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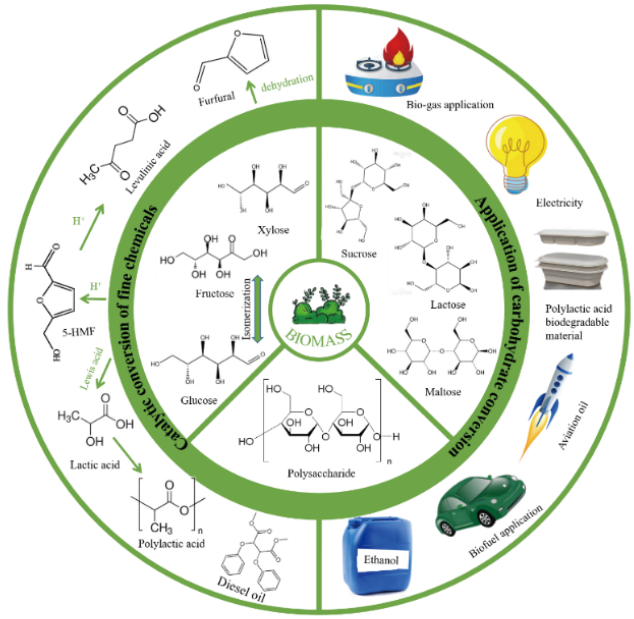
REVIEW

Catalytic conversion of carbohydrates: Opportunities and challenges en route to fuels and chemicals

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Abstract: Carbohydrates, derived from abundant biomass resources, hold great promise for their conversion into fine platform chemicals and fuels, which is crucial for the sustainable development. The processes for the conversion of carbohydrates are predominantly driven by catalysis, with active components such as Brønsted acids and Lewis acids. This review provides a comprehensive overview of the catalytic conversion of various carbohydrates (monosaccharides, disaccharides, and polysaccharides) into high-value-added compounds. It elaborates on the specific pathways and mechanisms involved in reactions like hydrolysis, isomerization, and dehydration for target molecules such as 5-hydroxymethylfurfural, lactic acid, and furfural. Furthermore, the subsequent derivatization of these platform compounds and their application prospects in energy-related fields, including bio-fuels and batteries, are discussed. Finally, the current challenges in research are summarized, and future directions for the development of low-cost and high-performance catalytic systems are outlined.



Key words: carbohydrates; catalytic conversion; fine chemicals; bio-fuel

As the depletion crisis of traditional fossil fuels intensifies, the demand for green and sustainable development becomes increasingly urgent. With policy instruments such as carbon taxes are progressively implemented, the development of a new, high-efficiency energy system has become a global consensus[1]. In recent years, the proportion of new energy sources such as nuclear, hydrogen, and solar power in the energy consumption structure has continued to grow. However, their potential risks and technological bottlenecks have also attracted widespread attention. Currently, the technologies for the production, storage, and safety regulation of these new energy sources are still rather immature. The far-reaching impacts of related incidents, such as the Japanese nuclear wastewater event, further underscore the strategic importance of building a safe, diversified, and resilient energy structure[2−3]. Biomass (renewable) resources, characterized by their abundant reserves, carbon neutrality, and potential for conversion into various high-value chemicals, are regarded as a critical component of the future energy system. Carbohydrate compounds, as the most abundant component of biomass, possess high energy density and diverse conversion pathways. Through efficient catalytic conversion, biomass-derived carbohydrate can not

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only supplement the existing energy supply but also have the potential to gradually replace some traditional fossil fuels and currently unstable emerging energy sources[4].

As a highly promising renewable resource, carbohydrates can be directed through catalytic conversion toward two major pathways: high-value-added chemicals and clean energy, demonstrating broad prospects for industrialization. In the chemical industry, carbohydrate compounds can be transformed into a wide variety of fine chemicals: monosaccharides can undergo reactions such as isomerization and aldol condensation to produce key platform compounds like 5-hydroxymethylfurfural (5-HMF), lactic acid and furfural[5−6], while disaccharides (e.g., sucrose, maltose, and lactose) can be converted into derivatives such as levulinic acid, sorbitol, and lactobionic acid[7−12]. In the energy sector, their applications are equally diverse: on one hand, the conversion products like biodiesel derived from polysaccharides exhibit calorific values comparable to those of petroleum-based fuels, making them a direct supplement to liquid fuels[13]; on the other hand, carbohydrate-based fuel cells offer advantages such as rapid response and high durability, while their carbon-neutral lifecycle further making them an ideal clean energy technology[14−18].

This article provides a systematic review of researches on the catalytic conversion of carbohydrates, offering an in-depth discussion of transformation pathways, reaction mechanisms, and product applications. A comparative analysis is conducted between the conversion processes of model compounds and complex biomass components, aiming to furnish theoretical insights and technical perspectives for the value-added utilization and energy-oriented transformation of carbohydrates.

1 Conversion of carbohydrate compounds

The diverse nature of carbohydrate compounds leads to a correspondingly high variety of catalytic conversion pathways. As illustrated in Figure 1[19], a series of representative examples, ranging from monosaccharides (e.g., the isomerization of glucose to lactic acid), disaccharides (e.g., the dehydration of sucrose to 5-HMF), to polysaccharides (e.g., the conversion of cellulose into bio-fuels), demonstrate the broad technical feasibility of efficiently transforming carbohydrates into both energy and chemical products[20].

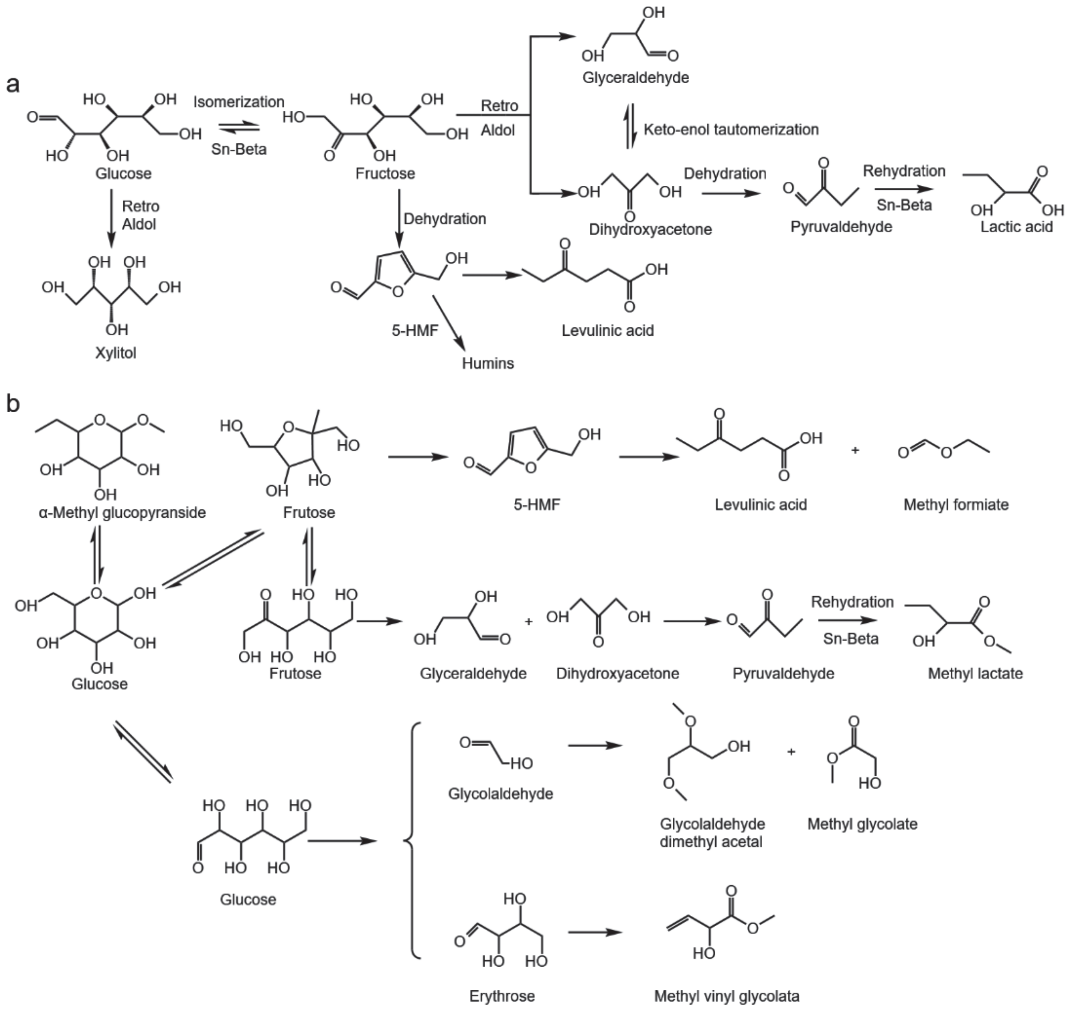


Fig. 1 Conversion of glucose into fine chemicals[19]
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These pathways collectively form a technological blueprint for the value-added utilization of carbohydrates, laying a foundation for further exploration of reaction mechanisms and specific processes.

1.1 Conversion of monosaccharides

1.1.1 Isomerization of glucose to fructose

The isomerization of glucose to fructose is a key step in the production of fuels and renewable platform chemicals from biomass resources. This transformation pathway and its underlying mechanisms have been extensively investigated. The process has evolved from enzymatic and inorganic base catalysis to the use of Lewis acid catalysts, emerging as an important research direction for the value-added utilization of biomass.

The catalytic mechanism of glucose isomerization primarily follows two pathways: acid and base catalysis. The acid pathway depends on the Lewis acid sites, where the formation of a cyclic intermediate, facilitating an intramolecular 1,2-hydride shift, enables the hydrogen transfer from the C2 to the C1 position of the open-chain glucose. In the base-catalyzed pathway, D-glucose undergoes sequential transformation *via trans*-enediol and *cis*-enediol intermediates, ultimately yielding D-fructose. This process essentially involves the conversion of an α-hydroxyaldehyde through proton transfer (*via* the enediol mechanism), resulting in the formal migration of a hydrogen atom from the C2 and O2 positions to the C1 and O1 positions, thereby generating the corresponding α-hydroxyketone (Figure 2(a)). This mechanism is corroborated by the base-catalyzed isomerization of glyceraldehyde 3-phosphate to dihydroxyacetone phosphate[21], in which proton transfer occurs between the aldehyde hydroxyl group and the carbonyl oxygen atom. Additionally, another possible reaction pathway exists under the influence of Brønsted bases or specific metal ions (Figure 2(b)), where the bonding electron pair at the C2 position can migrates directly to the C1 position *via* intramolecular pathways, accompanied by concurrent hydrogen transfer[22−23].

Alkaline catalysts, including sodium hydroxide, sodium carbonate, and sodium aluminate, are commonly employed in the base-catalyzed isomerization of glucose to fructose, where the base strength not only directly influences the isomerization efficiency but also critically affects the reaction selectivity[24]. Strong inorganic bases such as NaOH and $Ca(OH)_2$ tend to trigger side reactions like retro-aldol condensation, leading to the formation of by-products such as lactic acid, acetic acid, and formic acid, which generally restrict the fructose yield to below 10%[25−26]. In contrast, sodium aluminate ($NaAlO_2$) demonstrates superior selectivity for isomerization. As illustrated in Figure 2(c), the catalytic mechanism involves the initial formation of an enol-aluminate complex between glucose and sodium aluminate, which proceeds *via* a β-D-glucopyranose-1,3-aluminate intermediate and ultimately converts into an α-D-fructofuranose-1,3,6-aluminate complex. A key aspect of this pathway is the effective suppression of D-mannose-aluminate complex formation by the aluminate species, thereby significantly enhancing the fructose yield[27−28].

However, the base-catalyzed route exhibits notable limitations: even when processing low-concentration glucose feedstocks, high concentrations of alkaline reagents are still required, accompanied by issues such as equipment corrosion and wastewater treatment. These factors undermine the long-term economic viability of this approach in industrial applications. Consequently, current research emphasis has gradually shifted toward recyclable solid acid catalysts, aiming to develop greener and more efficient isomerization systems.

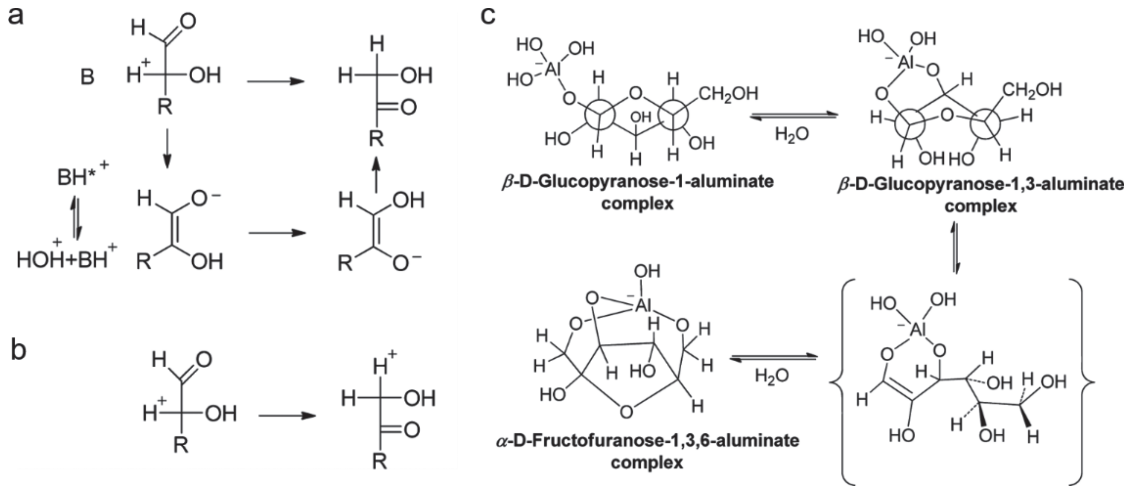


Fig. 2 Proton transfer (a) and hydride transfer (b) mechanism in the base-catalyzed glucose isomerization reaction; (c) glucose isomerization catalyzed by sodium aluminate[22−23]
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The Sn-β zeolite is recognized as one of the most promising solid Lewis acid catalysts, demonstrating exceptional performance in the glucose isomerization[29]. Its advantages stem from a unique three-dimensional 12-membered ring pore structure and a tunable coordination environment of the tin species. Studies reveal that both tetrahedral-coordinated Sn within the zeolite framework and octahedral-coordinated Sn outside the framework serve as active centers[30−31]. Based on this, researchers have proposed corresponding catalytic mechanisms[32−33]. As illustrated in Figure 3, octahedral-coordinated Sn in the form of SnO_2 outside the zeolite framework generate basic sites through dehydration/hydration processes, subsequently facilitate isomerization by abstracting the proton at the C2 position of glucose *via* the enediol mechanism. In contrast, the framework tetrahedral Sn promote isomerization by enabling an intramolecular hydride shift between the C1 (carbonyl) and C2 (hydroxyl) groups. These dual mechanisms collectively contribute to the high activity and selectivity of Sn-β zeolite, laying a theoretical foundation for its further application in the catalytic conversion of biomass.

In the Sn-β-catalyzed isomerization of glucose, the activation energy required for the process is not only influenced by the coordination geometry of the Sn species but also closely related to the structural factors. The silanol groups (Si–OH) adjacent to Sn can significantly reduce the isomerization activation energy by up to 13.66%[34], while the "open" configuration of the Sn species further helps lower the reaction energy barrier[35−38]. Desilication treatments often yield open Sn sites accompanied by neighboring silanol groups, which stabilizes reaction intermediates through hydrogen-bonding interactions, collectively reducing the activation energy barrier for glucose isomerization and thereby achieving high activity and selectivity. In addition, we have proposed an innovative strategy to further enhance the catalytic performance by introducing Ni^{2+} ions to stabilize the open Sn sites in the Sn-β zeolite[39], as shown in Figure 4. This approach not only significantly improves the apparent activity of the catalyst for glucose isomerization but also maintains excellent catalytic stability even under harsh conditions with a glucose mass concentration of as high as 33%, demonstrating promising potential for industrial application.

1.1.2 Catalytic conversion of glucose to lactic acid

Lactic acid serves as an important platform compound with broad applications in the food, pharmaceutical, chemical, and biodegradable plastics industries. Currently, approximately 90% of lactic acid production relies on traditional starch fermentation processes[40]. However, limitations such as constrained fermentation efficiency, lengthy reaction cycles, and sustainability concerns related to competition with food resources have motivated researchers to develop efficient catalytic routes utilizing non-food biomass[41]. The catalytic conversion of glucose to lactic acid represents a typical pathway for non-food biomass utilization[42] (Figure 5). Initially, glucose is isomerized to fructose under Lewis acid or base catalysis. The fructose then undergoes reverse retro-aldol cleavage and the C6 backbone is fragmented into two C3 units: dihydroxyacetone and glyceraldehyde. These C3 intermediates subsequently dehydrate to form methylglyoxal, which is finally converted to lactic acid *via* a 1,2-hydride shift rearrangement[25,43]. This catalytic route not only diversifies the feedstock options for lactic acid production but also offers a novel strategy for achieving highly efficient and selective conversion of glucose.

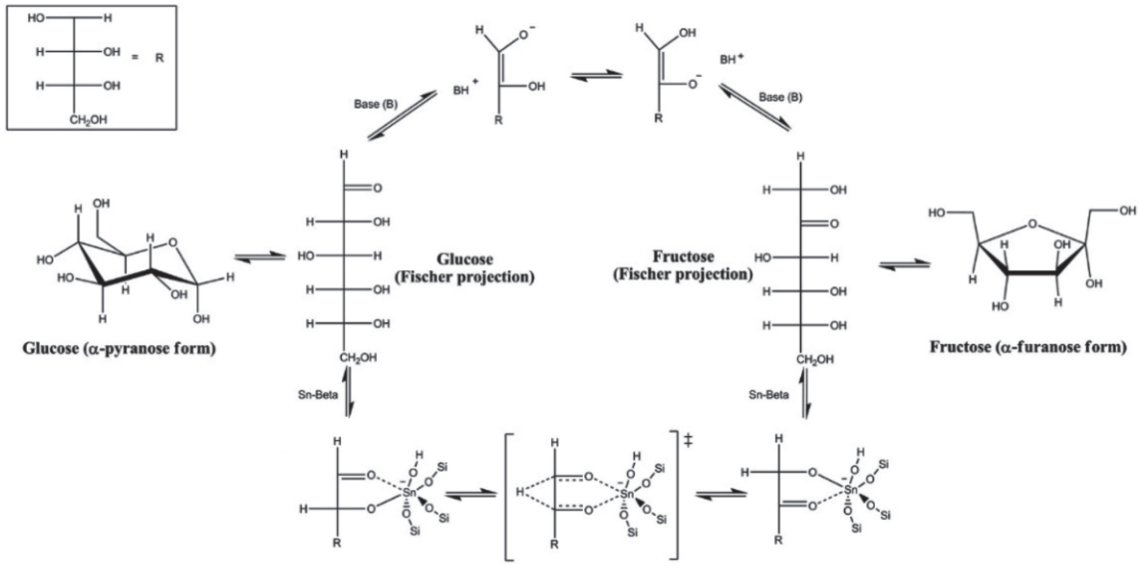


Fig. 3 Isomerization process of glucose to fructose catalyzed by Sn-β zeolite[33]
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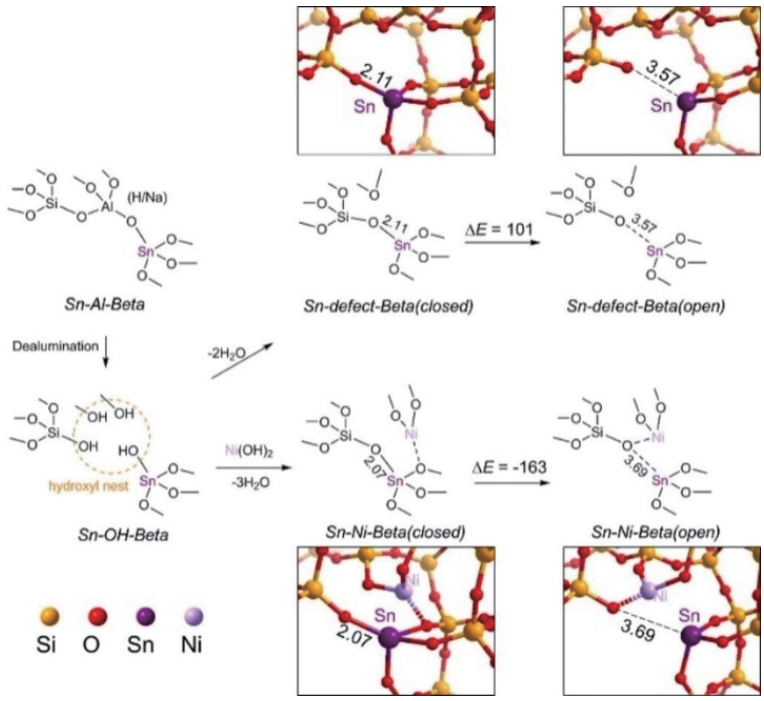


Fig. 4 Energy of Ni on the stabilization of open Sn site in Beta zeolite[39]
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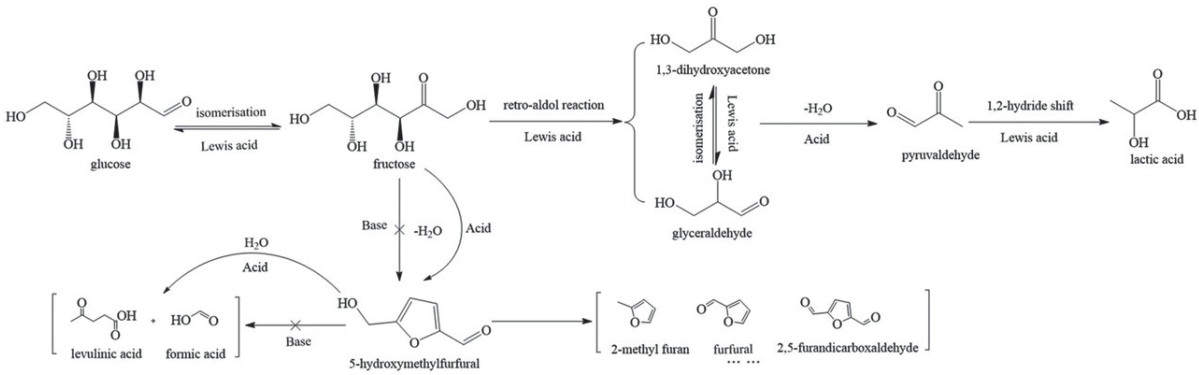


Fig. 5 Reaction pathway for the conversion of glucose to lactic acid[42]
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In the reaction for glucose conversion to lactic acid, Lewis acid sites play a critical role in the rate-determining step, where their strength directly govern the overall reaction efficiency. Therefore, rational design and precise regulation of the acidic sites in the catalysts constitute a primary strategy for enhancing lactic acid yield. De Clippel et al.[44] developed a bifunctional mesoporous silica catalyst incorporating both Lewis acid and weak Brønsted base sites and found that weak Brønsted base sites can effectively promote the dehydration of C3 intermediates, while the synergistic interplay between Lewis acid and Brønsted base sites can significantly enhance the overall reaction rate. Separately, Bai et al.[45] achieved a 47% lactic acid yield through post-treating commercial Sn-β zeolite by de-alumination and de-silication, thereby controlling the coordination state of framework tin species and Lewis acid strength. Furthermore, researchers have explored the catalytic performance of bimetallic-modified *X*-Sn-β zeolites (*X* = Mg, Ni, Zn, Zr, Ti, In)[46–49]. These materials achieve multidimensional catalytic optimization either by leveraging synergistic effects between bimetallic components, to enhance Lewis acid strength and facilitate the dehydration of C3 intermediates, or by introducing basic sites that suppress undesirable side reactions.

Although significant progress has been made in these studies, future efforts should focus on further enhancing the overall performance of catalytic systems, systematically elucidating the mechanistic roles of different acid sites during the reaction, and achieving simultaneous breakthroughs in both lactic acid yield and selectivity.

