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Environmentally Friendly Synthesis of γ-Valerolactone by Direct Catalytic Conversion of Renewable Sources

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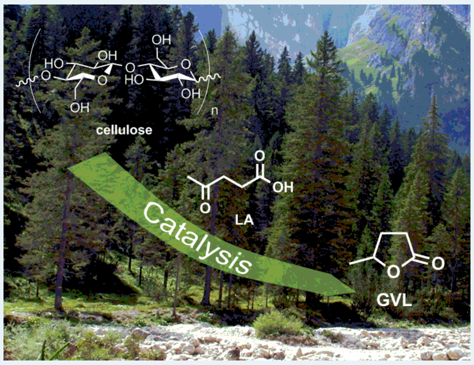
ABSTRACT: Gamma-valerolactone is a valuable chemical that can be obtained by catalytic methods from nonedible vegetable biomass. However, the demand is felt for more environmentally friendly and cost-effective production processes. The topic is reviewed in this paper from the perspective of catalyst design. Focus is on those systems enabling one-pot reaction sequences in the liquid phase at low energy expenses and combining metal and acid sites, spanning from homogeneous to heterogeneous catalysts. A final section is dedicated to continuous flow applications. The 230 references cover the most significant achievements published in the literature from January 2011 to July 2014 and highlight critical issues and future trends.



KEYWORDS: *γ-valerolactone, synthesis, one-pot, biomass, sustainable*

1. INTRODUCTION

Gamma-valerolactone (GVL) is an important chemical.[1,2] It is usable to produce liquid fuels[3] as a building block for polymers,[4] an intermediate in the fine chemicals synthesis,[5] a solvent,[6] and a flavoring agent,[7] and in the production of these items, it is safe.[8] Yet most interest in GVL − hence in the products thereof−is due to the opportunity to obtain it from plant renewable sources through chemical methods, which make it worthy of being called a “green” material.[9,10]

The nonedible portion of vegetable matter, called lignocellulosic biomass, consists of three main components from which several platform chemicals can be produced: cellulose (a homopolymer of glucose), hemicellulose (a polymer of C_6- and C_5-sugars, mainly glucose and xylose), and lignin (an aromatic polymer).[11] The conversion of cellulose and hemicellulose derivatives into GVL was extensively studied, and several homogeneous and heterogeneous catalysts were proposed. The main routes leading to GVL from plant biomass are sketched in Scheme 1. Depending on the starting material, the processes require a sequence of two or more consecutive catalytic reduction and acid-mediated steps via formation of levulinic acid (LA) or its esters.[12] Reductions are typically metal-catalyzed hydrogenations, although Meerwein−Ponndorf−Verley (MPV)[13] and catalytic hydrogen transfer (CHT)[14] reactions have also been reported.[15] Acid-catalyzed steps include hydrolysis, alcoholysis, dehydration, dealcoholization, or lactonization reactions.

However, the use of renewable sources is not enough to achieve sustainability of GVL manufacture on the industrial scale.[16] The challenge is to attain the highest yields at the lowest energy, environmental, and economic costs.[17] In principle, this requires the development of noble-metal-free catalysts[18] prepared through clean procedures,[19] featured by high activity, selectivity, and space-time-yield productivity[20] using mild conditions and friendly media, showing optimal resistance and the potential to be reused or to work under continuous flow.[21]

Further benefits in terms of efficiency, waste emission, volume output,[22] energy consumption, and the reduction of processing steps are offered by the catalytic systems enabling complex reaction sequences to be carried out in a single reactor unit.[23,24] Heterogeneous catalysts would be clearly preferred by industry to this purpose due to the easier catalyst reuse and product separation.[25] However, they usually need drastic reaction conditions, organic solvents, and/or the presence of strong soluble acids,[26] whereby the achievement of high selectivity requires the combination of well-defined supported acid and metal sites acting under the same reaction conditions.[27] It is therefore evident that a rational catalyst design is crucial.

