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Combining microbial production with chemical upgrading

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This review presents developments in the chemical processing of fermentation-derived compounds, focusing on ethanol, lactic acid, 2,3-butanediol and the acetone-butanol-ethanol mixture. We examine pathways from these products to biologically-derived drop-in fuels, polymers, as well as commodity chemicals, highlighting the role of homogeneous and heterogeneous catalysts in the development of green processes for the production of fuels and high-value-added compounds from biomass.

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Introduction

The increase of the temperature of the planet over the last few decades has been unequivocally attributed to the increase of the atmospheric concentration of CO₂ [1]. Mitigation of the negative consequences requires the reduction of CO₂ emissions [2]. This can be achieved by the use of alternative sources of energy for transportation and energy generation [2]. Among these, plant biomass is the most plentiful and widely used source of energy.

Utilization of plant biomass products as fuel has taken many forms, including direct combustion, reforming or gasification for the production of syngas [3]. Chemical treatment of biomass to obtain platform molecules, such as 5-hydroxymethylfurfural and furfural has also drawn considerable attention [3,4,5]. Fermentation processes to produce ethanol as a gasoline component have been very successful and currently produce about 9% of the gasoline

pool in the US [6] and up to 27.5% of the gasoline pool in Brazil [7].

The increased production and consequent price reduction of ethanol, as well as the upper limit in its percentage in gasoline in the U.S. — the 10% blend wall, makes it an attractive feedstock for the production of higher biofuels and chemicals. In addition to ethanol, recent work has highlighted the potential of other microbial fermentation products as chemicals and fuel precursors. This review will focus on the chemical processes that transform these fermentation products to fuels and commodity chemicals.

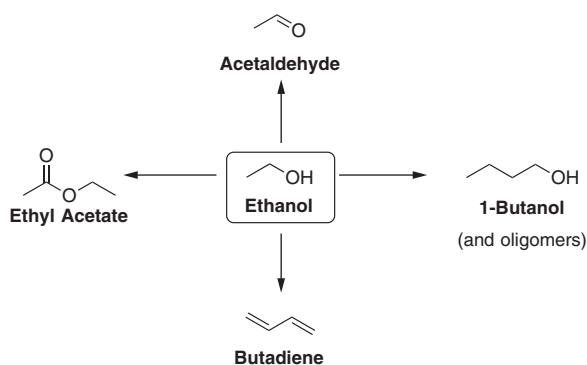
Ethanol

Ethanol is currently the most important chemical produced from fermentation. Beyond its use as fuel, it is used as a feedstock for the chemical industry, to produce ethyl acetate, acetaldehyde and other chemicals (Scheme 1). Recently, it has also drawn attention as a potential feedstock for the production of butadiene, because of interest in green polymers from butadiene, and because of the diminution of butadiene available from the traditional source, naphtha cracking, due to the increase in availability of shale gas [8,9]. The production of acetaldehyde and ethyl acetate from ethanol are widely known and practiced industrial processes, and so this review shall not cover them and shall instead focus on butanol and butadiene.

Of significant interest in the context of renewable fuels and chemicals is the dimerization of ethanol to 1-butanol. 1-Butanol is miscible with gasoline at higher proportions compared to ethanol and has higher energy density. It can be produced from ethanol via the Guerbet reaction, which proceeds via dehydrogenation of ethanol to acetaldehyde, which then couples with itself to form aldol. Aldol is then dehydrated to crotonaldehyde and hydrogenated to 1-butanol [10]. The reaction is usually carried out in the gas phase and is catalyzed by basic or bifunctional acidic-basic metal oxides, such as MgO, Mg-Zr-O [11], Na-Zr-O [12], Mg-Al-O [13] and Mg-Fe-O [13]. Strontium [14] and calcium [15] hydroxyl phosphates (hydroxyapatites) are selective and active catalysts for the reaction. Moreover, addition of transition metals, such as Pd or Cu, as co-catalysts tend to increase the rates by accelerating the dehydrogenation step [10,16].

Production of butadiene from ethanol can take place via a single-step or two-step process. In the former, also known as the Lebedev or Russian process, ethanol is fed over an

Scheme 1



Common pathways for ethanol utilization.