1.1.3 Catalytic conversion of glucose to 5-HMF

A variety of sugars, including glucose and fructose, can

serve as the raw materials for the production of 5-hydroxymethylfurfural (5-HMF) *via* a process that involves a series of complex reactions[50]. Among these sugar feedstocks, fructose is considered the most facile one for 5-HMF production due to its pentagonal ring structure, coupled with high conversion yields and straightforward reaction mechanisms. In contrast, the conversion of glucose to 5-HMF requires an additional isomerization step, generally resulting in relatively lower yield and selectivity. Nevertheless, the low cost and abundant availability of glucose make it a highly attractive feedstock for large-scale carbohydrate refining, thereby endowing it with greater potential for research and industrial application.

The conversion of glucose to 5-HMF centers on the isomerization of glucose to fructose, as illustrated in Figure 6[51]. In the presence of an alkaline catalyst, the reaction follows an acyclic pathway. This route typically initiates with the isomerization of glucose *via* the key intermediate 1,2-enediol, followed by three consecutive dehydration steps to form 5-HMF, viz., a process referred to "enediol mechanism". Under acidic conditions, however, a "1,2-hydride shift" mechanism operates, wherein D-fructofuranose undergoes dehydration to form (2R,3S,4S)-3,4-dihydroxy-2-(hydroxymethyl)-5-(hydroxymethylene) tetrahydrofuran, which undergoes further dehydration to (4S,5R)-4-hydroxy-5-(hydroxymethyl)-4,5-dihydrofuran-2-carbaldehyde, ultimately yielding 5-HMF. In this conversion system, Brønsted acids play a critical catalytic role in the dehydration steps[52]. However, 5-HMF is prone to further conversion into by-products such as levulinic acid or humins, making the choice of solvent environment particularly important[53−55]. Polar solvents, such as dimethyl sulfoxide[56−59], dimethylacetamide[60], acetone[61], and aqueous hydrochloric acid solutions[62], proved to be effective in promoting the target reaction while suppressing side pathways, often elevating 5-HMF yields to approximately 80%. Furthermore, the heterogeneous solid acid catalysts such as ion-exchange resins and zeolites are often comparable to the homogeneous ones in performance, leveraging their abundant Brønsted acid sites[63−65].

For the heterogeneous catalytic systems, there remains a need to develop green and efficient solvent systems along with structurally stable multifunctional catalysts. This aims to synergistically enhance the reaction efficiency of both glucose isomerization and fructose dehydration while effectively suppressing side-reaction pathways, thereby accelerating the industrialization of this technological route.

1.1.4 Catalytic conversion of xylose to furfural

The primary product of xylose conversion is furfural, which plays a significant role in lubricant refining and can be further transformed into high-value fine chemicals such as furfuryl alcohol, furan, and tetrahydrofuran. For the catalytic conversion of xylose to furfural, the water-toluene biphasic solvent system is widely employed. This system leverages the difference in hydrophilicity between the reactants and products, facilitating the preferential partitioning of furfural into the toluene phase, thereby improving the furfural yield. The conversion pathway and product selectivity of xylose are strongly influenced by the acidic properties (e.g., acid type, strength, and density) and structural characteristics of the catalyst. Brønsted and Lewis acid sites guide different steps of the reaction through distinct catalytic mechanisms, ultimately determining the final furfural yield and selectivity (Figure 7)[66]. Consequently, solid acid catalysts such as zeolites, metal salts with unique pore structures, and metal salt-supported materials have been utilized to improve furfural yield[67−74].

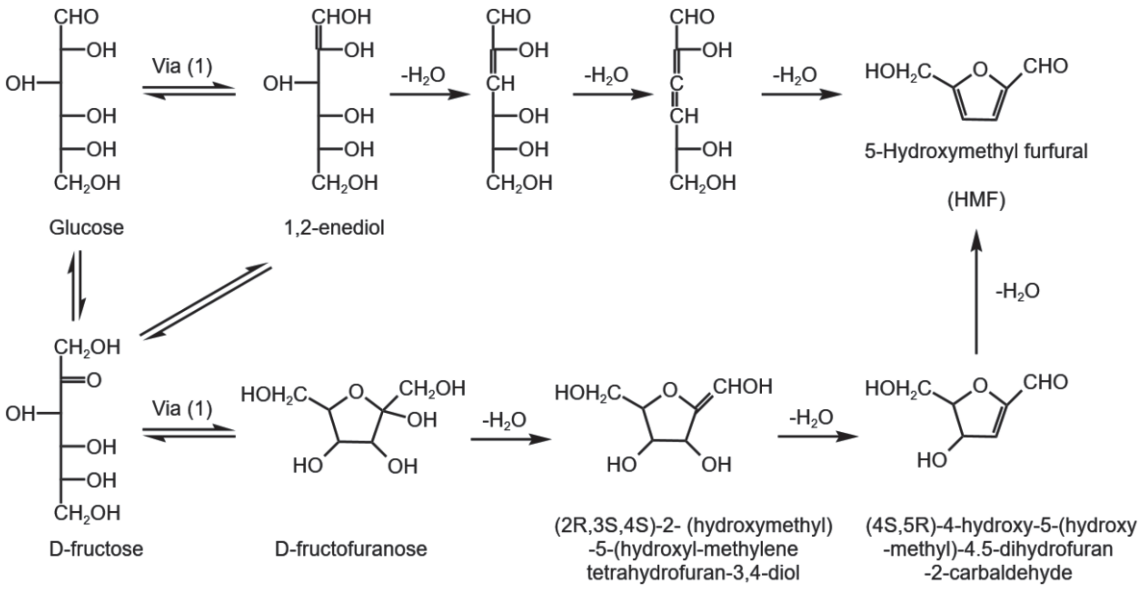


Fig. 6 Reaction pathway for the conversion of glucose to 5-HMF[51]
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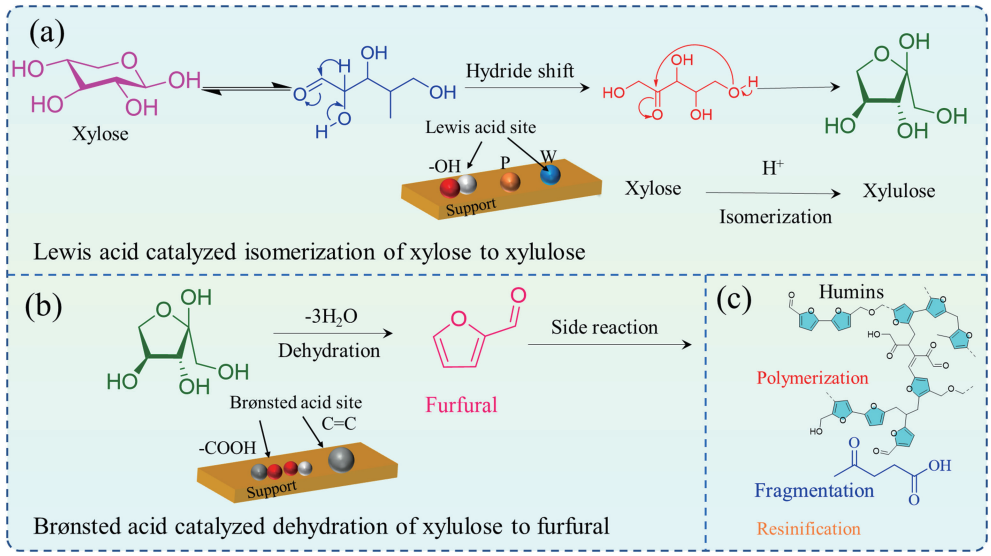


Fig. 7 Effect of the acid properties on the specific step of xylose conversion to furfural[66] (with permission from Elsevier)

Dias et al.[75] employed protonated cation-exchangeable layered metal oxide-derived nanosheets (HTiNbO, HNbO and HTiO) as solid acid catalysts for the dehydration of xylose to furfural. Owing to their high surface area and abundant accessible acid sites, these nanosheets achieved a xylose conversion of 92% with a furfural yield of 55%. Valadares et al.[76] constructed a balanced Brønsted-Lewis acid bifunctional catalyst by supporting niobium species on a dealuminated β-zeolite, which exhibited a furfural selectivity of up to 51% in the xylose conversion. Additionally, Parejas et al.[77] synthesized ZrO_2/MgO_2 catalysts *via* microemulsion and sol-gel methods for the liquid-phase dehydration of xylose to furfural, confirming that the incorporation of Zr plays a critical role in enhancing the catalytic activity.

1.2 Conversion of disaccharides

1.2.1 Conversion of sucrose

Sucrose can be hydrolyzed to glucose and fructose and is widely used in the food industry to enhance sweetness and texture. Furthermore, sucrose can undergo multiple reactions to generate a series of high-value fine chemicals. Therefore, a key research objective in sucrose conversion is the design and optimization of catalysts with tailored acid site functionalities to control the product selectivity (Figure 8)[78].

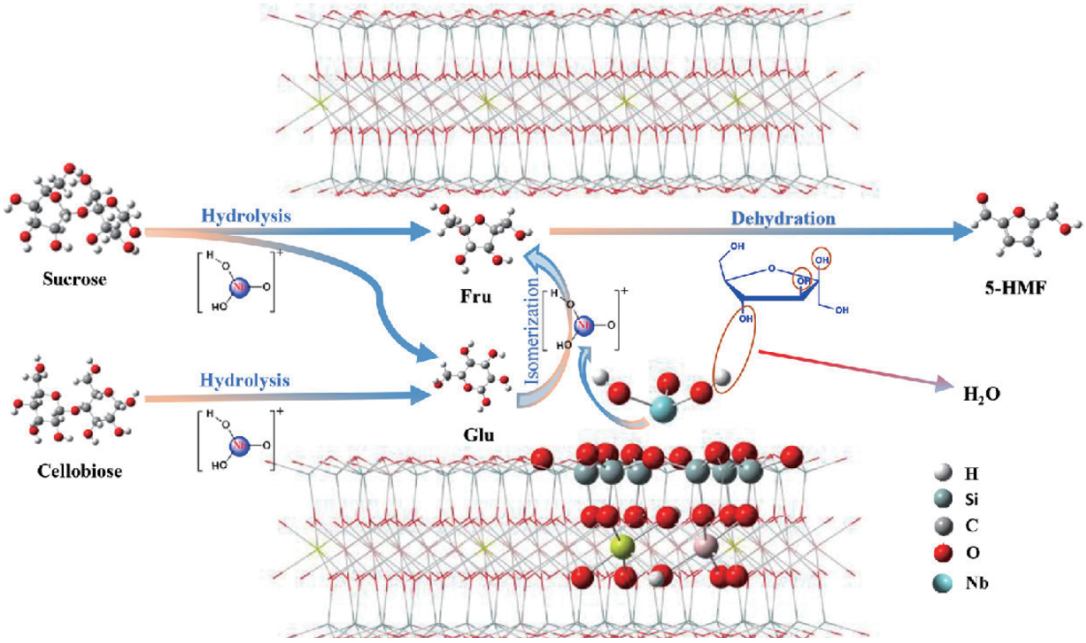


Fig. 8 One-pot conversion of sucrose to 5-HMF catalyzed by multi-functional acid sites[78] (with permission from Elsevier)

When inorganic acids are used alone as the catalysts for the conversion of sucrose to 5-HMF, even by increasing the acid concentration and reaction temperature or extending the reaction time, it remains rather difficult to significantly enhance the reaction selectivity. This is primarily due to the formation of humins and other by-products in such systems, which notably suppress the yield of the target product[79−81]. The application of ionic liquids holds significant promise for enhancing the selectivity of solid acid catalysts in sucrose conversion[82−83]. For example, Jain et al. employed mesoporous zirconium phosphate as a catalyst and found that its high surface area and dual Lewis/Brønsted acid functionality enabled a 5-HMF yield exceeding 50%[84]. Additionally, when ionic liquids such as 1-methyl-3-octylimidazolium chloride, or 1-hydroxyethyl-3-methylimidazolium tetrafluoroborate [(AEMIM)BF_4] were used in combination with HCl or metal chlorides ($CrCl_2$, $ZnCl_2$, $AlCl_3$) as catalysts, 5-HMF yields also surpassed 50%[85−87].

1.2.2 Conversion of maltose

Maltose and maltitol are important raw materials in the food and pharmaceutical industries, with extensive applications across food, medicine, and cosmetics, rendering them of high research value. Unlike sucrose, maltose consists of glucose units linked by α-1,4- and β-1,4-glycosidic bonds. As a result, hydrolysis of maltose yields glucose and its derivatives[88]. Conventional catalysts for maltose hydrolysis include sugar-degrading enzymes and acids. Although enzymatic hydrolysis offers significantly higher rates than acid catalysis, the poor stability and low recoverability of these enzymes limit their large-scale industrial application[89−91]. Marzo et al.[92] investigated strong acid resins, mixed oxides and niobium-containing solids as catalysts, achieving approximately 30% maltose conversion. Their study confirmed that selecting catalysts with highly active and stable acid sites is crucial for the efficient maltose hydrolysis.

The hydrogenation of maltose to maltitol primarily involves heterogeneous catalyst systems based on metals such as Ni and Fe, which are low-cost and achieve a maltose conversion of exceeding 95% (Figure 9)[93−96]. Notably, during the hydrogenation of maltose, glycosidic bonds may cleave, leading to the hydrolysis of maltose to glucose. Subsequent hydrogenation of glucose can then generate sorbitol as a by-product[97−98]. Therefore, suitable solvents to minimize hydrolysis side reactions induced by the catalyst is also a key research direction.

1.2.3 Catalytic conversion of lactose

Lactose is a major by-product of the dairy industry, composed of glucose and galactose molecules linked by β-1,4-glycosidic bonds. Therefore, lactose hydrolysis yields glucose, which can be further converted into various fine chemicals, including 5-HMF and lactic acid. Figure 10 shows the specific pathway for lactose conversion.

Similar to sucrose and maltose, the acidic functionality of the catalyst and the solvent environment are the two most critical factors influencing lactose conversion. These factors manifest in two main aspects: the acid sites required for hydrolysis, isomerization, and dehydration, and the solvation properties of the solvent system.

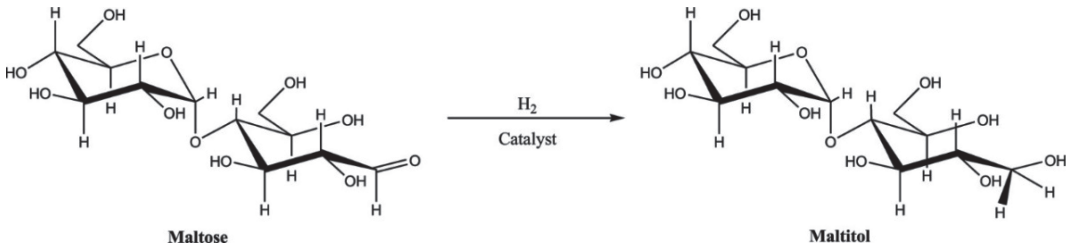


Fig. 9 Pathway for the catalytic hydrogenation of maltose to maltitol[99]
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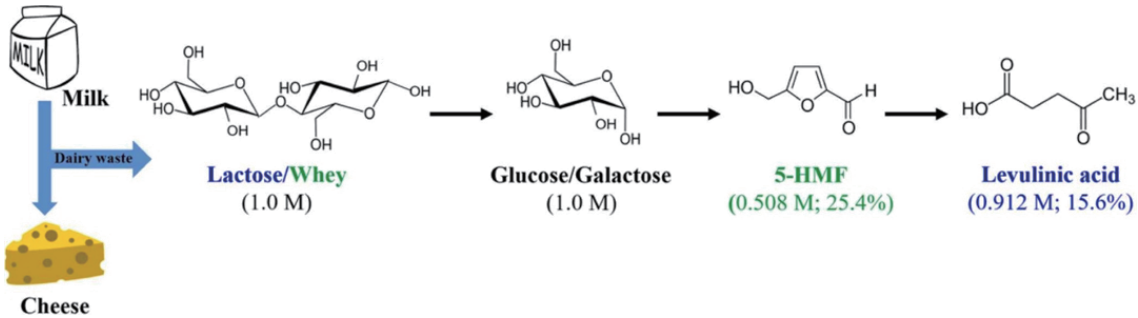


Fig. 10 Pathway for the conversion of lactose to 5-HMF and lactic acid[100]
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Early studies often employed inorganic acids (e.g., HCl, H_2SO_4) or heterogeneous solid acids (e.g., TiO_2, Al_2O_3, $AlCl_3$) for the conversion of lactose to 5-HMF, but the sucrose conversions were generally below 30%, with low product selectivity[101−104]. Improving the reaction solvent has become important strategies for increasing 5-HMF yield in lactose conversion. For instance, Pandey et al.[105] used $AlCl_3·6H_2O$ as the catalyst and acetic acid as the solvent, achieving a 59% yield of 5-HMF through synergistic effects between the catalyst and solvent. De et al.[106] employed TiO_2 as the catalyst in a dimethylacetamide-lithium chloride (DMA-LiCl) solvent system, obtaining a 5-HMF yield of approximately 40%. Although certain solvents such as DMSO and CH_2Cl_2 exhibit excellent selectivity for 5-HMF, their high separation costs and environmental concerns restrict their large-scale application. Consequently, bio-based solvents, such as γ-valerolactone, 2-methyltetrahydrofuran, and 2-butanone may represent more suitable and sustainable options for the industrial conversion of lactose[107−109].

1.3 Conversion of polysaccharides

1.3.1 Conversion of cellulose

Cellulose accounts for 30%–50% of lignocellulosic biomass by mass, making it the most abundant renewable carbohydrate in nature and thus a central focus of biomass conversion research. Cellulose is a polymer of glucose units connected by linear β-1,4-glycosidic bonds, thus achieving efficient and selective hydrolysis of cellulose is an essential step toward its conversion into energy and materials. However, its complex inter- and intramolecular hydrogen-bonding network imparts high chemical stability in common solvents such as water, alcohols, and ketones[110−112].

In cellulose depolymerization, concentrated inorganic acids are often regarded as benchmark catalysts[113−115]. The mechanism under concentrated acidic conditions is illustrated in Figure 11[116]: the acid dissociates to release protons (H^+), which protonate the oxygen atom of the glycosidic bond. Cleavage of the C–O bond follows, transferring positive charge to the anomeric carbon of the glucose unit to form a carbocation (C^+). A water molecule then attacks the carbocation, releasing free glucose and regenerating the hydronium ion (H_3O^+)[117−118]. Although concentrated acids can effectively disrupt the crystalline structure of cellulose and hydrolyze it to glucose in high yields, their use leads to severe equipment corrosion and poses significant challenges for waste liquid recovery. These drawbacks have limited the further development of concentrated acid hydrolysis technologies.

Recently, researchers have improved the process by reducing acid concentration (<10%) to extend equipment lifespan while increasing reaction rates and shortening processing times[113,119−121]. However, lower acid concentrations often necessitate more severe temperature and pressure conditions, which can promote secondary degradation of sugars into various by-products, thereby reducing the yield of target products[122]. Additionally, inorganic acids require neutralization after reaction to avoid adverse effects on downstream processes. In dilute H_2SO_4 hydrolysis, $Ca(OH)_2$ is typically used for neutralization, but this generates $CaSO_4$ precipitate, posing environmental pollution risks[123]. These factors collectively elevate overall process costs, prompting growing interest in ultra-dilute acid (acid concentration <0.1%) and organic acid hydrolysis technologies. Low-acidity conditions can significantly reduce $CaSO_4$ formation. Moreover, in the ultra-dilute acid environments, the system's corrosivity approaches that of neutral water, allowing the use of standard stainless-steel equipment instead of costly Ni-based alloys, thereby lowering capital investment[124−126]. Nevertheless, these technologies often still require relatively harsh operating conditions and remain inherently costly, thus frequently necessitating integration with the solid catalytic systems. For example, Qu et al.[127] hydrothermally synthesized hydroxyl-enriched glucose-based carbon spheres and carbon nanotubes leveraging strong adsorption interactions between hydroxyl groups and cellulose. These materials significantly enhanced the efficiency of a microwave-assisted hydrolysis system using extremely low sulfuric acid concentration (0.02 mol/L), achieving nearly complete cellulose hydrolysis with glucose accounting for over 70% of the sugar products.

The hydrolysis mechanism using organic acids (e.g., oxalic, maleic, and fumaric acids) is similar to that using inorganic acids, relying on proton attack to cleave cellulose β-1,4-glycosidic bonds, yielding glucose. Compared to inorganic acids, organic acids offer advantages such as lower corrosivity and easier recovery, but their weaker acidity generally results in lower hydrolysis efficiency under the same conditions. To achieve a performance comparable to that of inorganic acids, such reactions often require a higher temperature (>160 °C). Researchers have attempted to enhance organic acid hydrolysis by adding promoters.

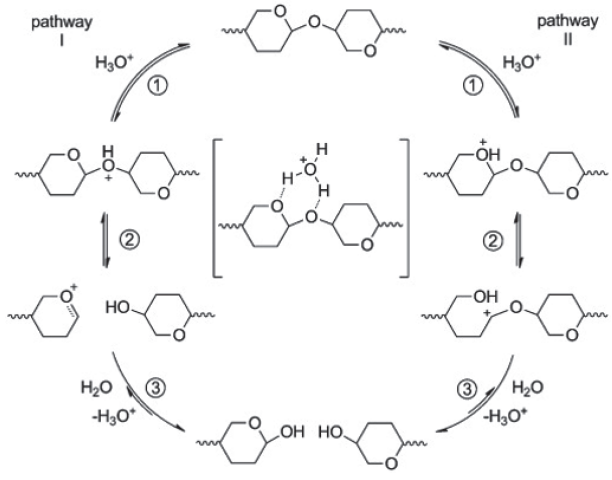


Fig. 11 Acid hydrolysis mechanism of glycosidic bonds[116] (with permission under a CC-BY-NC license)

For instance, Stein et al.[128] found that adding 30% NaCl to a 0.1 mol/L oxalic acid solution increased the glucose yield by 14–19.5 times compared to the salt-free system under conditions of 125 °C, 3 MPa CO_2 and 6 h reaction time. The introduction of inorganic salt effectively disrupted the hydrogen-bonding network of cellulose, promoting its swelling and dissolution, and thereby enhancing the acid hydrolysis efficiency. Moreover, Lyu et al.[129] combined organic acid pretreatment with enzymatic hydrolysis, increasing the glucose yield from about 40% to 89.65%, approximately 2–3 times higher than that with the untreated substrate.

In the enzymatic saccharification, cellulase, as a multicomponent enzyme system comprising endoglucanases, exoglucanases, and β-glucosidases, can specifically hydrolyze the β-1,4-glycosidic bonds in cellulose[130−131]. The enzymatic process generally involves three steps: endoglucanases first randomly cleave glycosidic bonds in the amorphous regions of cellulose, generating oligosaccharides of varying degrees of polymerization; exoglucanases then hydrolyze these oligosaccharides from the chain ends to produce cellobiose; finally, β-glucosidases convert cellobiose to glucose[132−133]. Compared to chemical hydrolysis, enzymatic methods offer advantages such as mild conditions, environmental friendliness, and absence of fermentation inhibitors. However, they also face challenges including low thermal stability, high cost, long reaction times, and difficulties in reusability. To overcome these limitations, enzyme immobilization has emerged as a key strategy, enabling the recycling of cellulases across multiple reaction batches[134−138]. Micron-sized particles have been used as the supports for immobilizing enzyme, but their large size relative to enzyme molecules often limits mass transfer efficiency and loading density. With the advances in nanotechnology, various nanomaterials, such as magnetic nanoparticles, carbon nanotubes, and nanofibers, have been widely employed for cellulase immobilization due to their high surface area and tunable surface properties[139]. Immobilizing cellulases on nanocarriers not only helps reduce enzyme costs but also enhances operational stability and extends service life, maintaining high activity across multiple reaction cycles.

1.3.2 Conversion of starch

Starch is widely present in crops such as potatoes, corn, wheat, and rice. It consists of glucose units linked by α-1,4-glycosidic bonds, forming linear or branched chains, where amylopectin additionally contains branch points connected by α-1,6-glycosidic bonds. Structurally, starch can be divided into six levels (Figure 12)[140]: Level 1 represents individual starch chains; Level 2 comprises fully branched amylose and amylopectin molecules; higher levels include lamellar structures with periodic crystalline and amorphous regions (Level 3), microgranular structures (Level 4), granule architecture (Level 5), and finally the complete starch granule (Level 6).