Aspects of GVL synthesis have been recently covered by excellent surveys.[28] Herein we will shortly review the topic from the perspective of *catalyst design*. Focus will be on those *catalytic systems aimed at the sustainable, one-pot production of GVL in the liquid phase*. The catalysts will be described in increasing order of refinement level and significance in terms of catalyzed process sustainability, thus starting from homogeneous catalysts to heterogeneous catalysts, bifunctional catalysts, with a final section dedicated to continuous flow applications of heterogeneous systems. Research in the field is flourishing, and new papers appear weekly. The present manuscript seeks to outline the most significant achievements published in the literature

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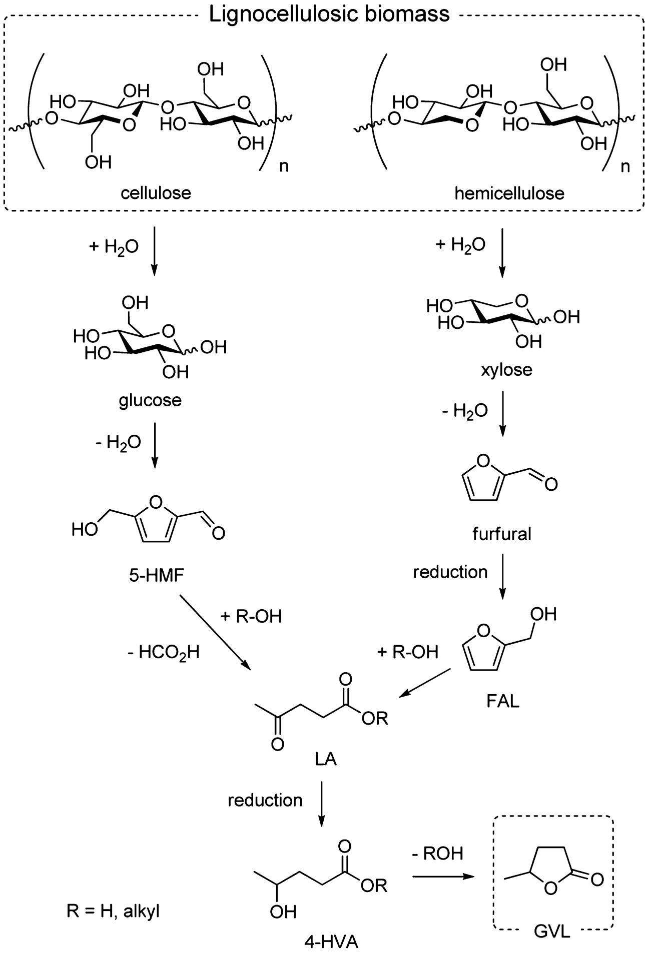
Scheme 1. Key Steps for the Catalytic Conversion of Plant Biomass to GVL



from January 2011 to July 2014. Pyrolytic and gas phase catalytic methods will not be considered because of the high temperatures required and, with few notable exceptions,[29] the poor selectivity.

1.1. Typical Processes for GVL Synthesis. The most common substrate for the one-pot synthesis of GVL is LA. LA is a highly versatile platform chemical produced from wood-based materials, mainly agricultural residues and paper waste.[30,31] Current technologies allow for the manufacture of LA on ton/day scale at competitive costs.[32] Bioderived LA feedstocks are available either as concentrated aqueous solution, eventually containing equimolar amounts of formic acid (FA) and variable quantities of H_2SO_4 due to cellulose sugars deconstruction process (Scheme 1),[33] or as pure material after demanding separation procedures.[34] Pathway of LA to GVL conversion under conventional liquid phase conditions involves reduction of LA (or its esters) to unstable 4-hydroxyvaleric acid (4-HVA or esters),[35] followed by lactonization at elevated temperatures or in the presence of an acid catalyst (Scheme 1).[36] If on one hand the presence of acids in the feed requires tolerant catalysts,[37] on the other hand, FA can be used as in situ hydrogen source for LA reduction, thus avoiding any external H_2 supply, which greatly improves the overall atom and cost economy of the process.[38]

Direct use of other upstream substrates other than LA (e.g., sugars) would be clearly more attractive owing to the intensification,[39] reduced complexity, and cost of biomass processing. However, product yields and selectivity of the relevant conversions strongly depends on type and strength of the acid catalyst.[40] In particular, the upgrade of glucose and cellulose, because of the recalcitrance to hydrolysis, requires strong acids and harsh conditions, which results in low GVL yields and significant amounts of humins byproduct.[41]

2. Homogeneous Catalysts. Several homogeneous or quasi-homogeneous catalysts,[42] namely, molecular metal complexes and colloidal metal nanoparticles (MNP), have been used to convert LA substrate into GVL. Recent data are summarized in Table 1, in which catalyst lifetime and activity are reported as turnover number (TON) and turnover frequency (TOF), respectively.[43]