MgO/SiO₂ catalyst [8,17]. In the latter process, also known as the Ostromislensky or American process, a portion of ethanol is first dehydrogenated to acetaldehyde and the mixture is fed over a Ta₂O₅/SiO₂ or ZrO₂/SiO₂ catalyst at temperatures of 300–325 °C [18,19]. More recently, Makshina *et al.* screened a number of transition metal additives to a MgO/SiO₂ catalyst in the single-step process and showed that the yield to butadiene reached a maximum of about 55% using Cu-promoted and Ag-promoted catalysis [20]. Angelici *et al.* proposed that the increases observed over Cu-MgO/SiO₂ catalyst compared to MgO/SiO₂ catalysts resulted from an increase in acetaldehyde formation rate [21]. They also highlighted the importance of the preparation method [21,22] and showed that the butadiene yields were strongly influenced by the balance of acid and base sites on the catalyst [22].

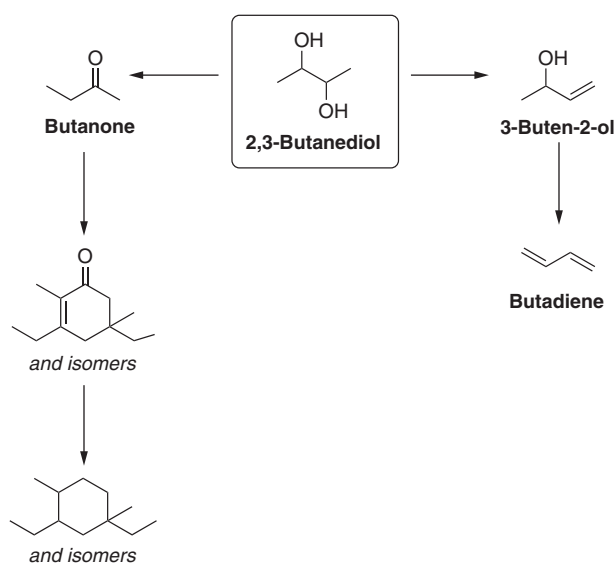
Ethanol conversion to butadiene has also been reported over Zr-substituted zeolites. More specifically, Sushkevich *et al.* reported that Zr-substituted into zeolite Beta gave much higher yields for the reaction compared to Zr-MCM-41 and ZrO₂/SiO₂ [23,24*], and attributed the activity to the predominance of Lewis acidic Zr open sites in the samples [23].

Butanediol

Extensive literature has covered the production of 2,3-butanediol by means of fermentation from the early 20th century to the present [25]. Beyond its niche applications as a specialty chemical [26], interest in 2,3-butanediol has been driven by the potential uses of its dehydration products, butanone and butadiene (Scheme 2).

Dehydration of 2,3-butanediol can be carried out at high yields over a range of catalysts. Selective butadiene formation was reported by Duan *et al.* over Sc₂O₃ [27*]. After screening a number of rare earth oxides, they found that 88% selectivity at quantitative conversion could be achieved at 411 °C. Milder conditions and lower

Scheme 2



Pathways to fuels and chemicals from 2,3-butanediol.

residence times tend to yield 3-buten-2-ol [27*], as do more basic catalysts, such as ZrO₂ [28,29]. Alkaline earth promotion of ZrO₂ tends to further increase selectivity for 3-buten-2-ol [28].

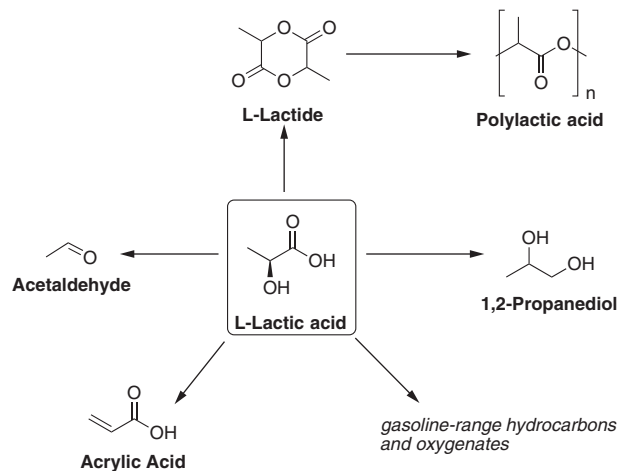
On the other hand, dehydration of 2,3-butanediol to 2-butanone has been widely practiced. Mineral acids have traditionally been used as catalysts [30], but their corrosiveness and difficulty in wastewater treatment has motivated the search for heterogeneous catalysts for this transformation. Zhang *et al.* reported highly selective (up to 78%) conversion to butanone over boron-modified H-ZSM-5 zeolites [31], while Multer *et al.* reported selectivity of 90% over unmodified H-ZSM-5 [32]. In both cases, the main side product was 2-methyl-propanal, which results from a 1,2-methyl shift.