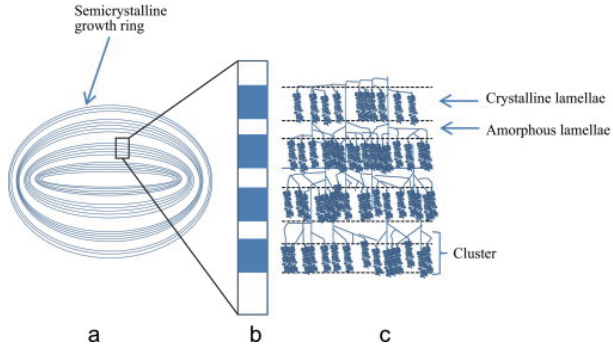


Fig. 12 Schematic diagrams of starch macrostructure and microstructure[140]: (a) whole granule, (b) lamellae and (c) polymer chains
(with permission from Elsevier)

Enzymatic hydrolysis of starch offers advantages such as mild conditions and environmental friendliness. This process relies on the synergistic action of starch-degrading enzymes to convert amylose and amylopectin into glucose. The amylolytic enzyme system primarily includes amylopectin endo-hydrolases, exo-pentosanases, and debranching enzymes[141]. The enzymatic process is divided into liquefaction (95–105 °C) and saccharification (60–65 °C) stages: during liquefaction, endoenzymes such as α-amylase randomly cleave α-1,4-glycosidic bonds in starch chains, producing maltodextrins and other medium- to low-molecular-weight oligosaccharides; in the saccharification stage, exoenzymes such as glucoamylase release glucose sequentially from the non-reducing ends, while debranching enzymes (e.g., isoamylase or pullulanase) specifically hydrolyze α-1,6-glycosidic bonds to remove branch structures[142−147]. In the conventional starch sugar production process, the initial starch concentration is typically maintained at 25%–35%, whereas only 5% moisture is required for chemical reactions during processing. The remaining water is retained in the crude product after saccharification, necessitating significant energy consumption for evaporation after liquefaction and saccharification; 2 tons of water must be evaporated per ton of product obtained[148−149]. Increasing the initial starch concentration can effectively reduce evaporation energy consumption and production costs. However, high starch concentrations not only increase viscosity, making mixing during liquefaction difficult, but also impair effective binding between enzyme and substrate, reducing starch hydrolysis efficiency. To enhance liquefaction efficiency, various pretreatment technologies are widely used to disrupt starch structure and improve enzyme accessibility[150−151].

Microwave irradiation can increase the starch hydrolysis rate by up to 100-fold compared to conventional heating methods. For instance, Sunarti et al.[152] reported that microwave treatment not only induced swelling and pasteurization of sago pith starch but also promoted the transformation of fibers into amorphous structures, thereby enhancing the enzyme reactivity. Staroszczyk and Janas[153] further observed that microwave treatment roughened starch granule surfaces and induced cracks, increasing the reactive

surface area. Saifuddin et al.[154] found that microwaves specifically activated enzymes, nearly doubling the initial reaction rate when combined with the enzymatic catalysis. Ultrasonic treatment similarly induces surface roughening, crack formation, and honeycomb-like pits on starch granules[155]. Zhang et al.[156] noted that ultrasound effectively reduces the apparent viscosity and crystallinity of starch, while improving paste transparency and retrogradation behavior within a short period. Additionally, ultrasound can modulate the structure of maltodextrins and their solubility, promoting the enzyme-substrate binding. It is noteworthy that both microwave and ultrasonic treatments reduce system viscosity and disrupt starch chain ordering; their thermal and mechanical effects can cause starch chain breakage, reducing average molecular weight, thereby collectively optimizing subsequent liquefaction and saccharification processes[157−161].

2 Conversion of platform compounds to fine chemicals

Platform compounds such as 5-HMF, acetylacetic acid, and furfural, generated through the catalytic conversion of sugar resources, can be selectively converted into a series of high-value chemicals including furandicarboxylic acids, acetylacetic acid esters, and furfuryl alcohol *via* key transformation pathways such as dehydration, oxidation, and hydrogenation. These derivatives are widely used in synthesizing pharmaceuticals, polymers, surfactants and food additives, forming the core link in the biomass refining.

2.1 Catalytic conversion of 5-HMF

In the biomass refining, 5-HMF, derived from the hydrolysis, isomerization, and dehydration of disaccharides and polysaccharides, holds a central position. As shown in Figure 13, this platform molecule can be directionally converted into various fine chemicals serving different industrial sectors: its acid-catalyzed products (e.g., levulinic acid) are ideal oxygenated additives for biodegradable gasoline/diesel and are also widely used in the synthesis of polymers and pharmaceutical intermediates; while its oxidation and hydrogenation derivatives (e.g., 2,5-furandicarboxylic acid FDCA, 2,5-diformylfuran DFF, 2,5-bis(hydroxymethyl)furan BHMF) can all be used in polyurethane production[52,56,162−163].

2.1.1 Catalytic conversion of 5-HMF to levulinic acid

Levulinic acid is a green intermediate widely used in fuel additives, polymer and resin synthesis. In the catalytic conversion of 5-HMF to levulinic acid, the catalysts used range from traditional homogeneous acid catalysts like hydrochloric acid, sulfuric acid and acids in broad sense such as heterogeneous solid acids, metal salts and functionalized resin polymers[164−165]. High levulinic acid yields can be achieved in homogeneous acid catalytic systems. For example, Qi et al.[166] used H_2SO_4 as the catalyst and γ-valerolactone as the solvent, achieving a two-step conversion from hexose sugars *via* the 5-HMF intermediate to levulinic acid, with yields controllable between 50%–70%. Mulk et al.[9] conducted the conversion of 5-HMF in an aqueous environment with H_2SO_4, obtaining a levulinic acid yield of 61%. Similarly, using HCl or $H_2C_2O_4$ as catalysts, yields can also exceed 50%[167−168]. Although homogeneous acid catalytic systems exhibit good reactivity, their inherent corrosiveness, difficulty in recovery, and environmental issues limit their large-scale industrial application.

To advance green catalytic processes, researchers have recently focused on developing efficient and reusable heterogeneous catalyst systems. Reported systems include SiO_2 nanocomposites[169], metal salts[170−171], activated carbon-supported aluminum[172], acid-base bifunctional mesoporous silica[173], mesoporous organosilica nanospheres[174], H-BEA zeolite[175], and various functional group-modified polymer resins[176]. For instance, Song et al.[174] utilized Brønsted acidic ionic liquid-functionalized mesoporous organosilica nanospheres to achieve efficient catalytic production of levulinic acid from 5-HMF (Figure 14)[174]; Zou et al.[177] used sulfonated chloromethyl polystyrene resin as a solid acid catalyst, leveraging its high-density surface sulfonic acid groups to effectively promote the reaction, increasing the levulinic acid yield to 65.5%. Kumar et al.[178] designed a composite system of Brønsted acidic ionic liquid [IL-SO_3H][Cl] and Lewis acid $NiSO_4·6H_2O$ co-catalyst, utilizing their synergistic effect to achieve a product yield of 56.33%. It is important to note that regardless of the catalytic system used, the generation of byproducts during the reaction is difficult to completely avoid. Therefore, while developing new catalysts, screening and designing highly selective solvents to inhibit side reactions remains important ongoing optimization topics in this field[179].

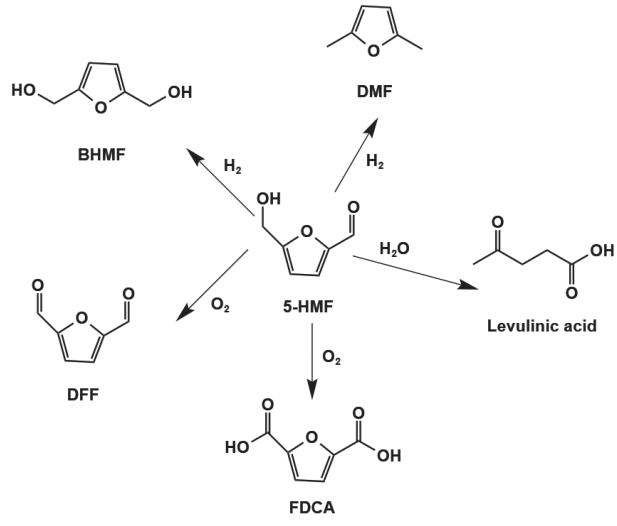


Fig. 13 Catalytic conversion of 5-HMF to fine chemicals

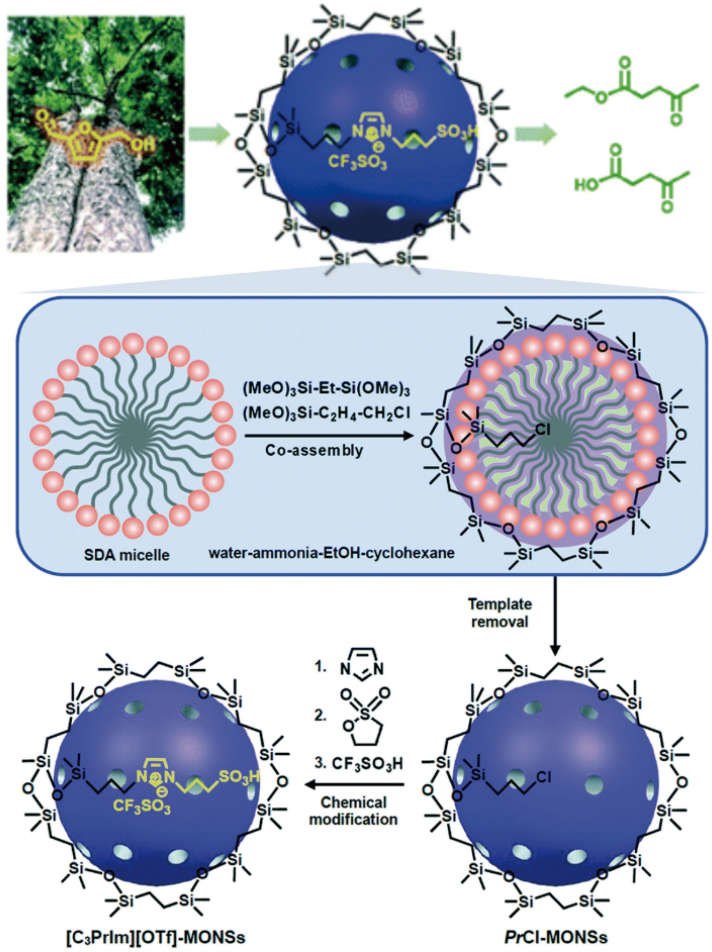


Fig. 14 Efficient conversion of 5-HMF to levulinic acid catalyzed by Brønsted acidic ionic liquid functionalized mesoporous organosilica nanospheres[174]
(with permission from Royal Society of Chemistry)

2.1.2 Oxidative conversion of 5-HMF

The selective catalytic oxidation of 5-HMF primarily leads to two high-value chemicals: 2,5-dimethylfuran (DFF) and 2,5-furan dicarboxylic acid (FDCA)[180−181]. The key to controlling this process lies in the precise matching of catalyst and solvent systems.

The synthesis of DFF relies on the selective oxidation of the hydroxymethyl group of 5-HMF to an aldehyde group while preserving the existing aldehyde group. This reaction typically employs heterogeneous catalytic systems, including noble metal nanoparticles[182−184], metal oxides or salts[185−187], supported polymers[188−189] and zeolites[190−191]. Besides the catalyst, the solvent environment decisively influences reaction selectivity. Early studies confirmed that DFF yields are generally low in aqueous or hydrogen peroxide systems[192], making suitable co-oxidation solvents a research focus. For example, Amarasekara et al.[193] used a biphasic (phosphate buffer/dichloromethane) catalytic system consisting of Mn(III) complex and NaClO, achieving a DFF yield of 89%. Additionally, with cross-linked poly(4-vinylpyridine) supported on functionalized SBA-15 mesoporous material, Navarro et al.[194] achieved a selectivity of over 90% to DFF through regulating the catalyst surface properties and solvent, highlighting the crucial role of catalyst-solvent synergy in enhancing product selectivity.

FDCA, the complete oxidation product of 5-HMF, is regarded as a potential bio-based alternative to terephthalic acid, with broad prospects in polyester and polyurethane synthesis[195]. Its preparation also widely relies on noble metal catalysts, but the reaction path requires alkaline conditions and relatively low temperatures to ionize the carboxylic acid, thereby promoting product conversion while suppressing side reactions[196−200]. For example, Taarning et al.[201] used supported Au nanoparticles as catalysts and CH_3OH as solvent under O_2 atmosphere, achieving efficient conversion of 5-HMF to FDCA. Gorbanev et al.[202] employed an Au/TiO_2 catalytic system in water and systematically investigated the effects of alkalinity and oxygen pressure, ultimately obtaining an FDCA yield of 71%. More notably, Liu et al.[203] utilized a nitrogen-doped carbon-supported cobalt-based catalyst where the electronegative nitrogen atoms on the surface acted as acceptors, forming hydrogen bonds with the hydroxyl groups of the substrate 5-HMF which induced the hydroxyl activation. This greatly increased the turnover

frequency (TOF) of the non-precious metal catalyst, achieving a maximum FDCA yield of 94.3%, demonstrating the potential for large-scale green synthesis (Figure 15).

2.1.3 Hydrogenation of 5-HMF

The target products of the catalytic hydrogenation of 5-HMF are 2,5-bis(hydroxymethyl)furan (BHMF) and 2,5-dimethylfuran (DMF), which have broad application prospects in the polyurethane industry and the biofuel sector, respectively[204−205].

5-HMF contains both an aldehyde group and a furan ring sensitive to hydrogenation, making the selective hydrogenation to BHMF challenging due to over-hydrogenation or ring-opening side reactions. Therefore, the key for a high selectivity to BHMF lies in the design of catalyst and the optimization of reaction temperature, hydrogen pressure, and solvent. Currently, the catalysts based on metals like Cu, Pt and Ru are widely used in this reaction[206−210]. For example, Ohyama et al.[211] used Au/Al_2O_3 nanoclusters as catalysts, leveraging the basic sites of the Al_2O_3 to selectively activate the aldehyde group, effectively suppressing side reactions, thereby achieving a high BHMF yield of 96%. Chen et al.[212] confined Pt nanoparticles within Y zeolite pores, utilizing the spatial constraints of the zeolite channels to finely tune the adsorption mode of reactants on the Pt surface; this significantly widened the activation energy gap between aldehyde hydrogenation and other competing reactions, ultimately achieving a selectivity of nearly 100% to BHMF.

DMF, the deep hydrogenation product of 5-HMF, is a liquid fuel with high energy density and a suitable boiling point, considered as a highly promising fossil fuel substitute in the transportation sector[213−214]. This pathway typically requires stronger deoxygenation capability. Supported Pd and Ru-based noble metal catalysts are widely studied due to their excellent activity for hydrogenation of deoxygenation and deoxygenation of C–O bonds[215−218]. Thananatthanachon et al.[219] used HCOOH as a hydrogen source, achieving a DMF yield of 95% under Pd/C catalysis. Jae et al.[220] demonstrated a transfer hydrogenation strategy using alcohols as hydrogen donors; with a supported Ru catalyst, the DMF yield reached 80%. Additionally, they developed a partially oxidized Ru/C bifunctional catalyst, through the synergy between metal sites and acid sites, which also achieved a 72% yield, offering novel insights for catalytic systems without using high-pressure hydrogen.

2.2 Catalytic conversion of lactic acid

Lactic acid is an important platform molecule obtainable *via* chemical synthesis or microbial fermentation of sugars. Its applications have expanded from the traditional food industry to polymer materials and pharmaceutical[221].

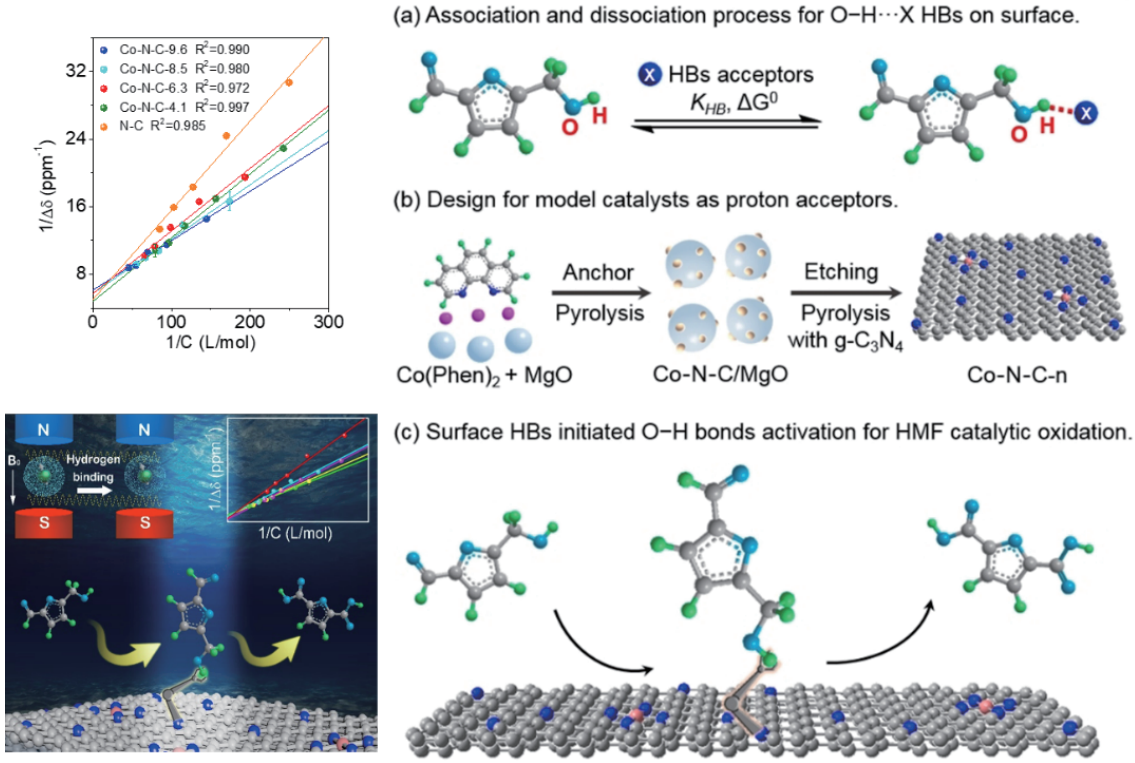


Fig. 15 Enhanced activity in the catalytic oxidation of 5-HMF to FDCA *via* hydrogen-bonding induction[203] (with permission from John Weily & Sons)

As shown in Figure 16, lactic acid can be converted into high-value-added chemicals including: self-esterification cyclization to lactide, followed by ring-opening polymerization to produce the biodegradable plastic polylactic acid (PLA); esterification with alcohols to generate various lactate esters, used as green solvents or chemical intermediates; catalytic dehydration to acrylic acid for polymer synthesis; selective oxidation to pyruvic acid, applied in pharmaceuticals and biochemistry; condensation to 2,3-pentanedione, used as a flavor compound or synthetic precursor; and catalytic hydrogenation to 1,2-propanediol (propylene glycol) for polyester resins and antifreeze production. These conversion pathways fully demonstrate the central role of lactic acid in building a green chemical value chain.

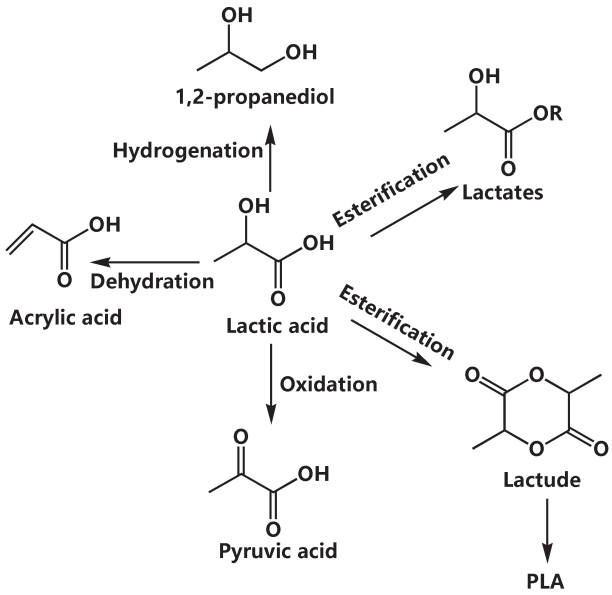


Fig. 16 Reaction pathway for the catalytic conversion of lactic acid to lactic acid derivatives

2.2.1 Esterification of lactic acid

Lactic acid esterification forms the core of high-value utilization of lactic acid, primarily following two pathways corresponding to the synthesis of polymer monomers and fine chemicals: first, intramolecular self-esterification to form the cyclic dimer lactide; second, intermolecular esterification in the presence of alcohols to generate various lactate esters.

Lactide is an indispensable cyclic intermediate for synthesizing the biodegradable plastic polylactic acid (PLA). Its synthesis primarily involves two steps: first, lactic acid molecules undergo self-esterification and oligomerization, followed by cyclization to form lactide; subsequently, lactide undergoes ring-opening polymerization to yield PLA[222]. A key challenge in this process is that lactide is prone to racemization during the esterification reaction, limiting the final yield and mechanical properties of PLA[223–225]. Therefore, optimizing reaction conditions and developing chiral catalysts are central to improving the economics of this process. Various heterogeneous systems have proven to exhibit excellent performance, including oxides and salts of metals such as Sn, Zn, Ti and Al[226–232]. For example, Ehsani et al.[233] systematically compared the catalytic effects of different Sn species (e.g., SnO_2, $SnCl_4$, Sn(II) octoate) on lactic acid self-esterification and observed that $SnCl_4$ and Sn(II) octoate could drive reaction conversions up to 90%, confirming that temperature and pressure significantly affect the product yield. Zhang et al.[234] developed a composite catalytic system comprising $Zn(La)_2$ and $NaHCO_3$, increasing the lactide yield to 95.66% (Figure 17). Studies showed that $NaHCO_3$ can react with oligomers to generate carboxylate anions, effectively inhibiting over-polymerization and thereby improving target product selectivity[234].

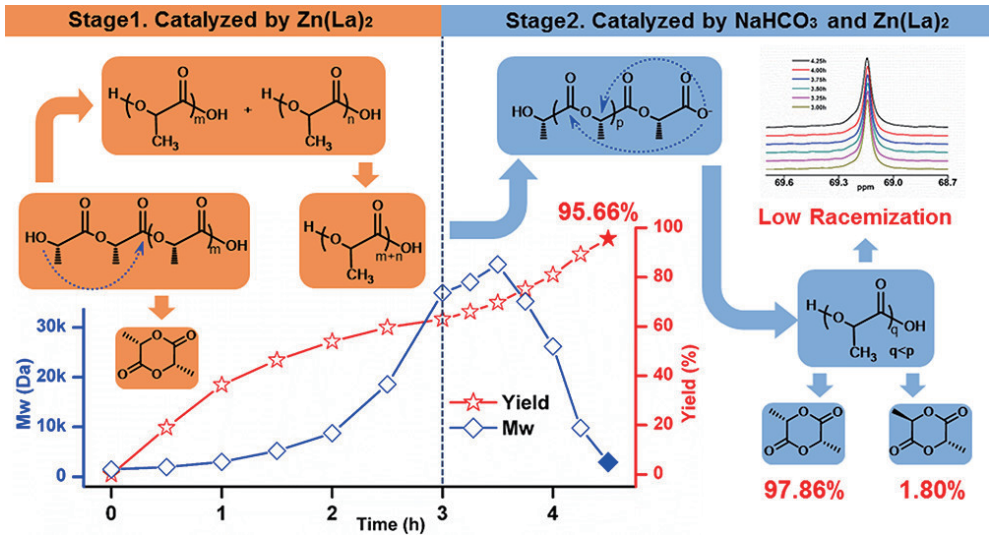


Fig. 17 Synergistic catalysis of $NaHCO_3$ and zinc lactate for efficient synthesis of low-racemic lactate esters[234] (with permission from American Chemical Society)

Furthermore, isolated Sn sites on the Sn-β zeolite were also confirmed to preferentially promote lactide formation, demonstrating the potential of shape-selective catalysis in this reaction[235].