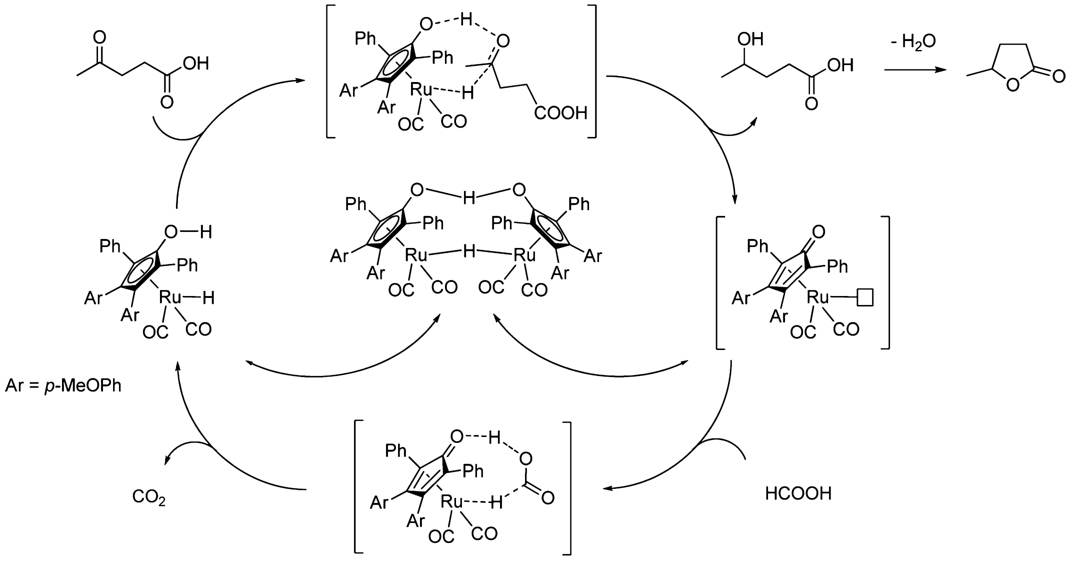
One of the most successful examples was the renowned Shvo-type ruthenium complex $\{[2,5\text{-}Ph_2\text{-}3,4\text{-}(p\text{-}MeOPh)_2(\eta 5\text{-}C_5O)]_2H\}Ru_2(CO)_4(\mu\text{-}H)]$.[44] It was shown that the complex is an effective precursor for the catalytic transfer hydrogenation reaction from FA to LA.[45] Indeed, using a FA/LA molar ratio as low as 2, neat LA and an open vessel at 100 °C, GVL was obtained in 99.9% yield, with H_2O and CO_2 as the sole coproducts, which were easily removed (TON 2400, Table 1, entry 1). No reaction was observed at 60 °C, as the conversion of the precursor to the catalytically active species required a minimum of 80 °C. The catalyst could be recovered by vacuum distillation of the reaction mixture, with slight activity decay upon four reuses. The homogeneous catalysts allowed for a detailed picture of the reaction mechanism, involving the

Table 1. Representative Data for Recent One-Pot Catalytic Conversions of LA to GVL in the Homogeneous Phase

	catalyst	solvent	H-source	T (°C)	P_{H_2}[a] (bar)	conv.[b] (%)	sel.[c] (%)	TON[d]	TOF[e] (h^{-1})	ref
1	Shvo Ru complex	-	FA	100	-	100	99.9	2400	300	45
2	Shvo Ru complex	GVL[f]	FA	100	-	86	99	-[g]	-[g]	46
3	$[Cp^*Ir(H_2O)(4,4\text{-di-MeO-}2,2\text{-diPy})]SO_4$	H_2O	FA	120	-	100	99	10 000	2500	47
4	$[Cp^*Ir(H_2O)(4,4\text{-di-MeO-}2,2\text{-diPy})]SO_4$	H_2O	H_2	120	10.1	99	99	9900	2475	47
5	$[Cp^*Ir(H_2O)(4,4\text{-di-MeO-}2,2\text{-diPy})]SO_4$	H_2O	H_2	120	10.1	79[h]	99	79 000	2194	47
6	RuNP	H_2O	FA	130	-	100	100	573	24	48
7	RuNP	H_2O	H_2	130	5	100	100	573	48	48
8	Ru(Bu-DPPDS) complex	-	H_2	140	100	100	99.9	6370	3539	49
9	Ru(DPPB) complex	-	H_2	140	100	100	99.9	6370	6370	51
10	$IrH_3(2,6\text{-di}(t\text{-}Bu_2PCH_2)Py)$	C_2H_5OH	H_2	100	50	98	100	9800	408	53

[a] Dihydrogen pressure. [b] Substrate conversion. [c] Selectivity to GVL, as (mol GVL)/(mol substrate converted). [d] Turnover number, as (mol substrate converted)/(mol noble metal). Calculated from literature data. [e] Turnover frequency, as (mol substrate converted)/(mol noble metal × h). Calculated from literature data at the conversion indicated. [f] Containing 1.5% vol. 5 M aq. H_2SO_4. [g] Not calculated. [h] Catalyst loading 0.001 mol %.