Beyond its uses as a solvent and potential fuel, butanone has recently been trimerized to form fuel molecules. This transformation was achieved over basic catalysts, such as calcined hydrotalcites, via a solid-base-catalyzed aldol condensation sequence that afforded mixtures of unsaturated ketones and aromatic products. The product mixture was subsequently hydrodeoxygenated over a Pt/NbOPO₄ catalyst to alkane products, suitable for mixing with jet fuel [33,34*].

Lactic acid

Over the last twenty years, production of lactic acid has shifted from the traditional chemical routes to completely fermentative routes [35]. As a result a wide range of derivatives have been synthesized from lactic acid, from

Scheme 3



Lactic acid as a platform molecule.

green polymers to solvents. Mäki-Arvela *et al.* have reviewed the production and reactions of lactic acid [36].

The most important derivative of lactic acid is polylactic acid (PLA), a biodegradable polymer (Scheme 3). PLA is normally produced via ring-opening polymerization of dilactide, the dimer produced by self-condensation of lactic acid [35,37]. This is most commonly catalyzed by Sn [38] or, less commonly, Al alkoxides [18,20]. Recently,

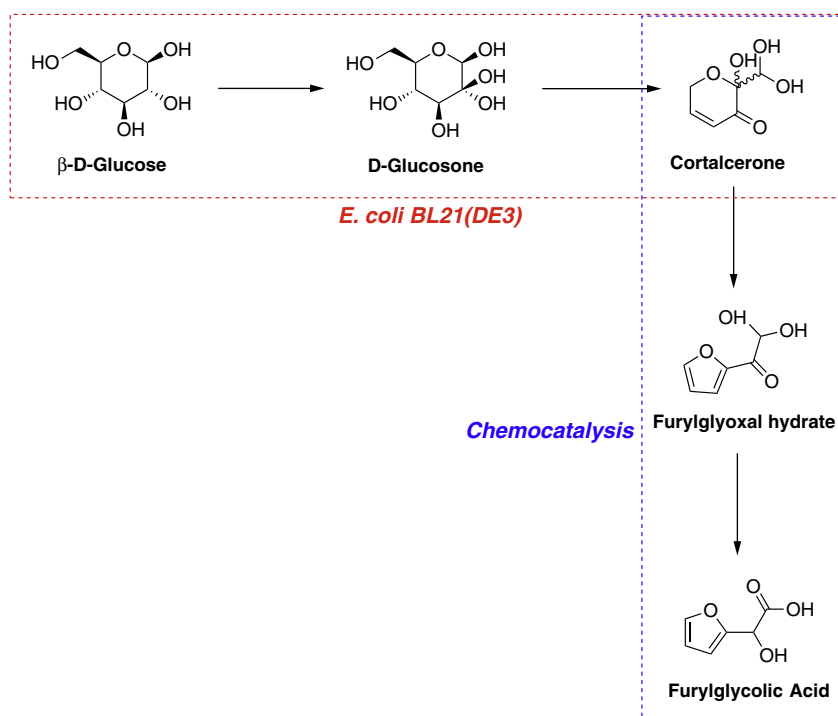
multinuclear Mg complexes have been reported as active and biocompatible catalysts for this polymerization [39].