In alcoholic solvents, lactic acid can undergo acid-catalyzed esterification reactions to form the corresponding lactate esters. Such products, with high boiling points and excellent solubility, are widely used as green solvents, surfactants, and plasticizers[236]. Both homogeneous acid catalysts like H_2SO_4 and heterogeneous catalysts such as ion exchange resins can catalyze lactic acid esterification, with the latter being more industrially attractive due to their easier recovery and lower corrosiveness[237−238]. Sanz et al.[239] studied the kinetics of ion-exchange resin-catalyzed esterification of lactic acid with methanol, finding that the reaction rate increased with rising temperature and catalyst loading, while the equilibrium conversion was closely related to the methanol/lactic acid ratio. Pereira et al.[240] used Amberlyst-15 cation exchange resin to catalyze the esterification of lactic acid and its oligomers with ethanol in a batch reactor, obtaining similar kinetic conclusions, further validating the applicability and efficiency of heterogeneous acid catalysts in this system.

2.2.2 Hydrogenation of lactic acid to 1,2-propanediol

Catalytic hydrogenation of lactic acid is a green pathway for producing 1,2-propanediol (propylene glycol), which is an important chemical raw material widely used in unsaturated polyester resins, cosmetic softeners, food processing solvents, and antifreeze agents[241−243].

In early studies, the hydrogenation of lactic acid often required harsh high-temperature and high-pressure conditions due to the low performance of available catalysts, which constrained its economic feasibility and application potential[244−245]. The introduction of Ru-based catalysts marked a significant breakthrough, enabling the reaction under milder conditions and greatly advancing the field. Current research primarily focuses on two key directions to further enhance the performance of Ru-based catalytic systems: first, developing more efficient supports to optimize the dispersion and stability of active sites; second, introducing a second metal component (e.g., Sn, Cu, Co, Fe, Zn) to modulate the electronic structure and reaction pathway through synergistic effects with Ru species[246−249]. For example, Zhang et al.[250] used an activated carbon-supported Ru catalyst under the conditions of 100–170 °C and 7–14 MPa H_2, achieving nearly complete conversion of lactic acid with a 1,2-propanediol yield close to 90%. Luo et al.[251] introduced Sn into a γ-Al_2O_3-supported Ru catalyst, significantly improving the dispersion and thermal stability of the active components while enhancing the catalyst's resistance to deep hydrogenation, thereby effectively increasing the selectivity and yield of 1,2-propanediol. These results indicate that precise regulation of the catalyst support and metal components is crucial for achieving efficient lactic acid hydrogenation.

2.2.3 Oxidation of lactic acid to pyruvic acid

Pyruvic acid has wide applications in pharmaceutical synthesis, agrochemicals, food supplements, and antioxidants[252]. Its industrial production pathways are diverse, including glucose fermentation, enzymatic conversion and chemical synthesis from tartaric acid. Recently, the catalytic oxidation of biomass-derived lactic acid to pyruvic acid has garnered significant attention due to its green and economic nature, providing an important reference for the sustainable production of this compound[253−255]. However, this oxidation process is prone to C–C bond cleavage, generating acetaldehyde and other byproducts[256].

In the heterogeneous catalytic systems, transition metal oxides are widely studied due to their tunable redox properties and surface acidity. Lomate et al.[257] systematically investigated the performance of NiNb composite oxides in the oxidative dehydrogenation of lactic acid and found that both the reductive capacity and surface active sites of the catalyst were directly related to the Ni/Nb ratio, with optimal conditions achieving a selectivity of 50% topyruvic acid. Ai et al.[258] observed that the synergistic effect of mixed Fe^{2+}/Fe^{3+} valence states was crucial in enhancing the catalytic performance of iron phosphate ($FePO_4$), where the selectivity to pyruvic acid reached 62%. To further enhance catalytic efficiency, researchers introduced metal components like Pd and Mo into $FePO_4$, effectively boosting the catalyst's oxidative dehydrogenation activity[259−260]. Similarly, when MoO_3 was highly dispersed on the TiO_2 surface, the strong interaction formed between them significantly increased pyruvic acid selectivity to 80%, demonstrating the importance of synergistic design between support and active phase[261]. In biocatalytic routes, the pathway of lactate dehydrogenase converting lactate to pyruvate with the participation of the cofactor NAD^+ has been thoroughly studied[262]. In contrast, the direct oxidation pathway catalyzed by lactate oxidase (LOX) holds greater application potential due to its lower costs; however, such a reaction process is accompanied by the generation of H_2O_2 byproducts[263−265]. Recent studies indicate that coupling lactate oxidase with catalase to form a dual-enzyme system can effectively decompose H_2O_2 and shift the reaction equilibrium towards the product, thereby further improving the overall yield of pyruvic acid.

2.3 Catalytic conversion of furfural

Furfural (FFR) serves as a bridge connecting renewable carbon sources to high-value chemicals, finding extensive applications in lubricant refining, foundry sand binders, and the synthesis of various fine chemicals[266−267]. The main conversion products of furfural are furfuryl alcohol (FA), furoic acid, and furan (Figure 18).

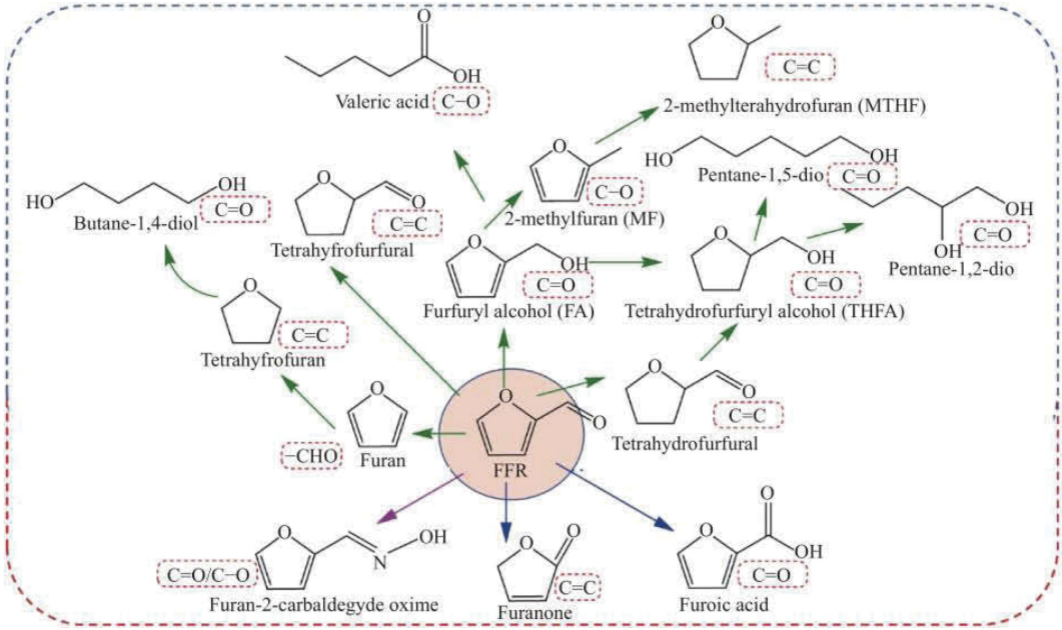


Fig. 18 Conversion pathway of furfural[267]
(with permission from Elsevier)

2.3.1 Hydrogenation of furfural to furfuryl alcohol

Furfuryl alcohol (FA) is an important intermediate for synthesizing corrosion-resistant resins, flavors and fragrances, and tetrahydrofurfuryl alcohol (THFA)[268]. Its industrial production primarily relies on the catalytic hydrogenation of furfural. However, this reaction is susceptible to over-hydrogenation or side reactions generating byproducts, making catalyst selectivity control crucial.

Currently, $CuCr_2O_4$ is widely used as a catalyst in industry, and its various forms have been confirmed to achieve high furfural alcohol yields[269−270]. However, environmental and safety concerns stemming from the toxicity of chromium species have driven the development of green and efficient non-chromium-based catalysts as a major research focus in this field. In this context, Pt-based noble metal catalysts show great potential due to their excellent hydrogenation activity and high selectivity. Vaidya et al.[271] used a Pt/C catalyst in an isopropanol/water mixed solvent, achieving a selectivity of up to 96% to furfuryl alcohol. Kijeński et al.[272] designed a Pt/TiO_2-V_2O_5/SiO_2 multilayer structure catalyst, which enhanced the adsorption capacity for reactants and reached the selectivity to 93.8%. Liu et al.[273] constructed a Pt-Fe bimetallic system on multi-walled carbon nanotubes, achieving a selectivity of 87.4% while significantly improving the catalyst stability. Concurrently, the Cu-based catalysts, which are more abundant and cost-effective, are also favored by researchers[274−276]. Studies show that supporting Cu species on carriers like zeolites or metal oxides, or combining them with metals like Pt, Al and Co to form composite catalysts, can effectively activate the C=O bond of furfural through synergistic effects while suppressing the side reactions, thereby achieving desirable furfuryl alcohol yields (Figure 19)[277].

2.3.2 Oxidation of furfural to furoic acid

The production of furoic acid primarily depends on the catalytic oxidation of furfural. This process faces challenges of catalyst deactivation, influenced by the pH value and oxidant type[278].

Current catalytic systems applied to oxidation of furfural mainly include two categories: noble metal oxides such as Au, Pt, Pd[279−283] and non-precious metal oxides like Fe, Cu, Mn[284−285]. Among them, manganese dioxide (MnO_2) shows significant potential in the furfural oxidation due to its rich tunable morphology and crystal structure. Yu et al.[286] reported that under alkali-free reaction conditions, the crystal phase of MnO_2 decisively influenced its oxidation capability. Furthermore, compounding Mn species with other metal oxides like Cu or Ce can further optimize the catalyst's electronic structure and surface properties, thereby significantly enhancing its activity and stability[287−289]. To overcome the dependence of traditional processes on highly alkaline solvents and improve reaction efficiency, developing new catalytic systems has become a current research focus[290−293]. Yu et al.[294] designed a green core-shell structured nitrogen-doped carbon-supported Ni catalyst that displayed a significant synergistic effect between the Ni metal centers and Ni–N_x coordination sites. In this structure-activity relationship, the Ni centers primarily adsorb and activate the aldehyde group of the furfural molecule, while the adjacent Ni–N_x sites enhance the system's electron transfer capability and apparent basicity, thereby promoting the oxygen activation and hydrogen abstraction steps in the reaction process, ultimately achieving a comprehensive improvement in catalytic efficiency (Figure 20).

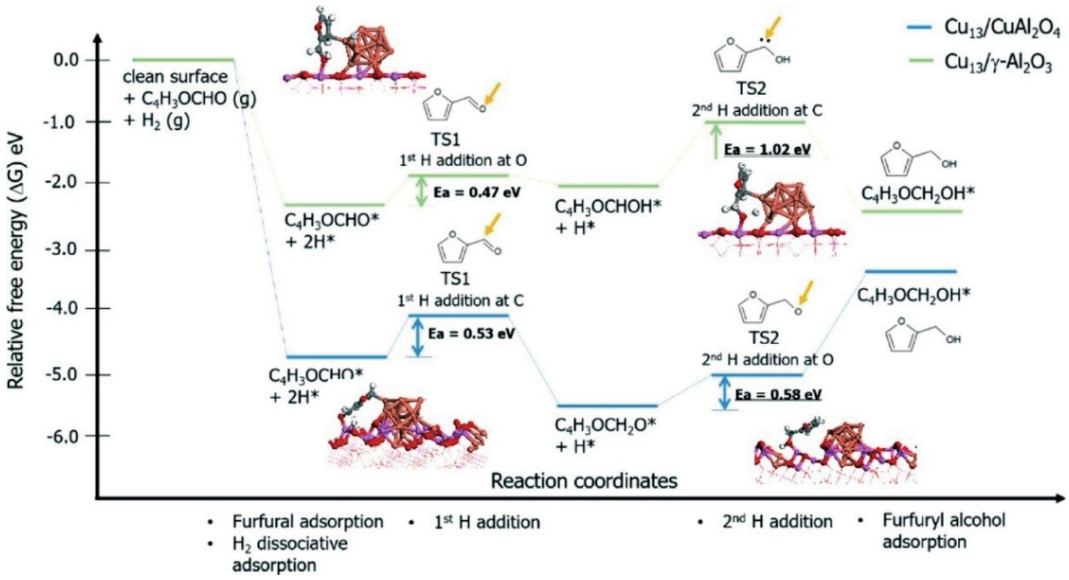


Fig. 19 Free energy (ΔG) diagram for furfural hydrogenation to furfuryl alcohol on the Cu-Al composite catalyst[277] (with permission from Elsevier)

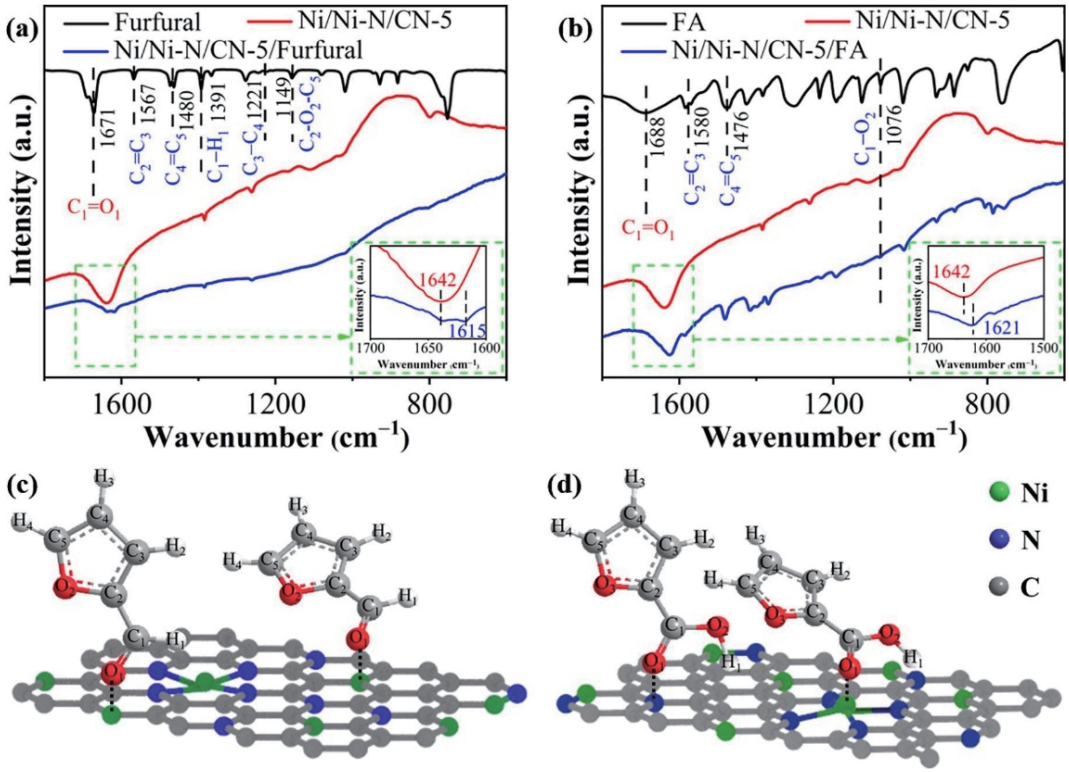


Fig. 20 IR spectroscopic elucidation of furfural adsorption models on a N-doped Ni-based catalyst[294] (with permission from Elsevier)

2.3.3 Decarbonylation of furfural to furan

Furan is widely used in modern industry as a synthesis solvent, fine chemical intermediate, and for gasoline blending to enhance octane number[295−297]. The catalytic decarbonylation of furfural is an important route for producing furan from biomass. Commonly used catalysts for this process are primarily based on metals such as Pt, Pd, Ni and Co[298−300]. For example, Chen et al.[301] used a hydrogen-pretreated Ni/SiO_2 catalyst and achieved a selectivity of 62% to furan. Ishida et al.[302] used a Pd/ZrO_2 catalyst under additive-free conditions, obtaining a high furan yield of 98%, and pointed out that the support surface area and Pd dispersion state are key factors affecting the catalytic performance. However, metal catalysts commonly face deactivation due to the carbon deposition during the

reaction, limiting their industrial service life[303]. Therefore, developing novel catalysts with both high activity and excellent stability is of significant importance.

Porous materials, especially zeolites, have attracted attention due to their tunable acid sites and pore structures. Kuterasiński et al.[304] introduced mesopores into FAU-31 zeolite through desilication treatment, significantly improving mass transfer efficiency and achieving a furan yield of 70%. Further introducing copper species into this zeolite increased Brønsted acid sites, effectively enhancing catalytic performance[305]. Wang et al.[306−307] designed a Pd@S-1-OH catalyst with tunable wettability, confining Pd nanoparticles within the hydrophilic silicalite-1 zeolite; this unique structure achieved precise control over reactant diffusion, resulting in a high furan selectivity up to 99.9%, demonstrating the great advantage of the nano-confinement effect in enhancing catalytic selectivity and stability (Figure 21).

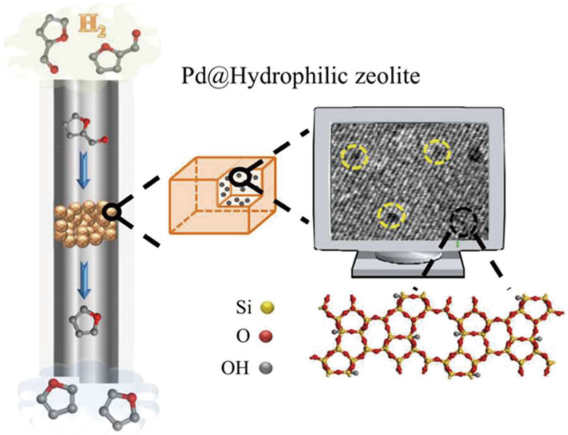


Fig. 21 Pd@S-1-OH catalyst with tunable wettability toward highly selective furfural hydrogenation to furan[306] (with permission from American Chemical Society)

3 Other applications of catalytic conversion of carbohydrates

3.1 Conversion of carbohydrates to biofuels

In the optimization process of the global energy structure, clean energies like hydrogen and solar power demonstrate immense potential. However, their large-scale application still faces constraints due to technological immaturity, storage/transportation bottlenecks, and cost-ineffectiveness. In contrast, biomass energy derived from carbohydrates, with its heating value comparable to fossil fuels and characteristics of being green, renewable, and directly usable, demonstrates unique advantages in the energy transition. It is particularly noteworthy that the process routes for producing bio-ethanol from specific carbohydrates or liquid alkanes (e.g., gasoline or aviation fuel) from lignocellulose bear certain similarities in principle to existing petroleum refining systems (Figure 22).

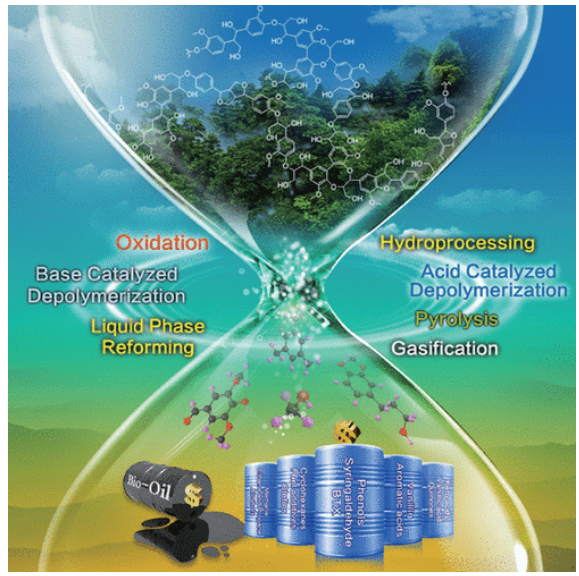


Fig. 22 Catalytic conversion of carbohydrates for bio-fuel[308] (with permission from American Chemical Society)

This characteristic endows carbohydrate-derived bio-fuel production with relatively high feasibility in terms of technology integration and facility adaptation[309]. Although current overall economics of this pathway, which is constrained by feedstock and technology costs, are difficult to directly surpass those of traditional fossil fuels, bio-fuels still possess strong long-term competitiveness in the future energy landscape with policy support and continuous process optimization[310−311]. The pathways for converting carbohydrates to biofuels are diverse, mainly including pyrolysis, hydrothermal liquefaction, and aqueous phase reforming. To focus the discussion, the following sections will emphasize the conversion pathways of structurally defined monosaccharide compounds to biofuels, without detailed elaboration on complex mixed biomass feedstocks like algae or food waste.

3.1.1 Pyrolysis of carbohydrates

Thermochemical conversion, particularly pyrolysis under anaerobic or oxygen-limited conditions, is a key pathway for converting carbohydrates into liquid bio-fuels and chemicals. This process primarily produces non-condensable gases, carbon deposits, and liquid bio-oil, with bio-oil as the main product potentially accounting for up to 70% of the initial feedstock mass[312−315]. However, bio-oil is a complex mixture containing over 400 organic compounds, including ketones, aldehydes, alcohols, carboxylic acids, phenols, and furan derivatives. Its high oxygen content and acidity, along with its complex composition, prevent its direct use as fuel, necessitating catalytic upgrading to improve quality[316−320].

In the catalytic upgrading strategies, hydrodeoxygenation using zeolite catalysts like H-ZSM-5, MCM-41 and SBA-15 is a core method for enhancing bio-oil quality. Williams et al.[321] used H-ZSM-5 for catalytic upgrading of bio-oil

and proposed a dual-path mechanism for aromatic and polycyclic aromatic hydrocarbon (PAH) formation: one involving aromatization *via* low molecular weight hydrocarbon intermediates on the catalyst surface, whereas the other represents a direct conversion path for non-phenolic oxygenated compounds. To optimize the reaction performance, researchers have modified H-ZSM-5 with metals. Zheng et al.[322] reported that loading specific metals could effectively inhibit coke formation and increase mono- and bi-cyclic aromatic selectivity, with different metals exhibiting precise control over product distribution. Widayatno et al.[323] found that after introducing Cu species into β-zeolite, the synergistic effect generated between metal sites and proton acid sites significantly enhanced the catalytic performance. Notably, even minimal Cu loading could significantly increase hydrocarbon selectivity in high-silica Beta zeolite, highlighting the importance of precise control of metal loading. In summary, designing zeolite catalysts with specific pore structures, coupled with the synergistic interaction between metal and acid sites, enables selective upgrading of pyrolytic bio-oil. This approach lays the foundation for eventual qualification as a fuel or chemical intermediate.

3.1.2 Hydrothermal liquefaction of carbohydrates

Hydrothermal liquefaction (HTL) is another important thermochemical pathway for converting carbohydrates into bio-fuels. Compared to the pyrolysis technology, this process typically occurs at a lower temperature (250–374 °C) and slower heating rate, yet requires maintaining higher reaction pressure (4–22 MPa) and longer liquefaction times. Its core reaction mechanism involves: macromolecular carbohydrates first undergo depolymerization and degradation under catalysis, generating small organic molecule intermediates; subsequently, these intermediates repolymerize through condensation, cyclization, and other reactions, ultimately forming bio-crude[324−326]. Bio-crude produced by HTL has the significant advantage of lower oxygen content (typically 12%–14%) compared to the pyrolysis bio-oil, meaning the subsequent required hydrodeoxygenation upgrading steps can be simplified, potentially reducing process energy consumption and cost.

The efficiency and product distribution of hydrothermal liquefaction are deeply influenced by the liquid solvent[327−328]. Rossum et al.[329] found that using oxygenated solvents as the liquefaction medium not only achieved high carbon-based oil yields up to 93% but also effectively suppressed solid residue yield to a very low level of 1%–2%, with comprehensive performance superior to traditional pressurized water liquefaction and pyrolysis processes. Xu et al.[330] investigated the effect of NH_3 atmosphere on cellulose hydrothermal liquefaction, confirming that increasing reaction temperature and extending reaction time effectively promoted the conversion of cellulose to liquid products and reduced residue formation, with temperature being a more critical control factor than time. Furthermore, Shahbeik et al.[331] provided a comprehensive summary of recent technological developments in carbohydrate hydrothermal liquefaction, while Beckman et al.[332] established quantitative relationships between key parameters like temperature, pressure, time, and their effects on the direct thermochemical liquefaction product yield and properties. These works collectively advance HTL technology towards greater controllability and efficiency.

3.1.3 Aqueous phase reforming of carbohydrates

Although pyrolysis, hydrothermal liquefaction, and gasification are mainstream thermochemical processes for producing bio-fuels and bio-oils, these technologies generally face challenges in cost control, product separation and environmental safety[333−334]. In contrast, aqueous phase reforming (APR) has emerged as a more promising alternative pathway in recent years. It proceeds directly in the aqueous phase, typically under conditions of 220–270 °C and 3–6 MPa. This process is not only milder than steam reforming (above 800 °C) but also able to avoid the energy loss associated with feedstock evaporation[335].