Scheme 2. Proposed Mechanism for CHT Reaction from FA to LA by the Homogeneous Shvo Catalyst



dissociation of the precursor to the monometallic active species, followed by their reaction with LA and FA, which complete the cycle by elimination of 4-HVA and CO_2, respectively (Scheme 2).

A ^{13}C NMR study on the CHT reaction by the Shvo catalyst, using a LA/FA mixture obtained from the dehydration of fructose with H_2SO_4 in GVL solvent, demonstrated the viability of GVL as solvent and the resistance of the catalysts in the reaction medium (Table 1, entry 2).[46]

The catalytic hydrogen transfer from FA to LA was efficiently carried out by the water-soluble, half-sandwich iridium complex shown in Figure 1.[47] A 1.0 M LA and FA aqueous solution (1:2 molar ratio) was converted to GVL in 99% yield at 120 °C using a 0.01 mol % catalyst loading (TON 10000, Table 1, entry 3). After extraction of GVL with diethyl ether, the catalyst could be reused showing 5% activity loss after five consecutive runs, however. The catalyst was also used with H_2 as hydrogen source instead of FA, resulting in a 98% GVL yield under identical reaction conditions and 10 bar hydrogen pressure (TON 9900, Table 1, entry 4). TON values up to an unprecedented 79 000 could be recorded by changing the substrate to catalyst ratio to 0.001% mol (TOF 2194 h^{-1}, Table 1, entry 5).

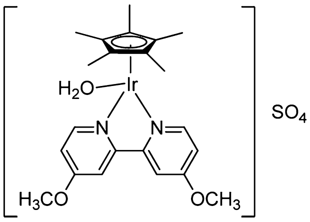


Figure 1. Sketch of water-soluble homogeneous iridium catalyst for LA to GVL conversion (see ref 47).

Both CHT (LA/FA/Et_3N = 1:4:0.4 molar ratio) and H_2 hydrogenation (5 bar) reactions were also performed at 130 °C using in situ formed RuNP of 2 nm size.[48] A higher catalyst activity was found in the latter case (24 vs 48 h^{-1}, Table 1, entry 6 and 7). Despite that the catalyst could be recovered and reused after vacuum distillation, complete loss of activity was observed after four cycles, which was attributed to RuNP agglomeration.

The hydrogenation of LA in the homogeneous phase was achieved using molecular catalysts generated in situ by the reaction of $Ru(acac)_3$ with an excess of water-soluble monodentate phosphine ligands in neat LA.[49] The best efficiency results were obtained for the Bu-DPPDS ligand ($P(C_6H_4$-*m*-$SO_3Na)_2$(*n*-Bu)), which provided GVL in >99% yield under 100 bar H_2 and 140 °C (TOF 3539 h^{-1}, Table 1, entry 8). The ligand concentration was found to be critical as the reaction rate went through a maximum for a ligand/metal = 10:1 molar ratio. It was also clearly demonstrated that, compared to parent triaryl ligands, e.g., TPPTS,[50] the catalytic activity is considerably enhanced by the incorporation of one or two alkyl functional group(s) into the phosphorus ligand.

The system was improved by the use of analogous bidentate phosphine ligands.[51] Thus, 1,4-bis(diphenylphosphino) butane (DPPB) provided the best TOF value of 6370 h^{-1} (Table 1, entry 9), under the same reaction conditions as above for Bu-DPPDS. An impressive TOF of 21 233 h^{-1} was obtained by increasing the reaction temperature to 160 °C (ligand/Ru = 10 mol). The catalyst could be recovered by vacuum distillation and recycled for 10 consecutive runs at 140 °C exhibiting no activity decay.

It is worth mentioning that the homogeneous-phase catalytic hydrogenation of LA was previously screened using $Ru(acac)_3$, mono-, bi-, and tridentate phosphine ligands, and acidic additives to result in up to 99% GVL yield under 160 °C and 100 bar.[52]

Use of iridium trihydride complexes bearing pyridine-based pincer ligands was also reported for the catalytic H_2-reduction of LA (Figure 2).[53] However, a large excess of KOH was required (KOH/LA = 1.2 mol) to achieve a 98% GVL yield in ethanol under 50 bar H_2 and 100 °C (TOF 408 h^{-1}, Table 1, entry 10).