In addition to the biocompatible catalysis, several investigators have sought to improve the properties of PLA. Among others, PLA block copolymers with isoprene [40], isobutylene [41], and ϵ -decalactone [42] have been reported to improve on the mechanical properties of PLA. However, isoprene and isobutylene are normally derived from petroleum, while ϵ -decalactone is prohibitively expensive. Recently, Xiong *et al.* showed that β -methyl- δ -valerolactone can be derived from biomass via fermentation or fermentation followed by chemical treatment and copolymerized with lactide, to form polyesters with desirable mechanical properties [43**].

Schwartz *et al.* proposed the use of 2-furylglycolic acid as a possible comonomer, and showed it can be produced through a novel approach, combining biological and chemical catalysis (Scheme 4). In their system, glucose is first oxidized and dehydrated using whole-cell catalysis. The reaction product, cortalcerone, is then converted to furylglycolic acid over a bifunctional Al-Sn-Beta zeolite catalyst, containing both Brønsted and Lewis acid sites [44**] (Scheme 4).

On the other hand, hydrogenation of lactic acid yields 1,2-propanediol (1,2-PD). 1,2-PD is an important commodity chemical, with uses as an antifreeze and as a food and

Scheme 4



Integration of biological and chemical catalysis [44**].

cosmetic additive [45]. Cortright *et al.* reported complete conversion of lactic acid over a Cu/SiO₂ catalyst, using 0.72 MPa of hydrogen at 473 K, with 88% selectivity to 1,2-PD [46]. Ruthenium catalysts have also been used for this transformation [47,48]. Recent advances in this reaction include the promotion of the Ru catalysts with Mo, which allows the reaction to be completed at a lower temperature, while preserving the stereochemistry [49]. In addition, the deactivation of the catalyst caused by sulfur-containing amino acids present in the fermentation broth [47,50] can be prevented by the coating of the Ru nanoparticles by polyvinyl alcohol [51*].

Dehydration of lactic acid gives acrylic acid, which is used as a monomer for a wide range of polymer applications. Early research focused on its dehydration in supercritical water [52], with and without catalysts. Selectivity to acrylic acid is relatively low under these conditions [53]. More recent research has focused on the use of alkali-modified Y zeolite as a catalyst for this reaction [54,55], resulting in yields of up to 66% [55]. In addition to NaY, calcium hydroxyapatites and SiO₂-supported calcium phosphates give high yields of acrylic acid from lactic acid [56] and methyl lactate [57], respectively. On the other hand, when dehydration of lactic acid is accompanied by decarbonylation, acetaldehyde is produced. Strongly acidic catalysts have been reported to be active for this transformation [52,58]. Finally, a hybrid approach, combining decarbonylation, dehydration and C–C bond formation over a multifunctional Pt/Nb₂O₅ catalyst has been reported by Serrano-Ruiz and Dumesic [59]. In this process, a multitude of organic fuel-range C₄–C₇ oxygenates are formed during phase-transfer catalysis (Scheme 5).

Acetone-butanol-ethanol (ABE) mixture

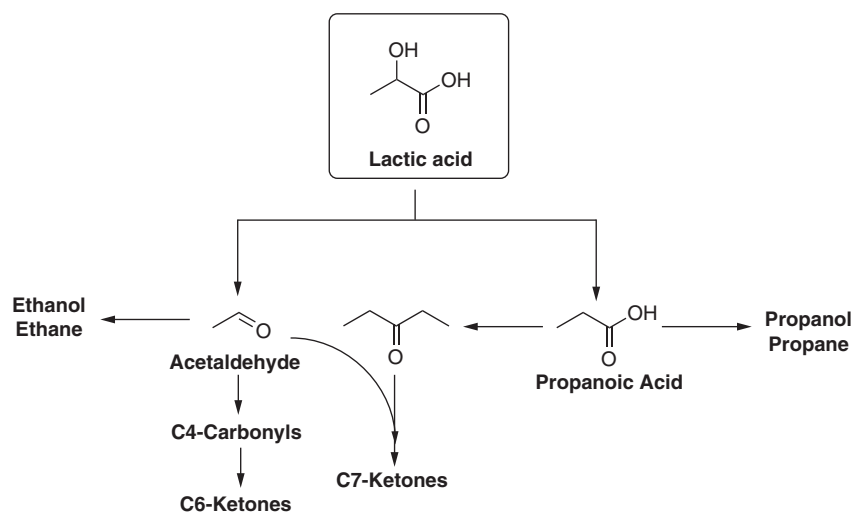
Production of acetone-butanol-ethanol (ABE) mixtures by fermentative pathways has been known for over 100 years [60]. However, only recently have they been utilized for the production of green chemicals and fuels [61].