Davda et al.[336] systematically evaluated the effect of temperature on the aqueous phase reforming of different carbohydrates, verified the thermodynamic feasibility of the process, and proposed basic reaction pathways for alkane and alcohol reforming (Equations (1)–(3)). Studies indicate that oxygenated compounds are more readily reformed in the aqueous phase at lower temperatures, especially when the ratio of carbon to oxygen ratio (C∶O) is 1∶1, favoring the production of CO and H_2. Based on this, polyols such as methanol, ethylene glycol, glycerol, and sorbitol, obtained from the degradation and hydrogenation of glucose and other sugars, can serve as ideal precursors for bio-fuel production *via* APR.

$$C_nH_{2n+2}O+nH_2O=nCO+(2n+1)H_2 \quad (1)$$

$$CO+H_2O=CO_2+H_2 \quad (2)$$

$$C_nH_yO_n=nCO+yH_2 \quad (3)$$

Metal-based catalysts such as Ni and Pt are widely employed in ARP[337−340]. Due to the differences in the functional groups of different carbohydrates, catalyst design must comprehensively consider the selective cleavage ability of C–C and C–O bonds as well as the influence of support properties[341−343]. In ARP of glycerol, Seretis et al.[344] and Luo et al.[345] effectively suppressed methanation side reactions on Pt-based catalysts, achieving a high H_2 mole fraction up to 70%, close to the theoretical maximum, with a very low CO content ($< 1.0\times10^{-5}$). Putra et al.[346] used Raney Ni to catalyze glycerol reforming coupled with phenol hydrogenation, consuming the generated hydrogen *in situ* to shift the reforming equilibrium toward products, providing a new idea for enhancing reaction rates. Support

characteristics are equally critical for the catalytic performance. Seretis et al.[347] found that the catalytic efficiency of Ni/SiO_2-Al_2O_3 was regulated by its loading, affecting C–C bond cleavage and hydrogen generation. Duarte et al.[348] reported that increasing the Pt loading in Pt/Al_2O_3 significantly enhanced sorbitol conversion and hydrogen yield, with H_2 content reaching 60%–70% and H_2 production rate of 22 mmol/(h·g_{cal}). Arandia et al.[349] further revealed the activity order of Ni/Al_2O_3 for various oxygenates as pyruvate > ethanol > catechol > acetic acid, and emphasized the contribution of metal-support interaction to the catalyst stability.

Bimetallic catalysts are often superior to the monometallic systems in performance, with optimization mechanisms primarily involving bridging defect sites, intermetallic synergistic effects, and electronic promotion[350−354]. A common strategy is to use Pt as the primary metal, introducing promoters like Fe, Co, Ru, or Pd to enhance the catalytic activity[355−358]. For example, Alvear et al.[359] developed a Pt-Pd/mesoporous carbon catalyst that achieved high hydrogen yields in the reforming of various polyols, attributed to the high intrinsic activity brought by the bimetallic combination. He et al.[360] reported that Pt-Ni/multi-walled carbon nanotubes could synergistically promote dehydrogenation-decarboxylation and dehydration-hydrogenation pathways, thereby simultaneously improving glycerol conversion and hydrogen selectivity. Ciftci et al.[361] further compared Pt/C and Pt-Re/C catalysts and observed that the introduction of Re not only enhanced C–O bond cleavage ability but also increased the C–C bond cleavage rate and ethanol formation selectivity. Although a particle size effect existed, the comprehensive performance of the most bimetallic system was still significantly better than that of the monometallic catalyst.

3.2 Electrochemical applications of carbohydrates

Converting carbohydrates into electrical energy represents a cutting-edge approach for expanding their applications and contributing to the future energy structure transition[362]. Among these, carbohydrate fuel cells, as direct electrochemical conversion devices, theoretically possess high energy efficiency. Their basic working principle is illustrated in Figure 23[363]: in the anode chamber, the fuel (e.g., carbohydrate) undergoes electrochemical oxidation, releasing electrons; electrons travel through an external circuit to the cathode chamber, where they combine with an oxidant (typically oxygen) to complete the reduction reaction, thereby generating electricity. However, the commercialization of such cells faces severe challenges. On one hand, the electrochemical oxidation process of carbohydrate molecules is complex and often incomplete, limiting power generation. On the other hand, high-performance catalysts still heavily rely on precious metals, posing problems of high cost and susceptibility to activity loss.

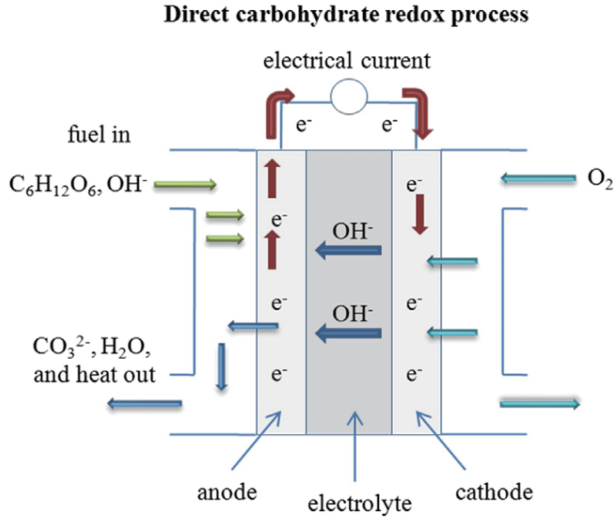


Fig. 23 Schematic diagram of carbohydrate fuel cell[363] (with permission from Elsevier)

Recently, researchers are committed to developing low-cost, high-efficiency non-precious metal and carbon-based catalysts. Irfan et al.[15] constructed a glucose fuel cell with an anode composed of reduced graphene oxide (*r*GO) supported Ni−Co bimetallic composite. Its unique composite structure provided a high density of exposed active sites, ultimately achieving a maximum power density of 28.807 W/m^2. Yi et al.[364] significantly enhanced the electrochemical performance of the catalysts in direct methanol fuel cells (DMFCs) by optimizing the structure and specific surface area of a rice husk-derived porous carbon support.

Besides catalysts, optimizing the core components of the cell (e.g., proton exchange membrane) and the reaction microenvironment are also crucial for overall performance of carbohydrate fuel cells[365−372]. Mandal et al.[373] synthesized an anion exchange membrane (AEM) based on the vinyl addition polymerization of norbornenes. This membrane exhibited remarkable long-term stability (no significant loss in ionic conductivity within 1200 h) in an 80 °C alkaline environment, and the assembled cell achieved a peak power density of 542.57 mW/cm^2 at 60 °C. Zheng et al.[374] designed a class of crosslinked/aggregated AEMs by introducing a hydrophilic-hydrophobic amphiphilic structure. This structure suppressed excessive membrane swelling, while effectively promoting the formation of ionic conduction channels, synergistically enhancing the membrane's mechanical strength and ionic conductivity. Ye et al.[375] studied a PVDF-based grafted ionic liquid composite membrane that underwent microphase separation, forming continuous ion transport channels, increasing the ionic conductivity by 3–4 orders of magnitude, demonstrating the decisive influence of microstructure control on macroscopic performance.

4 Conclusion and outlook

Confronted with the major strategic demands of global

energy structure transition and "Dual Carbon" goals, the development of green, sustainable alternatives to fossil fuels is urgently needed. This review systematically elaborates on the current research and development status of converting abundant biomass-derived carbohydrates into energy and chemicals. Researches have demonstrated that through precise catalyst design (e.g., constructing Brønsted acid, Lewis acid, and bifunctional sites) and optimization of reaction systems (e.g., employing green solvents like ionic liquids), key reaction pathways including hydrolysis, isomerization, dehydration, oxidation, and hydrogenation can be efficiently controlled. This enables the highly selective conversion of monosaccharides, disaccharides and polysaccharides into high-value platform molecules such as 5-hydroxymethylfurfural, lactic acid, and furfural. These platform molecules and their downstream derivatives are demonstrating significant potential to replace traditional fossil-based routes in the chemical and energy sectors, providing a rich technological blueprint for establishing "biorefineries".

However, surveying current research, the transition from laboratory to industry faces severe challenges, with the core issue lying in the economics and sustainability of the systems. Future research urgently needs breakthroughs in the following aspects:

(1) The future research focus should shift from designing high-performance catalysts to creating low-cost, highly stable, and recyclable catalytic systems. This includes vigorously developing non-precious metal catalysts to replace the currently widely used but costly Pt- and Ru-based catalysts, and deeply understanding the deactivation mechanisms of zeolite catalysts or catalysts in hydrothermal liquefaction systems to enhance their stability.

(2) The future technological breakthrough point lies in process integration and intensification. The researches should not only focus on the efficiency of single reactions but also pay attention to the synergistic optimization of multiple unit processes including pretreatment, catalytic conversion, product separation, and purification, developing integrated processes with low energy consumption and cost to fundamentally reduce the overall cost of biomass refining.

(3) Future efforts need to utilize interdisciplinary research methods to achieve precise understanding and control of reaction processes. Using *in situ* characterization techniques and theoretical calculations to reveal the structure of catalyst active centers and reaction mechanisms at the atomic/molecular level. Furthermore, integrating artificial intelligence and machine learning will accelerate the development of new catalytic materials and processes.

(4) Beyond producing chemicals and liquid fuels, future endeavors should actively explore the application of carbohydrates in broader fields such as new energy devices (e.g., high-performance fuel cells), biodegradable polymer materials and carbon-negative emission technologies, fully unleashing their potential value as renewable carbon resources.

Only through continuous interdisciplinary innovation can the core value of sugar-based biomass in building a green, low-carbon future be fully realized.

Declaration of Competing Interest

The authors declare no conflict of interest.

References

[1] TILMAN D, BALZAN M, HILL J, et al. Beneficial biofuels-the food, energy, and environment trilemma[J]. Science, 2009, 325(5938): 270−271.

[2] HUBER G W, IBORRA S, CORMA A. Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering[J]. Chem Rev, 2006, 106(9): 4044−4098.

[3] PANWAR N L, KAUSHIK S C, KOTHARI S. Role of renewable energy sources in environmental protection: A review[J]. Renewable Sustainable Energy Rev, 2011, 15(3): 1513−1524.

[4] HOLM M S, SARAVANAMURUGAN S, TAARNING E. Conversion of sugar compounds to lactic acid derivatives using heterogeneous zeotype catalysts[J]. Science, 2010, 328(5978): 602−605.

[5] LEE R, HARRIS J, CHAMPAGNE P, et al. CO_2-catalysed conversion of carbohydrates to 5-hydroxymethyl furfural[J]. Green Chem, 2016, 18(23): 6305−6310.

[6] JADHAV A H, KIM H, HWANG I T. Efficient selective dehydration of fructose and sucrose into 5-hydroxymethylfurfural (HMF) using dicationic room temperature ionic liquids as a catalyst[J]. Catal Commun, 2012, 21: 96−103.

[7] RATHOD P V, MUJMULE R B, CHUNG W-J, et al. Efficient dehydration of glucose, sucrose, and fructose to 5-hydroxymethylfurfural using tri-cationic ionic liquids[J]. Catal Lett, 2019, 149(3): 672−687.

[8] SHI J, LIU X, ZHANG H, et al. Catalytic conversion of fructose and sucrose to 5-hydroxymethylfurfural using simple ionic liquid/DMF binary reaction media[J]. Catal Commun, 2013, 42: 89−92.

[9] MULK S, SAJID M, WANG L, et al. Catalytic conversion of sucrose to 5-hydroxymethylfurfural in green aqueous and organic medium[J]. J Environ Chem Eng, 2022, 10(2): 106613.

[10] TAN-SOETEDJO J N M, WIBOWO Y, WIDJAJA E, et al. Experimental and kinetic modeling studies on the conversion of sucrose to levulinic acid and 5-hydroxymethylfurfural using sulfuric acid in water[J]. Ind Eng Chem Res, 2017, 56(45): 13228−13239.

[11] POLIDORO D, BELLOTTI M, BORGNA A, et al. CO_2-assisted hydrolytic hydrogenation of cellulose and cellulose-based waste into sorbitol over commercial Ru/C[J]. Green Chem, 2023, 25(17): 6677−6685.

[12] GUTIERREZ L F, HAMOUDI S, BELKACEMI K.

Selective production of lactobionic acid by aerobic oxidation of lactose over gold crystallites supported on mesoporous silica[J]. Appl Catal A: Gen, 2011, 402(1/2): 94−103.

[13] KNOTHE G, RAZON L F. Biodiesel fuels[J]. Prog Energy Combust Sci, 2017, 58: 36−59.

[14] SHEMESH M, KATZ E, GOLAN Y, et al. Light-driven and bias-free direct conversion of cellulose to electrical power[J]. Cell Rep Phys Sci, 2023, 4(9): 101546.

[15] IRFAN M, ALI A, KHAN M Z, et al. High-performance glucose fuel cell with bimetallic Ni-Co composite anchored on reduced graphene oxide as anode catalyst[J]. Renewable Energy, 2020, 155: 1118−1126.

[16] CHAUDHURI S K, LOVLEY D R. Electricity generation by direct oxidation of glucose in mediatorless microbial fuel cells[J]. Nat Biotechnol, 2003, 21(10): 1229−1232.

[17] HE J, ZHANG X, LIU J, et al. Upgrading of biomass-derived furanic compounds into high-quality fuels involving aldol condensation strategy[J]. Fuel, 2021, 306: 121765.

[18] STÖCKER M. Biofuels and biomass-to-liquid fuels in the biorefinery: Catalytic conversion of lignocellulosic biomass using porous materials[J]. Angew Chem Int Ed, 2008, 47(48): 9200−9211.

[19] MÄKI-ARVELA P, AHO A, MURZIN D Y. Heterogeneous catalytic synthesis of methyl lactate and lactic acid from sugar compounds and their derivatives[J]. ChemSusChem, 2020, 13(18): 4833−4855.

[20] CHHEDA J N, ROMÁN-LESHKOV Y, DUMESIC J A. Production of 5-hydroxymethylfurfural and furfural by dehydration of biomass-derived mono- and poly-saccharides[J]. Green Chem, 2007, 9(4): 342−350.

[21] RICHARD J P. Acid-base catalysis of the elimination and isomerization reactions of triose phosphates[J]. J Am Chem Soc, 1984, 106(17): 4926−4936.

[22] NAGORSKI R W, RICHARD J P. Mechanistic imperatives for aldose-ketose isomerization in water: Specific, general base- and metal ion-catalyzed isomerization of glyceraldehyde with proton and hydride transfer[J]. J Am Chem Soc, 2001, 123(5): 794−802.

[23] LI H, YANG S, SARAVANAMURUGAN S, et al. Glucose isomerization by enzymes and chemo-catalysts: Status and current advances[J]. ACS Catal, 2017, 7(4): 3010−3029.

[24] YANG B Y, MONTGOMERY R. Alkaline degradation of glucose: Effect of initial concentration of reactants[J]. Carbohydr Res, 1996, 280(1): 27−45.

[25] ESPOSITO D, ANTONIETTI M. Chemical conversion of sugar compounds to lactic acid by alkaline hydrothermal processes[J]. ChemSusChem, 2013, 6(6): 989−992.

[26] JIN F, ENOMOTO H. Rapid and highly selective conversion of biomass into value-added products in hydrothermal conditions: Chemistry of acid/base-catalysed and oxidation reactions[J]. Energy Environ Sci, 2011, 4(2): 382−397.

[27] CARRAHER J M, FLEITMAN C N, TESSONNIER J-P. Kinetic and mechanistic study of glucose isomerization using homogeneous organic Brønsted base catalysts in water[J]. ACS Catal, 2015, 5(6): 3162−3173.

[28] EKEBERG D, MORGENLIE S, STENSTRØM Y. Base catalysed isomerisation of aldoses of the arabino and lyxo series in the presence of aluminate[J]. Carbohydr Res, 2002, 337(9): 779−786.

[29] CORMA A, NEMETH L T, RENZ M, et al. Sn-zeolite beta as a heterogeneous chemoselective catalyst for Baeyer-Villiger oxidations[J]. Nature, 2001, 412(6845): 423−425.

[30] BERMEJO-DEVAL R, GOUNDER R, DAVIS M E. Framework and extraframework tin sites in zeolite beta react glucose differently[J]. ACS Catal, 2012, 2(12): 2705−2713.

[31] TARANTINO G, BOTTI L, OVERTOOM L, et al. Multiple active sites for glucose conversion identified in Sn-beta catalysts by CPMG MAS NMR and operando UV-Vis spectroscopy[J]. Catal Today, 2024, 429: 114459.

[32] ROMÁN-LESHKOV Y, MOLINER M, LABINGER J A, et al. Mechanism of glucose isomerization using a solid Lewis acid catalyst in water[J]. Angew Chem Int Ed, 2010, 49(47): 8954−8957.

[33] MOLINER M, ROMÁN-LESHKOV Y, DAVIS M E. Tin-containing zeolites are highly active catalysts for the isomerization of glucose in water[J]. Proc Natl Acad Sci, 2010, 107(14): 6164−6168.

[34] RAI N, CARATZOULAS S, VLACHOS D G. Role of silanol group in Sn-beta zeolite for glucose isomerization and epimerization reactions[J]. ACS Catal, 2013, 3(10): 2294−2298.

[35] BRAND S K, LABINGER J A, DAVIS M E. Tin silsesquioxanes as models for the “open” site in tin-containing zeolite beta[J]. ChemCatChem, 2016, 8(1): 121−124.

[36] HARRIS J W, BRAND S K, LABINGER J A, et al. Titration and quantification of open and closed Lewis acid sites in Sn-beta zeolites that catalyze glucose isomerization [J]. J Catal, 2016, 335: 141−154.

[37] SUN P, LIU Y, ZHANG H, et al. Acid-base cascades in zeotype single crystal for sugar conversion[J]. Angew Chem Int Ed, 2024, 63(10): e202318750.

[38] LI Y P, HEAD-GORDON M, BELL A T. Analysis of the reaction mechanism and catalytic activity of metal-substituted beta zeolite for the isomerization of glucose to fructose[J]. ACS Catal, 2014, 4(5): 1537−1545.

[39] SUN P, ZHANG H, LIU Y, et al. Rational positioning of metal ions to stabilize open tin sites in beta zeolite for catalytic conversion of sugar compounds[J]. Angew Chem Int Ed, 2023, 62(6): e202215737.

[40] WANG Y, CAO W, LUO J, et al. One step open fermentation for lactic acid production from inedible starchy biomass by thermophilic Bacillus coagulans IPE22[J]. Bioresour Technol, 2019, 272: 398−406.

[41] GUO Q, LI Z, WANG Y, et al. Highly active and

recyclable Sn-MWW zeolite catalyst for sugar conversion to methyl lactate and lactic acid[J]. ChemSusChem, 2013, 6(8): 1352−1356.

[42] DONG W, ZHANG H, LI Y, et al. Selective chemical conversion of sugar compounds in aqueous solutions without alkali to lactic acid over a Zn-Sn-beta Lewis acid-base catalyst[J]. Sci Rep, 2016, 6: 26713.

[43] LI Z, WANG Y, GUO Q, et al. Catalytic conversion of sugar compounds into lactic acid via a RuO_x/MoS_2 catalyst [J]. Catalysts, 2023, 13(3): 545.

[44] DE CLIPPEL F, DENAYER J F M, BARTHEL J, et al. Fast and selective sugar conversion to alkyl lactate and lactic acid with bifunctional carbon-silica catalysts[J]. J Am Chem Soc, 2012, 134(24): 10089−10101.

[45] BAI J, LI Z, GUO Q, et al. The role of aluminum in Sn-Al-beta zeolite catalyzing the conversion of glucose to methyl lactate[J]. Mol Catal, 2023, 541: 113071.

[46] YANG X, LV B, LU T, et al. Promotion effect of Mg on a post-synthesized Sn-beta zeolite for the conversion of glucose to methyl lactate[J]. Catal Sci Technol, 2020, 10(3): 700−709.

[47] WOLF P, HAMMOND C, CONRAD S, et al. Post-synthetic preparation of Sn-, Ti- and Zr-beta: A facile route to water tolerant, highly active Lewis acidic zeolites[J]. Dalton Trans, 2014, 43(11): 4514−4519.

[48] SUIB S L, PŘECH J, SZANIAWSKA E, et al. Recent advances in tetra- (Ti, Sn, Zr, Hf) and pentavalent (Nb, V, Ta) metal-substituted molecular sieve catalysis[J]. Chem Rev, 2023, 123(3): 877−917.

[49] PORNSETMETAKUL P, CHEN D, LIU Y, et al. Post-synthesis metal (Sn, Zr, Hf) modification of BEA zeolite: combined Lewis and Brønsted acidity for cascade catalysis [J]. Chin J Catal, 2023, 55: 200−215.

[50] MENEGAZZO F, GHEDINI E, SIGNORETTO M. 5-hydroxymethylfurfural (HMF) production from real biomasses[J]. Molecules, 2018, 23(9): 1−8.

[51] XU H, WANG Z, HUANG J, et al. Thermal catalytic conversion of biomass-derived glucose to fine chemicals[J]. Energy Fuels, 2021, 35(10): 8602−8616.

[52] TONG X, MA Y, LI Y. Biomass into chemicals: Conversion of sugar compounds to furan derivatives by catalytic processes[J]. Appl Catal A: Gen, 2010, 385(1/2): 1−13.

[53] GALLEZOT P. Conversion of biomass to selected chemical products[J]. Chem Soc Rev, 2012, 41(4): 1538−1558.

[54] PFAB E, FILICIOTTO L, LUQUE R. The dark side of biomass valorization: A laboratory experiment to understand humin formation, catalysis, and green chemistry [J]. J Chem Educ, 2019, 96(12): 3030−3037.

[55] ZHAO H, HOLLADAY J E, BROWN H, et al. Metal chlorides in ionic liquid solvents convert sugar compounds to 5-hydroxymethylfurfural[J]. Science, 2007, 316(5831): 1597−1600.

[56] MOREAU C, BELGACEM M N, GANDINI A. Recent catalytic advances in the chemistry of substituted furans from carbohydrates and in the ensuing polymers[J]. Top Catal, 2004, 27(1/4): 11−30.

[57] MA H, ZHANG Y, LIU J, et al. Organocatalytic dehydration of fructose-based carbohydrates into 5-hydroxymethylfurfural in the presence of a neutral inner salt[J]. ACS Omega, 2023, 8(18): 16345−16355.

[58] REN L-K, ZHANG Y, LIU J, et al. Performance of dimethyl sulfoxide and Brønsted acid catalysts in fructose conversion to 5-hydroxymethylfurfural[J]. ACS Catal, 2017, 7(3): 2199−2212.

[59] TONG X, LI Y. Efficient and selective dehydration of fructose to 5-hydroxymethylfurfural catalyzed by Brønsted-acidic ionic liquids[J]. ChemSusChem, 2010, 3(3): 350−355.

[60] BINDER J B, RAINES R T. Simple chemical transformation of lignocellulosic biomass into furans for fuels and chemicals[J]. J Am Chem Soc, 2009, 131(5): 1979−1985.

[61] QI X, WATANABE M, AIDA T M, et al. Sulfated zirconia as a solid acid catalyst for the dehydration of fructose to 5-hydroxymethylfurfural[J]. Catal Commun, 2009, 10(13): 1771−1775.

[62] ASGHARI F S, YOSHIDA H. Dehydration of fructose to 5-hydroxymethylfurfural in sub-critical water over heterogeneous zirconium phosphate catalysts[J]. Carbohydr Res, 2006, 341(14): 2379−2387.

[63] DEGIRMENCI V, HENSEN E J M. Development of a heterogeneous catalyst for lignocellulosic biomass conversion: glucose dehydration by metal chlorides in a silica-supported ionic liquid layer[J]. Environ Prog Sustainable Energy, 2014, 33(2): 657−662.

[64] SHIMIZU K-I, UOZUMI R, SATSUMA A. Enhanced production of hydroxymethylfurfural from fructose with solid acid catalysts by simple water removal methods[J]. Catal Commun, 2009, 10(14): 1849−1853.

[65] ILGEN F, BAUER F, SCHOMÄCKER R. Conversion of carbohydrates into 5-hydroxymethylfurfural in highly concentrated low melting mixtures[J]. Green Chem, 2009, 11(12): 1948−1954.

