**, *9*, 2739.

Manuscript received: June 19, 2025
Revised manuscript received: September 22, 2025
Version of record online: October 22, 2025