The basis of the upgrading of ABE mixtures to fuels is the ABE condensation (Scheme 6) [62**]. First, ethanol and butanol are dehydrogenated over a transition metal catalyst, such as Pd, Cu or Ru [63,64]. The resulting aldehydes react with an enolate formed from acetone over a basic oxide or phosphate, such as hydrotalcite or potassium phosphate. This step forms an unsaturated ketone, which is in turn reduced to the saturated product by the hydrogen produced in the alcohol dehydrogenation step. The use of hydrotalcite is generally preferred over K₃PO₄, as the water produced during the reaction hydrolyzes the K₃PO₄, greatly reducing the recyclability of the catalyst [62**,63,65].

The selectivity of this process can be tuned using metabolic engineering [63,66]; engineering *Clostridia* to produce isopropanol instead of acetone results in higher molecular weight products, as the alcohols dimerize in a Guerbet reaction before coupling with the acetone, while the co-expression of alcohol and aldehyde dehydrogenases and a heat shock protein (HSP33) resulted in higher titers and higher butanol to acetone ratios, with subsequent increases in the production of diesel-range ketones [66].

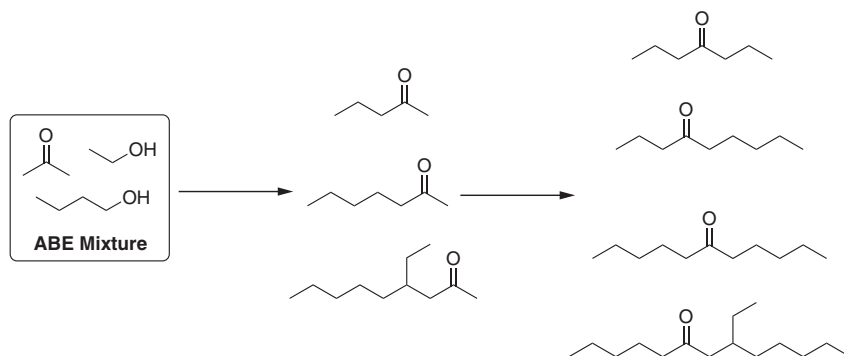
An alternative pathway to fuels and lubricants from the ABE process involves the use of the monoalkylated ketones. In this process, 2-pentanone, 2-heptanone and 4-ethyl-2-nonanone produced in the aforementioned reaction are condensed to form jet fuel (mixtures of

Scheme 5



Fuel production from lactic acid over a multifunctional Pt/Nb₂O₅ catalyst [59].

Scheme 6



Production of diesel-range ketones from ABE mixtures.

2-pentanone and 2-heptanone) and lubricants (4-ethyl-2-nonanone). Variants of this approach have been shown to reduce greenhouse gases up to 80% [34*].

Beyond the dehydrogenation-aldol condensation pathway, a recent report has proposed γ -Al₂O₃ as a catalyst for ABE mixture upgrading. In this chemistry, the ABE mixture undergoes a series of condensation and dehydration reactions to form two liquid phases (an aqueous and an organic) and a gas phase. The organic phase is comprised of a mixture of 6-undecanone, 2-heptanone and unsaturated hydrocarbons, while the gas phase is mainly comprised of CO₂ and butenes [67].

Summary and outlook

Significant amounts of literature have been devoted to the production of chemicals from ethanol. However, there is still ample space for innovation in the field of ethanol Guerbet and butadiene production, in terms of the selectivity and activity of the catalysts. The butadiene production process from ethanol could be expected to meet stiff competition from the butanediol production pathway, as the technology matures. On the other hand, the production of fuels and chemicals using the ABE process has not been adequately explored up to now; it might be a crucial part of biorefineries in the near future. Lastly, lactic acid fermentation followed by chemical upgrading presents many chances for innovation, especially in the fuels production process.

Acknowledgement

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