[66] QIU B-B, SHI J-C, HU W, et al. Efficient and selective conversion of xylose to furfural over carbon-based solid acid catalyst in water-γ-valerolactone[J]. Energy, 2024, 294: 130774−130787.

[67] DIAS A S, PILLINGER M, VALENTE A A. Liquid-phase dehydration of D-xylose over microporous and mesoporous niobium silicates[J]. Catal Lett, 2006, 108(3/4): 179−186.

[68] LIMA S, PILLINGER M, VALENTE A-A. Catalytic cyclodehydration of xylose to furfural in the presence of zeolite H-beta and a micro/mesoporous beta/TUD-1 composite material[J]. Appl Catal A: Gen, 2010, 388(1/2): 141−148.

[69] LIMA S, PILLINGER M, VALENTE A-A. Dehydration of D-xylose into furfural catalysed by solid acids derived from the layered zeolite Nu-6(1)[J]. Catal Commun, 2008,

9(11/12): 2144−2148.

[70] LIMA S, PILLINGER M, VALENTE A-A. Dehydration of xylose into furfural in the presence of crystalline microporous silicoaluminophosphates[J]. Catal Lett, 2010, 135(1/2): 41−47.

[71] GABRIEL J B, SANTOS L O, DIAS A S. New approach to dehydration of xylose to 2-furfuraldehyde using a mesoporous niobium-based catalyst[J]. ACS Omega, 2020, 5(34): 21392−21400.

[72] ANTUNES M M, PILLINGER M, VALENTE A A. Aqueous-phase dehydration of xylose to furfural in the presence of MCM-22 AND ITQ-2 solid acid catalysts[J]. Appl Catal A: Gen, 2012, 417−418: 243−252.

[73] GARCÍA-SANCHO C, MORENO-TOST R, MAIRELES-TORRES P. Mesoporous Nb_2O_5 as solid acid catalyst for dehydration of D-xylose into furfural[J]. Catal Today, 2014, 234: 119−124.

[74] LI H, FANG Z, SMITH R L, et al. Efficient valorization of biomass to biofuels with bifunctional solid catalytic materials[J]. Prog Energy Combust Sci, 2016, 55: 98−194.

[75] DIAS A S, PILLINGER M, VALENTE A A. Exfoliated titanate, niobate and titanoniobate nanosheets as solid acid catalysts for the liquid-phase dehydration of D-xylose into furfural[J]. J Catal, 2006, 244(2): 230−237.

[76] VALADARES D S, OLIVEIRA M C, DIAS A S. Niobium on BEA dealuminated zeolite for high selectivity dehydration reactions of ethanol and xylose into diethyl ether and furfural[J]. Nanomaterials, 2020, 10(7): 1−20.

[77] PAREJAS A, MARTÍNEZ A, LÓPEZ P. Microemulsion and sol-gel synthesized ZrO_2-MgO catalysts for the liquid-phase dehydration of xylose to furfural[J]. Molecules, 2017, 22(12): 1−18.

[78] ZHU N-N, ZHANG M-Y, QIU G, et al. One-pot synthesis of 5-hydroxymethylfurfural from cellobiose and sucrose using niobium-modified montmorillonite catalysts[J]. Mol Catal, 2022, 532: 112720−112731.

[79] STEINBACH D, KRUSE A, SAUER J, et al. Sucrose is a promising feedstock for the synthesis of the platform chemical hydroxymethylfurfural[J]. Energies, 2018, 11(3): 1−15.

[80] BOWER S, WICKRAMASINGHE R, NAGLE N J, et al. Modeling sucrose hydrolysis in dilute sulfuric acid solutions at pretreatment conditions for lignocellulosic biomass[J]. Bioresour Technol, 2008, 99(15): 7354−7362.

[81] TAKEUCHI Y, JIN F, TOHJI K, et al. Acid catalytic hydrothermal conversion of carbohydrate biomass into useful substances[J]. J Mater Sci, 2008, 43(7): 2472−2475.

[82] HU S, LI Y, WANG Y. Direct conversion of inulin to 5-hydroxymethylfurfural in biorenewable ionic liquids[J]. Green Chem, 2009, 11(6): 873−877.

[83] KÖRNER P, JUNG D, KRUSE A. The effect of different Brønsted acids on the hydrothermal conversion of fructose to HMF[J]. Green Chem, 2018, 20(10): 2231−2241.

[84] JAIN A, SHORE A M, JONNALAGADDA S C, et al. Conversion of fructose, glucose and sucrose to 5-hydroxymethyl-2-furfural over mesoporous zirconium phosphate catalyst[J]. Appl Catal A: Gen, 2015, 489: 72−76.

[85] CHUN J-A, LEE J-W, YI Y-B, et al. Catalytic production of hydroxymethylfurfural from sucrose using 1-methyl-3-octylimidazolium chloride ionic liquid[J]. Korean J Chem Eng, 2010, 27(3): 930−935.

[86] TIAN X, QI B, ZHANG S, et al. Catalytic production of 5-hydroxymethylfurfural from sucrose and molasses by aluminum chloride in green aqueous γ-valerolactone system[J]. Biomass Convers Biorefin, 2021, 11(5): 1931−1941.

[87] QU Y, ZHANG H, LI Y, et al. One-pot conversion of disaccharide into 5-hydroxymethylfurfural catalyzed by imidazole ionic liquid[J]. Sci Rep, 2016, 6: 26067.

[88] ZHAO Y, LI Y, WANG Y. Comparative study on the dehydration of biomass-derived disaccharides and polysaccharides to 5-hydroxymethylfurfural[J]. Energy Fuels, 2019, 33(10): 9985−9995.

[89] SINGH H, KAUR P, SINGH A. Surfactant-assisted synthesis of zero-dimensional iron nanomaterial for cellobiose hydrolysis[J]. Mater Adv, 2024, 5(1): 306−314.

[90] ANDÉREZ M, BENITO-ROMÁN Ó, ROMERO A, et al. Hydrolytic hydrogenation of cellobiose into hexitols by means of Ru/MCM48 catalysts[J]. Catal Lett, 2021, 151(5): 1350−1360.

[91] LIU Q, LIU H, GAO D-M. Establishing a kinetic model of biomass-derived disaccharide hydrolysis over solid acid: A case study on hierarchically porous niobium phosphate[J]. Chem Eng J, 2022, 430: 132756.

[92] MARZO M, GERVAINI A, CARNITI P. Hydrolysis of disaccharides over solid acid catalysts under green conditions[J]. Carbohydr Res, 2012, 347(1): 23−31.

[93] SADIER A, PAUL S, MARCEAU E, et al. Ni-Fe alloying enhances the efficiency of the maltose hydrogenation process: the role of surface species and kinetic study[J]. Appl Catal B: Environ, 2022, 313: 121446.

[94] FAN H, WANG Y, LIU Q, et al. Maltose hydrogenation to maltitol over industrial raney Ni catalyst: Kinetics and mechanism[J]. AIChE J, 2023, 69(7): e18056.

[95] REN Y, LI W, HAN Y, et al. Hydrogenation of maltose over NiFeB amorphous alloy catalyst[J]. 2008, 37(1): 29−33.

[96] YAO H, LI H, BAI X, et al. Amorphous alloy Ni-Fe-B: preparation, characterization and its catalytic ability for hydrogen generation[J]. Appl Mech Mater, 2014, 672−674: 592−596.

[97] LI H, YAO H, BAI X, et al. A novel ruthenium-phosphorus amorphous alloy catalyst for maltose hydrogenation to maltitol[J]. Adv Synth Catal, 2008, 350(6): 829−836.

[98] SULMAN E M, PODGORSKAYA O A, KUSTOV L M. Maltose hydrogenation over ruthenium nanoparticles impregnated in hypercrosslinked polystyrene[J]. Chem Eng J, 2015, 282: 37−44.

[99] YANG Y, GU H, ZHANG Q, et al. Ordered mesoporous

Ni-p amorphous alloy nanowire arrays: High-efficiency catalyst for production of polyol from sugar[J]. ACS Appl Mater Interfaces, 2020, 12(23): 26101−26112.

[100] JEONG G-T. Valorization of dairy by-products: Optimized synthesis of 5-hydroxymethylfurfural and levulinic acid from lactose and whey[J]. J Environ Chem Eng, 2022, 10(5): 108413.

[101] BINDER J B, CEFALI A V, BLANK J J, et al. Mechanistic insights on the conversion of sugar compounds into 5-hydroxymethylfurfural[J]. Energy Environ Sci, 2010, 3(6): 765−771.

[102] JIA S, HE Y, WANG G. Dimethylsulfoxide/water mixed solvent mediated synthesis of 5-hydroxymethylfurfural from galactose with aluminum salt catalyst[J]. ChemistrySelect, 2017, 2(8): 2356−2362.

[103] SU K, ZHANG H, LI Y, et al. Effective conversion sucrose into 5-hydroxymethylfurfural by tyrosine in [Emim]Br[J]. J Mol Catal A: Chem, 2013, 379: 350−354.

[104] JAYA T, NISHIMURA S, EBITANI K. One-pot synthesis of furans from various saccharides using a combination of solid acid and base catalysts[J]. Bull Chem Soc Jpn, 2012, 85(3): 275−281.

[105] PANDEY S, DUMONT M-J, ORSAT V. Catalytic conversion of whey permeate into 5-hydroxymethylfurfural: Optimization and kinetic modeling approach[J]. Food Bioprod Process, 2021, 129: 134−143.

[106] DE S, BHATTACHARYYA S, ROY D. Biopolymer templated porous TiO_2: An efficient catalyst for the conversion of unutilized sugar compounds derived from hemicellulose[J]. Appl Catal A: Gen, 2012, 435−-436: 197−203.

[107] WON W, MOTAGAMWALA A H, DUMESIC J A, et al. A co-solvent hydrolysis strategy for the production of biofuels: Process synthesis and technoeconomic analysis[J]. React Chem Eng, 2017, 2(3): 397−405.

[108] SAHA B, ABU-OMAR M M. Advances in 5-hydroxymethylfurfural production from biomass in biphasic solvents[J]. Green Chem, 2014, 16(1): 24−38.

[109] PRAT D, CANALS I, ESPINET P. CHEM21 selection guide of classical- and less classical-solvents[J]. Green Chem, 2016, 18(1): 288−296.

[110] REZAYAN A, ZHANG Y, LI B, et al. Catalytic conversion of cellulose to 5-hydroxymethylfurfural: Advancements in heterogeneous catalysts and cutting-edge hydrolysis strategies[J]. ChemCatChem, 2023, 15(22): e202300973.

[111] KOBAYASHI H, KOMANOYA T, GUHA S K, et al. Conversion of cellulose into renewable chemicals by supported metal catalysis[J]. Appl Catal A: Gen, 2011, 409-410: 13−20.

[112] YANG P, KOBAYASHI H, FUKUOKA A. Recent developments in the catalytic conversion of cellulose into valuable chemicals[J]. Chin J Catal, 2011, 32(5): 716−722.

[113] GURGEL L V A, MARABEZI K, ZANBOM M D, et al. Dilute acid hydrolysis of sugar cane bagasse at high temperatures: A kinetic study of cellulose saccharification and glucose decomposition. part I: Sulfuric acid as the catalyst[J]. Ind Eng Chem Res, 2012, 51(3): 1173−1185.

[114] SHEN J, WYMAN C E. Hydrochloric acid-catalyzed levulinic acid formation from cellulose: Data and kinetic model to maximize yields[J]. AIChE J, 2012, 58(1): 236−246.

[115] LI M, ZHANG Y, WANG L, et al. Coloration of cotton fibers with natural plant dyes using an overlay dyeing method[J]. Ind Crops Prod, 2024, 212: 118284.

[116] RINALDI R, SCHUTH F. Acid hydrolysis of cellulose as the entry point into biorefinery schemes[J]. ChemSusChem, 2009, 2(12): 1096-1107.

[117] NEVELL T P, UPTON W R. The hydrolysis of cotton cellulose by hydrochloric acid in benzene[J]. Carbohydr Res, 1976, 49: 163−174.

[118] XIANG Q, LEE Y Y, PETTERSSON P O, et al. Heterogeneous aspects of acid hydrolysis of α-cellulose [J]. Appl Biochem Biotechnol, 2003, 105: 505−514.

[119] XU T T, BAI Z Z, WANG L J, et al. Breeding of D(-)-lactic acid high producing strain by low-energy ion implantation and preliminary analysis of related metabolism[J]. Appl Biochem Biotechnol, 2010, 160(2): 314−321.

[120] ZHANG Y-H P, DING S-Y, MIELENZ J R, et al. Fractionating recalcitrant lignocellulose at modest reaction conditions[J]. Biotechnol Bioeng, 2007, 97(2): 214−223.

[121] HUANG H-J, LIN W, RAMASWAMY S, et al. Process modeling of comprehensive integrated forest biorefinery-an integrated approach[J]. Appl Biochem Biotechnol, 2009, 154(1-3): 26−37.

[122] CHIN S X, TAN R R, LEE K T. A kinetic study on acid hydrolysis of oil palm empty fruit bunch fibers using a microwave reactor system[J]. Energy Fuels, 2014, 28(4): 2589−2597.

[123] CHIMENTÃO R J, LORENTE E, GISPERT-GUIRADO F, et al. Hydrolysis of dilute acid-pretreated cellulose under mild hydrothermal conditions[J]. Carbohydr Polym, 2014, 111: 116−124.

[124] KIM J S, LEE Y Y, TORGET R W. Cellulose hydrolysis under extremely low sulfuric acid and high-temperature conditions[J]. Appl Biochem Biotechnol, 2001, 91: 331−340.

[125] XIANG Q, KIM J S, LEE Y Y. A comprehensive kinetic model for dilute-acid hydrolysis of cellulose[J]. Appl Biochem Biotechnol, 2003, 105: 337−352.

[126] ZHANG Z, WANG Y, LIU Q, et al. Utilization of hydroxyl-enriched glucose-based carbonaceous sphere (HEGCS) as a catalytic accelerator to enhance the hydrolysis of cellulose to sugar[J]. ACS Appl Mater Interfaces, 2020, 12(33): 25693−25699.

[127] QU H, ZHANG Y, LIU J, et al. Graphene oxide nanofiltration membrane based on three-dimensional size-controllable metal-organic frameworks for water

treatment[J]. ACS Appl Nano Mater, 2022, 5(4): 5196−5207.

[128] VOM STEIN T, BAUER F, SCHOMÄCKER R. Salt-assisted organic-acid-catalyzed depolymerization of cellulose[J]. Green Chem, 2010, 12(10): 1844−1849.

[129] LYU Q, ZHANG H, LI Y, et al. One-pot fractionation of corn stover with peracetic acid and maleic acid[J]. Bioresour Technol, 2021, 320: 124306.

[130] HOUFANI A A, ANDERS N, SPIESS A C, et al. Insights from enzymatic degradation of cellulose and hemicellulose to fermentable sugar compounds-a review[J]. Biomass Bioenergy, 2020, 134: 105481.

[131] PATEL A K, SINGHANIA R R, SIM S J, et al. Thermostable cellulases: Current status and perspectives[J]. Bioresour Technol, 2019, 279: 385−392.

[132] SIQUEIRA J G W, RODRIGUES C, VANDENBERGHE L P D S, et al. Current advances in on-site cellulase production and application on lignocellulosic biomass conversion to biofuels: A review[J]. Biomass Bioenergy, 2020, 132: 105419.

[133] LIU Y-J, LI B, FENG Y, et al. Consolidated bio-saccharification: Leading lignocellulose bioconversion into the real world[J]. Biotechnol Adv, 2020, 40: 107535.

[134] MUTALIB M ABD, RAHMAN M A, OTHMAN M H D, et al. Membrane Characterization[M]. Amsterdam: Elsevier, 2017: 161−179.

[135] SRIVASTAVA N, SINGHANIA R R, PANDEY A. Applications of fungal cellulases in biofuel production: advances and limitations[J]. Renewable Sustainable Energy Rev, 2018, 82: 2379−2386.

[136] YAN W, LANG T, QI X, et al. Engineering immunogenic cell death with nanosized drug delivery systems improving cancer immunotherapy[J]. Curr Opin Biotechnol, 2020, 66: 36−43.

[137] TAOERDAHONG, ZHOU K, YANG F, et al. Structure, immunostimulatory activity, and the effect of ameliorating airway inflammation of polysaccharides from Pyrus sinkiangensis Yu[J]. Int J Biol Macromol, 2022, 195: 246−254.

[138] RAI M, SINGHANIA R R, PANDEY A. Emerging role of nanobiocatalysts in hydrolysis of lignocellulosic biomass leading to sustainable bioethanol production[J]. Catal Rev, 2019, 61(1): 1−26.

[139] VERMA M L, PURI M, BARROW C J. Recent trends in nanomaterials immobilised enzymes for biofuel production[J]. Crit Rev Biotechnol, 2016, 36(1): 108−119.

[140] KARIMI M, JENKINS B, STROEVE P. Ultrasound irradiation in the production of ethanol from biomass[J]. Renewable Sustainable Energy Rev, 2014, 40: 400−421.

[141] DE CASTRO A M, DE ANDRÉA T V, DOS REIS CASTILHO L, et al. Use of mesophilic fungal amylases produced by solid-state fermentation in the cold hydrolysis of raw babassu cake starch[J]. Appl Biochem Biotechnol, 2010, 162(6): 1612−1625.

[142] NOROUZIAN D, AKBARZADEH A, SCHARER J M, et al. Fungal glucoamylases[J]. Biotechnol Adv, 2006, 24(1): 80−85.

[143] VAN DER MAAREL M J E C, VAN DER VEEN B, UITDEHAAG J C M, et al. Properties and applications of starch-converting enzymes of the α-amylase family[J]. J Biotechnol, 2002, 94(2): 137−155.

[144] KIKANI B A, SUTHAR S, JOSHI D. Nanomaterials: an efficient support to immobilize microbial α-amylases for improved starch hydrolysis[J]. Starch-Stä rke, 2022, 74(9/10): 2200093.

[145] ALMEIDA R L J, RIOS N S, DOS SANTOS E S. Modification of red rice starch by a combination of hydrothermal pretreatments and α-amylase hydrolysis[J]. Carbohydr Polym, 2022, 296: 119963.

[146] IRSHAD I, YASMIN M. Feminism and literary translation: A systematic review[J]. Heliyon, 2022, 8(3): e09082.

[147] YANG X, LI A, LI D, et al. Applications of mixed polysaccharide-protein systems in fabricating multi-structures of binary food gels-a review[J]. Trends Food Sci Technol, 2021, 109: 197−210.

[148] LI X, XU Z, YU J, et al. In situ pretreatment during distillation improves corn fiber conversion and ethanol yield in the dry mill process[J]. Green Chem, 2019, 21(5): 1080−1090.

[149] PAL P, KUMAR R, BANERJEE S. Manufacture of gluconic acid: A review towards process intensification for green production[J]. Chem Eng Process, 2016, 104: 160−171.

[150] PEJIN D J, PETROVIĆ N, JOVANOVIĆ M. Increase in bioethanol production yield from triticale by simultaneous saccharification and fermentation with application of ultrasound[J]. J Chem Technol Biotechnol, 2012, 87(2): 170−176.

[151] LUFT L, DOS SANTOS E S, DA SILVA E K. Transformation of residual starch from brewer's spent grain into fermentable sugar compounds using supercritical technology[J]. J Supercrit Fluids, 2018, 140: 85−90.

[152] SUNARTI T C, DWIKO M, DEROSYA V, et al. Effect of microwave treatment on acid and enzymes susceptibilities of sago pith [J]. Procedia Chem, 2012, 4: 301-307.

[153] STAROSZCZYK H, JANAS P. Microwave-assisted synthesis of zinc derivatives of potato starch[J]. Carbohydr Polym, 2010, 80(3): 962−969.

[154] SAIFUDDIN N, HUSSAIN R. Microwave assisted bioethanol production from sago starch by co-culturing of ragi tapai and saccharomyces cerevisiae[J]. J Math Stat, 2011, 7(3): 198−206.

[155] ZHANG J, YU P, FAN L, et al. Effects of ultrasound treatment on the starch properties and oil absorption of potato chips[J]. Ultrason Sonochem, 2021, 70: 105347.

[156] ZHANG Y, LIU J, ZHANG H, et al. Preparation of octenyl succinic anhydride-modified cassava starch by the ultrasonic-assisted method and its influence mechanism[J].

J Food Process Preserv, 2019, 43(12): e14222.

[157] ZHONG Y, LIU J, ZHANG H, et al. Microwave pretreatment promotes the annealing modification of rice starch[J]. Food Chem, 2020, 304: 125432.

[158] PUNIA S. Barley starch modifications: Physical, chemical and enzymatic-a review[J]. Int J Biol Macromol, 2020, 144: 578−585.

[159] LI Z, WANG Y, GUO Q, et al. Designing liquefaction and saccharification processes of highly concentrated starch slurry: Challenges and recent advances[J]. Compr Rev Food Sci Food Saf, 2023, 22(3): 1597−1612.

[160] JIN J, ZHANG H, LI Y, et al. Effects of high power ultrasound on the enzymolysis and structures of sweet potato starch[J]. J Sci Food Agric, 2020, 100(8): 3498−3506.

[161] LI C, ZHANG H, LI Y, et al. Ultrasonic pretreatment improves the high-temperature liquefaction of corn starch at high concentrations[J]. Starch-Stä rke, 2017, 69(3/4): 1600002.

[162] ZAKRZEWSKA M E, BOGEL-ŁUKASIK E, BOGEL-ŁUKASIK R. Ionic liquid-mediated formation of 5-hydroxymethylfurfural-a promising biomass-derived building block[J]. Chem Rev, 2011, 111(2): 397−417.

[163] ROSATELLA A A, SIMEONOV S P, FRADE R F M, et al. 5-hydroxymethylfurfural (HMF) as a building block platform: Biological properties, synthesis and synthetic applications[J]. Green Chem, 2011, 13(4): 754−793.

[164] GIRISUTA B, JANSSEN L P B M, HEERES H J. A kinetic study on the decomposition of 5-hydroxymethylfurfural into levulinic acid[J]. Green Chem, 2006, 8(8): 701−709.

[165] SOUKUP-CARNE D, FAN X, ESTEBAN J. An overview and analysis of the thermodynamic and kinetic models used in the production of 5-hydroxymethylfurfural and furfural[J]. Chem Eng J, 2022, 442: 136313.

[166] QI L, WANG Y, GUO Q, et al. Catalytic conversion of fructose, glucose, and sucrose to 5-(hydroxymethyl)furfural and levulinic and formic acids in γ-valerolactone as a green solvent[J]. ACS Catal, 2014, 4(5): 1470−1477.

[167] PATTNAIK F, MISHRA S, BEHERA S. Catalytic conversion of lignocellulosic polysaccharides to commodity biochemicals: A review[J]. Environ Chem Lett, 2021, 19(6): 4119−4136.

[168] SAJID M, BAI Y, LIU D, et al. Organic acid catalyzed production of platform chemical 5-hydroxymethylfurfural from fructose: Process comparison and evaluation based on kinetic modeling[J]. Arab J Chem, 2020, 13(10): 7430−7444.

[169] YOUSATIT S, OSUGA R, KONDO J N, et al. Selective synthesis of 5-hydroxymethylfurfural over natural rubber-derived carbon/silica nanocomposites with acid-base bifunctionality[J]. Fuel, 2022, 311: 122577.

[170] JUNIOR M M D J, FERNANDES S A, BORGES E, et al. Kinetic study of the conversion of glucose to 5-hydroxymethylfurfural using niobium phosphate[J]. Mol Catal, 2022, 518: 112079.

[171] WIESFELD J J, GAQUERE R, HENSEN E J M. Mesoporous doped tungsten oxide for glucose dehydration to 5-hydroxymethylfurfural[J]. ACS Sustain Chem Eng, 2019, 7(8): 7552−7562.

[172] ZHANG S, SHENG K, CHEN X, et al. Conversion of glucose to 5-hydroxymethyl furfural in water-acetonitrile-dimethyl sulfoxide solvent with aluminum on activated carbon and maleic acid[J]. Ind Crops Prod, 2021, 174: 114220.

[173] MODAK A, MANKAR A R, SONDE R R, et al. One-pot conversion of glucose to 5-hydroxymethylfurfural under aqueous conditions using acid/base bifunctional mesoporous silica catalyst[J]. Renewable Energy, 2023, 212: 97−110.

[174] SONG D, LIU J, ZHANG C, et al. Design of Brønsted acidic ionic liquid functionalized mesoporous organosilica nanospheres for efficient synthesis of ethyl levulinate and levulinic acid from 5-hydroxymethylfurfural[J]. Catal Sci Technol, 2021, 11(5): 1827−1842.

[175] LEÓN M, SWIFT T D, NIKOLAKIS V, et al. Adsorption of the compounds encountered in monosaccharide dehydration in zeolite beta[J]. Langmuir, 2013, 29(22): 6597−6605.

[176] HU L, ZHANG H, LI Y, et al. Adsorption of 5-hydroxymethylfurfural, levulinic acid, formic acid, and glucose using polymeric resins modified with different functional groups[J]. ACS Omega, 2021, 6(26): 16955−16968.

[177] ZUO Y, ZHANG Y, FU Y. Catalytic conversion of cellulose into levulinic acid by a sulfonated chloromethyl polystyrene solid acid catalyst[J]. ChemCatChem, 2014, 6(3): 753−757.

[178] KUMAR K, PATHAK S, UPADHYAYULA S. 2nd generation biomass derived glucose conversion to 5-hydroxymethylfurfural and levulinic acid catalyzed by ionic liquid and transition metal sulfate: Elucidation of kinetics and mechanism[J]. J Clean Prod, 2020, 256: 120292.

[179] KUNNIKURUVAN S, NAIR N N. Mechanistic insights into the Brønsted acid-catalyzed dehydration of β-d-glucose to 5-hydroxymethylfurfural under ambient and subcritical conditions[J]. ACS Catal, 2019, 9(8): 7250−7263.

[180] HALLIDAY G A, YOUNG R J, GRUSHIN V V. One-pot, two-step, practical catalytic synthesis of 2, 5-diformylfuran from fructose[J]. Org Lett, 2003, 5(11): 2003−2005.

[181] GAUTHIER D R, RICCI J S, RAUCHFUSS T B. Synthesis of 5-pyridyl-2-furaldehydes via palladium-catalyzed cross-coupling with triorganozincates[J]. Org Lett, 2002, 4(3): 375−378.

[182] HAYASHI E, KOMANOYA T, KAMATA K, et al. Heterogeneously-catalyzed aerobic oxidation of 5-hydroxymethylfurfural to 2, 5-furandicarboxylic acid with MnO_2[J]. ChemSusChem, 2017, 10(4): 654−658.

[183] ZHANG Z, WANG Y, LIU Q, et al. Iron oxide encapsulated by ruthenium hydroxyapatite as heterogeneous catalyst for the synthesis of 2, 5-diformylfuran[J]. ChemSusChem, 2014, 7(12): 3496−3504.

[184] ZHANG S, WANG Y, LIU Q, et al. Recent progress in metal-catalyzed selective oxidation of 5-hydroxymethylfurfural into furan-based value-added chemicals[J]. Chem Rec, 2023, 23(5): e202300019.

[185] MA J, DU Z, XU J, et al. Efficient aerobic oxidation of 5-hydroxymethylfurfural to 2, 5-diformylfuran, and synthesis of a fluorescent material[J]. ChemSusChem, 2011, 4(1): 51−54.

[186] KARIMI B, MIRZAEI H M, FARHANGI E. Fe_3O_4@SiO_2-TEMPO as a magnetically recyclable catalyst for highly selective aerobic oxidation of 5-hydroxymethylfurfural into 2, 5-diformylfuran under metal- and halogen-free conditions[J]. ChemCatChem, 2014, 6(3): 758−762.

[187] ZHAO J, ANJALI J, YAN Y, et al. Cr-MIL-101-encapsulated keggin phosphomolybdic acid as a catalyst for the one-pot synthesis of 2, 5-diformylfuran from fructose[J]. ChemCatChem, 2017, 9(7): 1187−1191.

[188] XU F, ZHANG Z. Polyaniline-grafted $VO(acac)_2$: An effective catalyst for the synthesis of 2, 5-diformylfuran from 5-hydroxymethylfurfural and fructose[J]. ChemCatChem, 2015, 7(9): 1470−1477.

[189] GUO Y, CHEN J. Bicomponent assembly of VO_2 and polyaniline-functionalized carbon nanotubes for the selective oxidation of biomass-based 5-hydroxymethylfurfural to 2, 5-diformylfuran[J]. ChemPlusChem, 2015, 80(12): 1760−1768.

[190] LIU X, WANG Y, GUO Q, et al. Catalytic aerobic oxidation of 5-hydroxymethylfurfural over VO^{2+} and Cu^{2+} immobilized on amino functionalized SBA-15[J]. Chem Eng J, 2016, 283: 1315−1321.

[191] PANG Y, ZHANG H, LI Y, et al. A unique air-assisted DMSO oxidation pathway for the highly efficient synthesis of 2, 5-diformylfuran from 5-hydroxymethylfurfural/ fructose[J]. Green Chem, 2023, 25(23): 9680−9688.

[192] CARLINI C, PATRONO P, GALLETTI A M R, et al. Selective oxidation of 5-hydroxymethyl-2-furaldehyde to furan-2, 5-dicarboxaldehyde by catalytic systems based on vanadyl phosphate[J]. Appl Catal A: Gen, 2005, 289(2): 197−204.

[193] AMARASEKARA A S, GREEN D, MCMILLAN E. Efficient oxidation of 5-hydroxymethylfurfural to 2, 5-diformylfuran using Mn(III)-salen catalysts[J]. Catal Commun, 2008, 9(2): 286−288.

[194] NAVARRO O C, CANÓS A C, CHORNET S I. Chemicals from biomass: aerobic oxidation of 5-hydroxymethyl-2-furaldehyde into diformylfurane catalyzed by immobilized vanadyl-pyridine complexes on polymeric and organofunctionalized mesoporous supports[J]. Top Catal, 2009, 52(3): 304−314.

[195] LEWKOWSKI J. Convenient synthesis of furan-2, 5-dicarboxylic acid and its derivatives[J]. Pol J Chem, 2001, 75(12): 1943−1946.

[196] ZUO X, VENKITASUBRAMANIAN P, MARTIN K J, et al. Facile production of 2, 5-furandicarboxylic acid via oxidation of industrially sourced crude 5-hydroxymethylfurfural[J]. ChemSusChem, 2022, 15(13): e202102050.

[197] YI G, TEONG S P, LI X, et al. Purification of biomass-derived 5-hydroxymethylfurfural and its catalytic conversion to 2, 5-furandicarboxylic acid[J]. ChemSusChem, 2014, 7(8): 2131−2135.

[198] CASANOVA O, IBORRA S, CORMA A. Biomass into chemicals: One pot-base free oxidative esterification of 5-hydroxymethyl-2-furfural into 2, 5-dimethylfuroate with gold on nanoparticulated ceria[J]. J Catal, 2009, 265(1): 109−116.

[199] KRÖGER M, PRÜSSE U, VORLOP K-D. A new approach for the production of 2, 5-furandicarboxylic acid by in situ oxidation of 5-hydroxymethylfurfural starting from fructose[J]. Top Catal, 2000, 13(3): 237−242.

[200] LILGA M A, HALLEN R T, GRAY M. Production of oxidized derivatives of 5-hydroxymethylfurfural (HMF)[J]. Top Catal, 2010, 53(15/18): 1264−1269.

[201] TAARNING E, NIELSEN I S, EGEBLAD K, et al. Chemicals from renewables: Aerobic oxidation of furfural and hydroxymethylfurfural over gold catalysts[J]. ChemSusChem, 2008, 1(1/2): 75−78.

[202] GORBANEV Y Y, KLITGAARD S K, WOODLEY J M, et al. Gold-catalyzed aerobic oxidation of 5-hydroxymethylfurfural in water at ambient temperature[J]. ChemSusChem, 2009, 2(7): 672−675.

[203] LIU X, LUO Y, MA H, et al. Hydrogen-binding-initiated activation of O-H bonds on a nitrogen-doped surface for the catalytic oxidation of biomass hydroxyl compounds[J]. Angew Chem Int Ed, 2021, 60(48): 18103−18110.

[204] CORMA A, IBORRA S, VELTY A. Chemical routes for the transformation of biomass into chemicals[J]. Chem Rev, 2007, 107(6): 2411−2502.

[205] THANANATTHANACHON T, RAUCHFUSS T B. Efficient route to hydroxymethylfurans from sugar compounds via transfer hydrogenation[J]. ChemSusChem, 2010, 3(10): 1139−1141.

[206] GARCÍA-ZARAGOZA A, CEREZO-NAVARRETE C, OÑA-BURGOS P, et al. Boosting the catalytic performance of graphene-supported pt nanoparticles via decorating with-$SnBu_n$: An efficient approach for aqueous hydrogenation of biomass-derived compounds[J]. Nanoscale, 2023, 15(29): 12319−12332.

[207] GUPTA K, RAI R K, SINGH S K. Metal catalysts for the efficient transformation of biomass-derived HMF and furfural to value added chemicals[J]. ChemCatChem, 2018, 10(11): 2326−2349.

[208] ALAMILLO R, TUCKER M, CHIA M, et al. The selective hydrogenation of biomass-derived 5-hydroxymethylfurfural

using heterogeneous catalysts[J]. Green Chem, 2012, 14(5): 1413−1419.

[209] CAO Q, WANG Y, GUO Q, et al. Catalytic synthesis of 2, 5-bis-methoxymethylfuran: A promising cetane number improver for diesel[J]. Appl Catal A: Gen, 2014, 481: 49−53.

[210] SARKAR C, CHAKRABORTY A, PAUL S. Navigating copper-atom-pair structural effect inside a porous organic polymer cavity for selective hydrogenation of biomass-derived 5-hydroxymethylfurfural[J]. ACS Sustainable Chem Eng, 2021, 9(5): 2136−2151.

[211] OHYAMA J, ESAKI A, YAMAMOTO Y, et al. Selective hydrogenation of 2-hydroxymethyl-5-furfural to 2, 5-bis(hydroxymethyl)furan over gold sub-nano clusters[J]. RSC Adv, 2013, 3(4): 1033−1036.

[212] CHEN Q, WANG Y, GUO Q, et al. Selective hydrogenation of 5-hydroxymethylfurfural via zeolite encapsulation to avoid further hydrodehydroxylation[J]. Ind Eng Chem Res, 2020, 59(26): 12004−12012.

[213] ROMÁN-LESHKOV Y, BARRETT C J, LIU Z Y, et al. Production of dimethylfuran for liquid fuels from biomass-derived carbohydrates[J]. Nature, 2007, 447(7147): 982−985.

[214] YANG W, SEN A. One-step catalytic transformation of carbohydrates and cellulosic biomass to 2, 5-dimethyltetrahydrofuran for liquid fuels[J]. ChemSusChem, 2010, 3(5): 597−603.

[215] HU B, WANG Y, GUO Q, et al. Formic acid-assisted selective hydrogenolysis of 5-hydroxymethylfurfural to 2, 5-dimethylfuran over bifunctional Pd nanoparticles supported on N-doped mesoporous carbon[J]. Angew Chem Int Ed, 2021, 60(12): 6807−6815.

[216] MAAT L, BEKKUM H, LUIJKX G, et al. Ether formation in the hydrogenolysis of hydroxymethylfurfural over palladium catalysts in alcoholic solution[J]. Heterocycles, 2009, 77(2): 1037−1044.

[217] CHIDAMBARAM M, BELL A T. A two-step approach for the catalytic conversion of glucose to 2, 5-dimethylfuran in ionic liquids[J]. Green Chem, 2010, 12(7): 1253−1262.

[218] SCHOLZ D, AELLIG C, HERMANS I. Catalytic transfer hydrogenation/hydrogenolysis for reductive upgrading of furfural and 5-(hydroxymethyl)furfural[J]. ChemSusChem, 2014, 7(1): 268−275.

[219] THANANATTHANACHON T, RAUCHFUSS T B. Efficient production of the liquid fuel 2, 5-dimethylfuran from fructose using formic acid as a reagent[J]. Angew Chem Int Ed, 2010, 49(37): 6616−6618.

[220] JAE J, ZHENG W, LOBO R F, et al. Production of dimethylfuran from hydroxymethylfurfural through catalytic transfer hydrogenation with ruthenium supported on carbon[J]. ChemSusChem, 2013, 6(7): 1158−1162.

[221] DATTA R, HENRY M. Lactic acid: Recent advances in products, processes and technologies-a review[J]. J Chem Technol Biotechnol, 2006, 81(7): 1119−1129.

[222] YARKOVA A V, NOVIKOV V T, GLOTOVA V N, et al. Vacuum effect on the lactide yield[J]. Procedia Chem, 2015, 15: 301−307.

[223] DUSSELIER M, VAN WOUWE P, DEWAELE A, et al. Shape-selective zeolite catalysis for bioplastics production[J]. Science, 2015, 349(6243): 78−80.

[224] CUNHA B L C, BAHÚ J O, XAVIER L F, et al. Lactide: Production routes, properties, and applications[J]. Bioengineering, 2022, 9(4): 1−21.

[225] BAICK I H, LUCIANI C V, PARK S Y, et al. Kinetics of reversible oligomerization of l-lactic acid with a $SnCl_2{\cdot}2H_2O$/p-toluenesulfonic acid catalyst[J]. Ind Eng Chem Res, 2012, 51(51): 16617−16625.

[226] ALBERTI C, ENTHALER S. Depolymerization of end-of-life poly(lactide) to lactide via zinc-catalysis[J]. ChemistrySelect, 2020, 5(46): 14759−14763.

[227] YOO D K, KIM D, LEE D S. Synthesis of lactide from oligomeric PLA: Effects of temperature, pressure, and catalyst[J]. Macromol Res, 2006, 14(5): 510−516.

[228] GHADAMYARI M, CHAEMCHUEN S, ZHOU K, et al. One-step synthesis of stereo-pure l, l lactide from l-lactic acid[J]. Catal Commun, 2018, 114: 33−36.

[229] LUO Z, CHAEMCHUEN S, ZHOU K, et al. Influence of lactic acid on the catalytic performance of MDABCO for ring-opening polymerization of l-lactide[J]. Appl Catal A: Gen, 2017, 546: 15−21.

[230] UPARE P P, LEE M, HWANG D W, et al. New heterogeneous Pb oxide catalysts for lactide production from an azeotropic mixture of ethyl lactate and water[J]. Catal Commun, 2014, 56: 179−183.

[231] HAMMOND C, CONRAD S, HERMANS I. Simple and scalable preparation of highly active Lewis acidic Sn-beta[J]. Angew Chem Int Ed, 2012, 51(47): 11736−11739.

[232] LUNT J. Large-scale production, properties and commercial applications of polylactic acid polymers[J]. Polym Degrad Stabil, 1998, 59(1/3): 145−152.

[233] EHSANI M, KHODABAKHSHI K, ASGARI M. Lactide synthesis optimization: Investigation of the temperature, catalyst and pressure effects[J]. e-Polymers, 2014, 14(5): 353−361.

[234] ZHANG Y, LIU J, ZHANG H, et al. Efficient synthesis of lactide with low racemization catalyzed by sodium bicarbonate and zinc lactate[J]. ACS Sustainable Chem Eng, 2020, 8(7): 2865−2873.

[235] XU Y, WANG Y, GUO Q, et al. Controlled synthesis of l-lactide using Sn-beta zeolite catalysts in a one-step route[J]. Ind Eng Chem Res, 2021, 60(37): 13534−13541.

[236] HOYDONCKX H E, DE VOS D E, CHAVAN S A, et al. Esterification and transesterification of renewable chemicals[J]. Top Catal, 2004, 27(1/4): 83−96.

[237] ZHANG H, LI H, YANG S. Biomass Conversion to Value-Added Chemicals[M]. Biomass Biofuels Biochemicals, 2020: 227−257.

[238] PEREIRA C S M, SILVA V M T M, RODRIGUES A E. Ethyl lactate as a solvent: Properties, applications and production processes-a review[J]. Green Chem, 2011, 13(10): 2658−2671.

[239] SANZ M T, MURGA R, BELTRÁN S, et al.

Autocatalyzed and ion-exchange-resin-catalyzed esterification kinetics of lactic acid with methanol[J]. Ind Eng Chem Res, 2002, 41(3): 512−517.

[240] PEREIRA C S M, PINHO S P, SILVA V M T M, et al. Thermodynamic equilibrium and reaction kinetics for the esterification of lactic acid with ethanol catalyzed by acid ion-exchange resin[J]. Ind Eng Chem Res, 2008, 47(5): 1453−1463.

[241] DMITRIEV G S, KHADZHIEV V I, NIKOLAEV S A, et al. Copper-containing catalysts in the liquid-phase hydrogenolysis of glycerol[J]. Pet Chem, 2020, 60(9): 1066−1072.

[242] LI X, WU D. Synthesis of Co-doped micro-mesoporous SAPO-11 zeolite for glycerol hydrogenolysis[J]. Korean J Chem Eng, 2020, 37(2): 216−223.

[243] LEENA M, SRINIVASAN S. A comparative study on thermal conductivity of TiO_2/ethylene glycol-water and TiO_2/propylene glycol-water nanofluids[J]. J Therm Anal Calorim, 2018, 131(2): 1987−1998.

[244] ADKINS H, PAVLIC A A. Hydrogenation of esters to alcohols over raney nickel. I[J]. J Am Chem Soc, 1947, 69(12): 3039−3041.

[245] BROADBENT H S, CAMPBELL G C, BARTLEY W J, et al. Rhenium and its compounds as hydrogenation catalysts. III. rhenium heptoxide[1, 2, 3][J]. J Org Chem, 1959, 24(12): 1847−1854.

[246] SIMONOV M N, ZAIKIN P A, SIMAKOVA I L. Highly selective catalytic propylene glycol synthesis from alkyl lactate over copper on silica: performance and mechanism[J]. Appl Catal B: Environ, 2012, 119−120: 340−347.

[247] PRIMO A, CONCEPCIÓN P, CORMA A. Synergy between the metal nanoparticles and the support for the hydrogenation of functionalized carboxylic acids to diols on Ru/ TiO_2[J]. Chem Commun, 2011, 47(12): 3613−3615.

[248] LUO G, YAN S, QIAO M, et al. Effect of promoters on the structures and properties of the Rub/γ-Al_2O_3 catalyst[J]. J Mol Catal A: Chem, 2005, 230(1/2): 69−77.

[249] CORTRIGHT R D, SANCHEZ-CASTILLO M, DUMESIC J A. Conversion of biomass to 1, 2-propanediol by selective catalytic hydrogenation of lactic acid over silica-supported copper[J]. Appl Catal B: Environ, 2002, 39(4): 353−359.

[250] ZHANG Z, JACKSON J E, MILLER D J. Aqueous-phase hydrogenation of lactic acid to propylene glycol[J]. Appl Catal A: Gen, 2001, 219(1/2): 89−98.

[251] LUO G, YAN S, QIAO M, et al. Effect of tin on Ru-b/γ-Al_2O_3 catalyst for the hydrogenation of ethyl lactate to 1, 2-propanediol[J]. Appl Catal A: Gen, 2004, 275(1/2): 95−102.

[252] XU P, QIU J, GAO C, et al. Biotechnological routes to pyruvate production[J]. J Biosci Bioeng, 2008, 105(3): 169−175.

[253] PAL D, KESHAV A, MAZUMDAR B, et al. Production and recovery of pyruvic acid: Recent advances[J]. J Inst Eng India Ser E, 2017, 98: 165−175.

[254] RETIEF D H, HARRIS B E, BRADLEY E L, et al. Pyruvic acid as an etching agent in clinical dentistry[J]. J Biomed Mater Res, 1985, 19(3): 335−348.

[255] HAYASHI H, SUGIYAMA S, KATAYAMA Y, et al. Liquid-phase oxidation of ethyl lactate to pyruvate over suspended oxide catalysts[J]. J Mol Catal, 1993, 83(1/2): 207−217.

[256] LIU K, HUANG X, PIDKO E A, et al. Photocatalytic decarboxylation of lactic acid by Pt/TiO_2[J]. Chem Commun, 2016, 52(78): 11634−11637.

[257] LOMATE S, BONNOTTE T, PAUL S, et al. Synthesis of pyruvic acid by vapour phase catalytic oxidative dehydrogenation of lactic acid[J]. J Mol Catal A: Chem, 2013, 377: 123−128.

[258] AI M, OHDAN K. Effects of differences in the structures of iron phosphates on the catalytic action in the oxidative dehydrogenation of lactic acid to pyruvic acid[J]. Appl Catal A: Gen, 1997, 165(1/2): 461−465.

[259] AI M. Catalytic activity of palladium-doped iron phosphate in the oxidative dehydrogenation of lactic acid to pyruvic acid[J]. Appl Catal A: Gen, 2002, 232(1/2): 1−6.

[260] AI M. Catalytic activity of iron phosphate doped with a small amount of molybdenum in the oxidative dehydrogenation of lactic acid to pyruvic acid[J]. Appl Catal A: Gen, 2002, 234(1/2): 235−243.

[261] LIU K, HUANG X, PIDKO E A, et al. MoO_3-TiO_2 synergy in oxidative dehydrogenation of lactic acid to pyruvic acid[J]. Green Chem, 2017, 19(13): 3014−3022.

[262] TSVIK L, STEINER B, HERZOG P, et al. Flavin mononucleotide-dependent l-lactate dehydrogenases: Expanding the toolbox of enzymes for l-lactate biosensors[J]. ACS Omega, 2022, 7(45): 41480−41492.

[263] GAO C, MA C, XU P. Biotechnological routes based on lactic acid production from biomass[J]. Biotechnol Adv, 2011, 29(6): 930−939.

[264] MA C Q, XU P, DOU Y M, et al. Highly efficient conversion of lactate to pyruvate using whole cells of acinetobacter sp[J]. Biotechnol Prog, 2003, 19(6): 1672−1676.

[265] GU J, XU P, QU Y. A biocatalyst for pyruvate preparation from DL-lactate: Lactate oxidase in a pseudomonas sp[J]. J Mol Catal B-Enzym, 2002, 18(4/6): 299−305.

[266] DIAS A S, PILLINGER M, VALENTE A A. Liquid phase dehydration of D-xylose in the presence of Keggin-type heteropolyacids[J]. Appl Catal A: Gen, 2005, 285(1/2): 126−131.

[267] ZHANG J, LI D-N, YUAN H-R, et al. Advances on the catalytic hydrogenation of biomass-derived furfural and 5-hydroxymethylfurfural[J]. J Fuel Chem Technol, 2021, 49(12): 1752−1766.

[268] ZHENG H-Y, ZHU Y-L, TENG B-T, et al. Towards understanding the reaction pathway in vapour phase hydrogenation of furfural to 2-methylfuran[J]. J Mol Catal A: Chem, 2006, 246(1/2): 18−23.

[269] RAO R, DANDEKAR A, BAKER R T K, et al. Properties of copper chromite catalysts in hydrogenation reactions[J]. J Catal, 1997, 171(2): 406−419.

[270] SEO G, CHON H. Hydrogenation of furfural over copper-containing catalysts[J]. J Catal, 1981, 67(2): 424−429.

[271] VAIDYA P D, MAHAJANI V V. Kinetics of liquid-phase hydrogenation of furfuraldehyde to furfuryl alcohol over a pt/c catalyst[J]. Ind Eng Chem Res, 2003, 42: 3(17)881−3885.

[272] KIJEŃSKI J, WINIAREK P, PARYJCZAK T, et al. Platinum deposited on monolayer supports in selective hydrogenation of furfural to furfuryl alcohol[J]. Appl Catal A: Gen, 2002, 233(1/2): 171−182.

[273] LIU L, LOU H, CHEN M. Selective hydrogenation of furfural over Pt based and Pd based bimetallic catalysts supported on modified multiwalled carbon nanotubes (MWNT)[J]. Appl Catal A: Gen, 2018, 550: 1−10.

[274] LESIAK M, BINCZARSKI M, KARSKI S, et al. Hydrogenation of furfural over Pd-Cu/ Al_2O_3 catalysts. the role of interaction between palladium and copper on determining catalytic properties[J]. J Mol Catal A: Chem, 2014, 395: 337−348.

[275] MARINELLI T B L W, PONEC V, RAAB C G, et al. Furfural-hydrogen reactions, manipulation of actmty and selectmty of the catalyst[J]. Stud Surf Sci Catal, 1993, 78: 195−202.

[276] REDDY B M, REDDY G K, RAO K N, et al. Silica supported transition metal-based bimetallic catalysts for vapour phase selective hydrogenation of furfuraldehyde[J]. J Mol Catal A: Chem, 2007, 265(1/20): 276−282.

[277] THONGRATKAEW S, LUADTHONG C, KIATPHUENGPORN S, et al. Cu-Al spinel-oxide catalysts for selective hydrogenation of furfural to furfuryl alcohol[J]. Catal Today, 2021, 367: 177−188.

[278] KAR S, ZHOU Q-Q, BEN-DAVID Y, et al. Catalytic furfural/5-hydroxymethyl furfural oxidation to furoic acid/furan-2, 5-dicarboxylic acid with H_2 production using alkaline water as the formal oxidant[J]. J Am Chem Soc, 2022, 144(3): 1288−1295.

[279] GUPTA K, RAO R K, DWIVEDI A D, et al. Catalytic aerial oxidation of biomass-derived furans to furan carboxylic acids in water over bimetallic nickel-palladium alloy nanoparticles[J]. ChemCatChem, 2017, 9(14): 2760−2767.

[280] REN Z, YANG Y, WANG S, et al. Pt atomic clusters catalysts with local charge transfer towards selective oxidation of furfural[J]. Appl Catal B: Environ, 2021, 295: 120290.

[281] DANIEL S, SUBBIAH V P, RAMAGANTHAN B, et al. Upgrading the strategy of multistage torrefaction liquid by the selective oxidation reaction route using a reusable MgO-based Au/Al_2O_3 catalyst[J]. Energy Fuels, 2021, 35(19): 15831−15841.

[282] PAPANIKOLAOU G, LANZAFAME P, PERATHONER S, et al. High performance of Au/ZTC based catalysts for the selective oxidation of bio-derivative furfural to 2-furoic acid[J]. Catal Commun, 2021, 149: 106234.

[283] FERRAZ C P, ZIELIŃSKI M, PIETROWSKI M, et al. Influence of support basic sites in green oxidation of biobased substrates using Au-promoted catalysts[J]. ACS Sustainable Chem Eng, 2018, 6(12): 16332−16340.

[284] ZHOU H, XU H, WANG X, et al. Convergent production of 2, 5-furandicarboxylic acid from biomass and CO_2[J]. Green Chem, 2019, 21(11): 2923−2927.

[285] TIAN Q, SHI D, SHA Y. CuO and Ag_2O/CuO catalyzed oxidation of aldehydes to the corresponding carboxylic acids by molecular oxygen[J]. Molecules, 2008, 13(4): 948−957.

[286] YU X, ZUO M, JIA W L, et al. Insight into the α-MnO_2 boosts concentrated furfural or xylose conversion to furoic acid over 1, 4-dioxane-H_2O mixed solvent[J]. Biomass Bioenergy, 2022, 167: 106642.

[287] WU X, GUO H Q, JIA L T, et al. Effect of MnO_2 crystal type on the oxidation of furfural to furoic acid[J]. Catalysts, 2023, 13(4): 663.

[288] NOCITO F, DITARANTO N, LINSALATA D, et al. Selective aerobic oxidation of furfural into furoic acid over a highly recyclable MnO_2 @CeO_2 core-shell oxide: The role of the morphology of the catalyst[J]. ACS Sustainable Chem Eng, 2022, 10(26): 8615−8623.

[289] LIU Q, SUN Y, ZENG X, et al. Efficient oxidation of furfural to furancarboxylic acid over CuO-$MnCO_3$ catalyst[J]. ChemistrySelect, 2023, 8(20): e202300450.

[290] FELLAH M F. Direct decarbonylation of furfural to furan: A density functional theory study on Pt-graphene[J]. Appl Surf Sci, 2017, 405: 395−404.

[291] ZHANG Z, LIU R Z, HUANG L, et al. Understanding the reaction route of selectively converting furfural to furan over the alkali-induced Co-Mo_2C heterostructure[J]. Chem Eng J, 2023, 466: 143237.

[292] WANG Z, FU Z, LIN W, et al. In-situ hydrodeoxygenation of furfural to furans over supported Ni catalysts in aqueous solution[J]. Korean J Chem Eng, 2019, 36(8): 1235−1242.

[293] JIMÉNEZ-GÓMEZ C P, CECILIA J A, GARCÍA-SANCHO C, et al. Selective production of furan from gas-phase furfural decarbonylation on Ni-MgO catalysts[J]. ACS Sustainable Chem Eng, 2019, 7(8): 7676−7685.

[294] YU X, MIAO Z, WANG H Q et al. Insight into the catalytic mechanism of core-shell structured Ni/Ni-N/CN catalyst towards the oxidation of furfural to furancarboxylic acid[J]. Fuel, 2022, 317: 123579.

[295] BHOGESWARARAO S, SRINIVAS D. Catalytic conversion of furfural to industrial chemicals over supported Pt and Pd catalysts[J]. J Catal, 2015, 327: 65−77.

[296] MASHKINA A V. A catalytic process for preparation of thiophene from furan and hydrogen sulfide[J]. Russ J Appl Chem, 2011, 84(7): 1223−1228.

[297] MASHKINA A V, KHAIRULINA L N. Activity of catalysts in thiophene synthesis from furan and hydrogen sulfide[J]. Kinet Catal, 2008, 49(2): 245−252.

[298] PUSHKAREV V V, MUSSELWHITE N, AN K, et al. High structure sensitivity of vapor-phase furfural decarbonylation/hydrogenation reaction network as a function of size and shape of Pt nanoparticles[J]. Nano Lett, 2012, 12(10): 5196−5201.

[299] GUNAWAN R, CAHYADI H S, INSYANI R, et al. Density functional theory investigation of the conversion of 5-(hydroxymethyl)furfural into 2, 5-dimethylfuran over the Pd(111), Cu(111), and Cu_3Pd(111) surfaces[J]. J Phys Chem C, 2021, 125(19): 10295−10317.

[300] AHORSU R, CONSTANTI M, MEDINA F. Recent impacts of heterogeneous catalysis in biorefineries[J]. Ind Eng Chem Res, 2021, 60(51): 18612−18626.

[301] CHEN S-H, TSENG Y-C, YANG S-C, et al. Investigating hydrogenation and decarbonylation in vapor-phase furfural hydrotreating over Ni/SiO_2 catalysts: Propylene production[J]. Appl Catal A: Gen, 2021, 613: 118020.

[302] ISHIDA T, KUME K, KINJO K et al. Efficient decarbonylation of furfural to furan catalyzed by zirconia-supported palladium clusters with low atomicity[J]. ChemSusChem, 2016, 9: 3441−3447.

[303] MARISCAL R, MAIRELES-TORRES P, OJEDA M, et al. Furfural: a renewable and versatile platform molecule for the synthesis of chemicals and fuels[J]. Energy Environ Sci, 2016, 9(24): 1144−1189.

[304] KUTERASIŃSKI Ł, ROJEK W, GACKOWSKI M, et al. Sonically modified hierarchical FAU-type zeolites as active catalysts for the production of furan from furfural[J]. Ultrason Sonochem, 2020, 60: 104785.

[305] KUTERASIŃSKI Ł, SMOLIŁO-UTRATA M, KAIM J, et al. On the role of protonic acid sites in Cu loaded FAU31 zeolite as a catalyst for the catalytic transformation of furfural to furan[J]. Molecules, 2021, 26(7): 2−22.

[306] WANG C, LIU Z Q, WANG L, et al. Importance of zeolite wettability for selective hydrogenation of furfural over Pd@zeolite catalysts[J]. ACS Catal, 2018, 8(1): 474−481.

[307] WANG C, Wang L, ZHANG J, et al. Product selectivity controlled by zeolite crystals in biomass hydrogenation over a palladium catalyst[J]. J Am Chem Soc, 2016, 138(25): 7880−7883.

[308] LI C, ZHAO X, WANG A, et al. Catalytic transformation of lignin for the production of chemicals and fuels[J]. Chem Rev, 2015, 115(21): 11559−11624.

[309] BALAT M. Production of bioethanol from lignocellulosic materials via the biochemical pathway: A review[J]. Energy Convers Manag, 2011, 52(2): 858−875.

[310] LOZANO P, SIMÓN A, GARCÍA L, et al. Influence of the Ni-Co/Al-Mg catalyst loading in the continuous aqueous phase reforming of the bio-oil aqueous fraction[J]. Processes, 2021, 9(1): 1−17.

[311] VAIDYA P D, LOPEZ-SANCHEZ J A. Review of hydrogen production by catalytic aqueous-phase reforming[J]. ChemistrySelect, 2017, 2: 6563−6576.

[312] REZAEI P S, SHAFAGHAT H, DAUD W M A W. Production of green aromatics and olefins by catalytic cracking of oxygenate compounds derived from biomass pyrolysis: A review[J]. Appl Catal A: Gen, 2014, 469: 490−511.

[313] XU Z-X, CHENG J-L, SONG H, et al. Production of bio-fuel from plant oil asphalt via pyrolysis[J]. J Energy Inst, 2020, 93(5): 1763−1772.

[314] MEILE K, JERMOLAJEVA A, VOLKOVA E, et al. Solid-phase extraction of the aromatic by-products obtained by fast pyrolysis of pretreated lignocellulose[J]. Chem Eng Technol, 2023, 46(6): 1212−1217.

[315] RATNASARI D K, YANG W, JÖNSSON P G. Kinetic study of an H-ZSM-5/Al-MCM-41 catalyst mixture and its application in lignocellulose biomass pyrolysis[J]. Energy Fuels, 2019, 33(6): 5360−5367.

[316] YU W, TANG Y, MO L Y, et al. One-step hydrogenation-esterification of furfural and acetic acid over bifunctional Pd catalysts for bio-oil upgrading[J]. Bioresour Technol, 2011, 102(17): 8241−8246.

[317] THEGARID N, FOGASSY G, SCHUURMAN Y, et al. Second-generation biofuels by co-processing catalytic pyrolysis oil in FCC units[J]. Appl Catal B: Environ, 2014, 145: 161−166.

[318] ZHANG H, XIAO R, HUANG H, et al. Comparison of non-catalytic and catalytic fast pyrolysis of corncob in a fluidized bed reactor[J]. Bioresour Technol, 2009, 100(3): 1428−1434.

[319] YANG Y, XU X, HE H, et al. The catalytic hydrodeoxygenation of bio-oil for upgradation from lignocellulosic biomass[J]. Int J Biol Macromol, 2023, 242: 124773.

[320] VITOLO S, BRESCI B, SEGGIANI M, et al. Catalytic upgrading of pyrolytic oils over HZSM-5 zeolite: behaviour of the catalyst when used in repeated upgrading-regenerating cycles[J]. Fuel, 2001, 80(1): 17−26.

[321] WILLIAMS P T, HORNE P A. The influence of catalyst regeneration on the composition of zeolite-upgraded biomass pyrolysis oils[J]. Fuel, 1995, 74(12): 1839−1851.

[322] ZHENG Y, WANG F, YANG X Q, et al. Study on aromatics production via the catalytic pyrolysis vapor upgrading of biomass using metal-loaded modified H-ZSM-5[J]. J Anal Appl Pyrolysis, 2017, 126: 169−179.

[323] WIDAYATNO W B, GUAN G Q, RIZKIANA J, et al. Upgrading of bio-oil from biomass pyrolysis over Cu-modified β-zeolite catalyst with high selectivity and stability[J]. Appl Catal B: Environ, 2016, 186: 166−172.

[324] HU S, LUO X, LI Y. Polyols and polyurethanes from the liquefaction of lignocellulosic biomass[J]. ChemSusChem, 2014, 7(1): 66−72.

[325] FUNKE A, ZIEGLER F. Hydrothermal carbonization of biomass: A summary and discussion of chemical mechanisms for process engineering[J]. Biofuels Bioprod Bioref, 2010, 4(2): 160−177.

[326] GOLLAKOTA A R K, KISHORE N, GU S. A review on hydrothermal liquefaction of biomass[J]. Renewable Sustainable Energy Rev, 2018, 81: 1378−1392.

[327] ELLIOTT D C. Historical developments in hydroprocessing bio-oils[J]. Energy Fuels, 2007, 21(3): 1792−1815.

[328] KUMAR S, LANGE J-P, VAN ROSSUM G, et al. Liquefaction of lignocellulose in fluid catalytic cracker feed: A process concept study[J]. ChemSusChem, 2015, 8(23): 4086−4094.

[329] AN ROSSUM G, ZHAO W, CASTELLVI BARNES M, et al. Liquefaction of lignocellulosic biomass: Solvent, process parameter, and recycle oil screening[J]. ChemSusChem, 2014, 7(1): 253−259.

[330] XU Z-X, CHENG J-H, HE Z-X, et al. Hydrothermal liquefaction of cellulose in ammonia/water[J]. Bioresour Technol, 2019, 278: 311−317.

[331] SHAHBEIK H, PANAHI H K S, DEHHAGHI M, et al. Biomass to biofuels using hydrothermal liquefaction: a comprehensive review[J]. Renewable Sustainable Energy Rev, 2024, 189: 113976.

[332] BECKMAN D, ELLIOTT D C. Comparisons of the yields and properties of the oil products from direct thermochemical biomass liquefaction processes[J]. Can J Chem Eng, 1985, 63(1): 99−104.

[333] CHIARAMONTI D, PRUSSI M, BUFFI M, et al. Review and experimental study on pyrolysis and hydrothermal liquefaction of microalgae for biofuel production[J]. Appl Energy, 2017, 185: 963−972.

[334] PANISKO E, WIETSMA T, LEMMON T, et al. Characterization of the aqueous fractions from hydrotreatment and hydrothermal liquefaction of lignocellulosic feedstocks[J]. Biomass Bioenergy, 2015, 74: 162−171.

[335] PIPITONE G, ZOPPI G, PIRONE R, et al. A critical review on catalyst design for aqueous phase reforming[J]. Int J Hydrog Energy, 2022, 47(1): 151−180.

[336] DAVDA R R, SHABAKER J W, HUBER G W, et al. A review of catalytic issues and process conditions for renewable hydrogen and alkanes by aqueous-phase reforming of oxygenated hydrocarbons over supported metal catalysts[J]. Appl Catal B: Environ, 2005, 56(1/2): 171−186.

[337] JUSTICIA J, BAEZA J A, CALVO L, et al. Valorization to hydrogen of bio-oil aqueous fractions from lignocellulosic biomass pyrolysis by aqueous phase reforming over Pt/C catalyst[J]. Chem Eng J, 2023, 477: 146860.

[338] CORONADO I, STEKROVA M, REINIKAINEN M, et al. A review of catalytic aqueous-phase reforming of oxygenated hydrocarbons derived from biorefinery water fractions[J]. Int J Hydrog Energy, 2016, 41(26): 11003−11032.

[339] MORALES-MARÍN A, AYASTUY J L, IRIARTE-VELASCO U, et al. Nickel aluminate spinel-derived catalysts for the aqueous phase reforming of glycerol: effect of reduction temperature[J]. Appl Catal B: Environ, 2019, 244: 931−945.

[340] CORONADO I, PITÍNOVÁM, KARINEN R, et al. Aqueous-phase reforming of Fischer-Tropsch alcohols over nickel-based catalysts to produce hydrogen: product distribution and reaction pathways[J]. Appl Catal A: Gen, 2018, 567: 112−121.

[341] ALONSO D M, BOND J Q, DUMESIC J A. Catalytic conversion of biomass to biofuels[J]. Green Chem, 2010, 12(9): 1493−1513.

[342] REMÓN J, GIMÉNEZ J R, VALIENTE A, et al. Production of gaseous and liquid chemicals by aqueous phase reforming of crude glycerol: Influence of operating conditions on the process[J]. Energy Convers Manag, 2016, 110: 90−112.

[343] GARCÍA L, VALIENTE A, OLIVA M, et al. Influence of operating variables on the aqueous-phase reforming of glycerol over a Ni/Al coprecipitated catalyst[J]. Int J Hydrog Energy, 2018, 43(45): 20392−20407.

[344] SERETIS A, TSIAKARAS P. A thermodynamic analysis of hydrogen production via aqueous phase reforming of glycerol[J]. Fuel Process Technol, 2015, 134: 107−115.

[345] LUO N, ZHAO X, CAO F, et al. Thermodynamic study on hydrogen generation from different glycerol reforming processes[J]. Energy Fuels, 2007, 21(6): 3505−3512.

[346] PUTRA R D D, TRAJANO H L, LIU S D, et al. In-situ glycerol aqueous phase reforming and phenol hydrogenation over raney Ni®[J]. Chem Eng J, 2018, 350: 181−191.

[347] SERETIS A, TSIAKARAS P. Hydrogenolysis of glycerol to propylene glycol by in situ produced hydrogen from aqueous phase reforming of glycerol over SiO_2-Al_2O_3 supported nickel catalyst[J]. Fuel Process Technol, 2016, 142: 135−146.

[348] DUARTE H A, SAD M E, APESTEGUÍA C R. Aqueous phase reforming of sorbitol on Pt/Al_2O_3: Effect of metal loading and reaction conditions on H_2 productivity[J]. Int J Hydrog Energy, 2016, 41(39): 17290−17296.

[349] ARANDIA A, CORONADO I, REMIRO A, et al. Aqueous-phase reforming of bio-oil aqueous fraction over nickel-based catalysts[J]. Int J Hydrog Energy, 2019, 44(26): 13157−13168.

[350] HE Z-H, JIANG C-S, WANG Z-Y, et al. Catalytic hydrodeoxygenation of biomass-derived oxygenates to bio-fuels over Co-based bimetallic catalysts[J]. Sustainable Energy Fuels, 2020, 4(9): 4558−4569.

[351] RAHMAN M M. H_2 production from aqueous-phase reforming of glycerol over Cu-Ni bimetallic catalysts supported on carbon nanotubes[J]. Int J Hydrog Energy, 2015, 40(43): 14833−14844.

[352] HUBER G W, SHABAKER J W, DUMESIC J A. Raney Ni-Sn catalyst for H_2 production from biomass-derived hydrocarbons[J]. Science, 2003, 300(5628): 2075−2077.

[353] SHABAKER J W, HUBER G W, DUMESIC J A. Aqueous-phase reforming of oxygenated hydrocarbons over Sn-modified Ni catalysts[J]. J Catal, 2004, 222(1): 180−191.

[354] HUBER G W, SHABAKER J W, EVANS S T, et al. Aqueous-phase reforming of ethylene glycol over supported Pt and Pd bimetallic catalysts[J]. Appl Catal B: Environ, 2006, 62(3/4): 226−235.

[355] KIM M-C, KIM T-W, KIM H J, et al. Aqueous phase reforming of polyols for hydrogen production using supported Pt-Fe bimetallic catalysts[J]. Renewable Energy, 2016, 95: 396−403.

[356] SOARES A V-H, PEREZ G, PASSOS F B. Alumina supported bimetallic Pt-Fe catalysts applied to glycerol

hydrogenolysis and aqueous phase reforming[J]. Appl Catal B: Environ, 2016, 185: 77−87.
[357] JEON S, PARK Y M, SARAVANAN K, et al. Aqueous phase reforming of ethylene glycol over bimetallic platinum-cobalt on ceria-zirconia mixed oxide[J]. Int J Hydrog Energy, 2017, 42(15): 9892−9902.
[358] NEIRA D'ANGELO M F, ORDOMSKY V, VAN DER SCHAAF J, et al. Continuous hydrogen stripping during aqueous phase reforming of sorbitol in a washcoated microchannel reactor with a Pt-Ru bimetallic catalyst[J]. Int J Hydrog Energy, 2014, 39(31): 18069−18076.
[359] ALVEAR M, AHO A, SIMAKOVA I L, et al. Aqueous phase reforming of alcohols over a bimetallic Pt-Pd catalyst in the presence of formic acid[J]. Chem Eng J, 2020, 398: 125541.
[360] HE C, ZHENG J W, WANG K, et al. Sorption enhanced aqueous phase reforming of glycerol for hydrogen production over Pt-Ni supported on multi-walled carbon nanotubes[J]. Appl Catal B: Environ, 2015, 162: 401−411.
[361] CIFTCI A, LIGTHART D A J M, HENSEN E J M. Influence of Pt particle size and Re addition by catalytic reduction on aqueous phase reforming of glycerol for carbon-supported Pt(Re) catalysts[J]. Appl Catal B: Environ, 2015, 174−175: 126−135.
[362] PARTRIDGE I. Cost comparisons for wind and thermal power generation[J]. Energy Policy, 2018, 112: 272−279.
[363] WATT G D. A new future for carbohydrate fuel cells[J]. Renew Energy, 2014, 72: 99−104.
[364] YI Y, LEE B D, KIM S K, et al. Performance of porous carbon as catalyst support for anode from rice husk in a direct methanol fuel cell[J]. Int J Electrochem Sci, 2016, 11(7): 5909−5923.
[365] UL HASSAN N, GANESAN P, LANDO A A, et al. Stable, high-performing bifunctional electrodes for anion exchange membrane-based unitized regenerative fuel cells[J]. J Power Sources, 2022, 541: 231599.
[366] YELEGEN N, KÜMÜK B, KAPLAN R N, et al. Numerical and experimental studies on unitized regenerative proton exchange membrane fuel cell[J]. Int J Hydrog Energy, 2023, 48(35): 12969−12981.
[367] UL HASSAN N, MANDAL M, ZULEVI B, et al. Understanding and improving anode performance in an alkaline membrane electrolyzer using statistical design of experiments[J]. Electrochim Acta, 2022, 409: 140001.
[368] GUARNIERI M, ALOTTO P, MORO F. Modeling the performance of hydrogen-oxygen unitized regenerative proton exchange membrane fuel cells for energy storage[J]. J Power Sources, 2015, 297: 23−32.
[369] LIM A, KIM H J, HENKENSMEIER D, et al. A study on electrode fabrication and operation variables affecting the performance of anion exchange membrane water electrolysis[J]. J Ind Eng Chem, 2019, 76: 410−418.
[370] LU X, XUAN J, LEUNG D Y C, et al. A switchable pH-differential unitized regenerative fuel cell with high performance[J]. J Power Sources, 2016, 314: 76−84.
[371] GABBASA M, SOPIAN K, FUDHOLI A, et al. A review of unitized regenerative fuel cell stack: Material, design and research achievements[J]. Int J Hydrog Energy, 2014, 39(31): 17765−17778.
[372] WANG Y, LEUNG D Y C, XUAN J, et al. A review on unitized regenerative fuel cell technologies, part B: Unitized regenerative alkaline fuel cell, solid oxide fuel cell, and microfluidic fuel cell[J]. Renewable Sustainable Energy Rev, 2017, 75: 775−795.
[373] MANDAL M, HUANG G, KOHL P A. Anionic multiblock copolymer membrane based on vinyl addition polymerization of norbornenes: Applications in anion-exchange membrane fuel cells[J]. J Membr Sci, 2019, 570-571: 394−402.
[374] ZHENG X, LU Y H, LI W T, et al. Alkali-resistant poly (vinyl benzyl chloride) based anion exchange membranes with outstanding flexibility and high hydroxide ion conductivity[J]. Int J Hydrog Energy, 2024, 50: 854−869.
[375] YE Y, HE H B, ZHOU X Y, et al. Composite anion-exchange-membranes: Construction of percolated structures and exponential improvement of ionic conductivity[J]. Compos Commun, 2024, 46: 101833.

糖类化合物催化转化的机遇与挑战: 从平台分子到能源与化学品

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摘　要: 糖类化合物源于储量丰富的生物质可再生资源, 其向精细平台化合物与燃料的转化, 对满足社会可持续发展的能源与化学品需求具有重要意义。该转化过程高度依赖催化作用, 如 Brønsted 酸和 Lewis 酸等催化活性位点。本综述围绕不同催化剂作用下各类糖类(单糖、二糖及多糖)向高附加值化合物的转化展开系统研究, 详细阐述了糖类化合物通过水解、异构化、脱水等反应生成目标产物(如 5-羟甲基糠醛、乳酸、糠醛)的路径与机理。此外, 本综述还探讨了这些平台化合物后续衍生化及其在生物燃料和电池等能源领域的应用前景。最后, 总结了当前研究面临的挑战, 并对未来低成本、高性能催化体系的发展方向进行了展望。

关键词: 糖类化合物; 催化转化; 精细化学品; 生物燃料

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