The above examples show that homogeneous catalysts for GVL synthesis can be produced featuring very high activity and selectivity. However, the main problem of these systems is the relatively fast catalyst deactivation, which often result in too low TON numbers for practical applications. Further issues about their use relate to catalyst recovery, need of additives, cost of

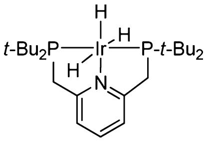


Figure 2. Sketch of iridium pincer complex for LA hydrogenation (see ref 53).

sophisticated ligands, sometimes exceeding that of the noble metal employed, and the high boiling point of GVL (207−208 °C), which makes product/catalyst separation by means of distillation uneconomical. Strategies have thus been devised to increase the stability of catalysts, including embedding of the active species into a solid matrix, with additional benefits in terms of product purification and catalyst recycle. Arguably, a realistic manufacturing of GVL will thus rely on the use of heterogeneous catalysts.[28e]

3. HETEROGENEOUS CATALYSTS

Heterogeneous systems reported for the one-pot conversion of lignocellulose derivatives into GVL may be roughly classified into four main groups: (a) metal catalysts supported onto inert solids, (b) metal catalysts onto inert solids in the presence of strong soluble acid additives, (c) mechanical mixtures of solid-supported metals and solid acids, (d) metal catalysts supported onto solid acids, hereinafter referred to as *bifunctional catalysts*.[54,55] Yet this classification should be taken with care as it implies the exact knowledge of the role of the support and, thus, the clear identification of supported Brønsted and/or Lewis acid sites.[56] The metal catalysts are usually noble MNP in the case of H_2 hydrogenation reactions-based systems, whereas metal oxides or other non-noble metal species may be involved for MPV and CHT reduction-based catalysts.[57] Occasional use of unsupported catalysts (e.g., Ni Raney, stainless steel, Co oxides) has also been reported.[58]

3.1. Metal Catalysts onto Inert Supports.

Synthesis of GVL from LA by H_2 hydrogenation has been carried out using noble MNP catalysts onto nonacidic solid supports.[59] In these systems, both acidic (Lewis) and hydrogenation activity can be ascribed to the metallic sites.[60] Reaction conditions more intense than those adopted using homogeneous catalysts are generally required to achieve comparable efficiency (Table 2).

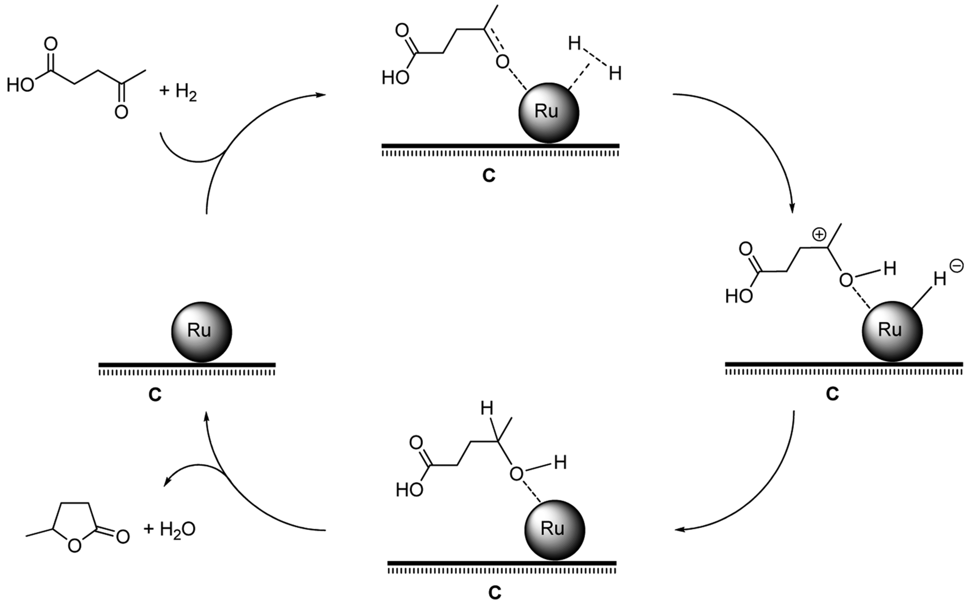
The best results which represent a compromise between energy inputs and productivity were recently reported using commercial 5 wt % Ru/C in water to give GVL with 86.6% selectivity at 99.5% conversion under 12 bar H_2 and 130 °C (TOF 130 h^{-1}, Table 2, entry 1).[36] Reactions performed in 9:1 ethanol/water (v/v) slightly increased the overall GVL yield because of the improved selectivity. Use of alcoholic solvents was motivated by the fact that conversion of lignocellulosic biomass to levulinic esters, instead of LA, avoids the expensive separation of water from LA feeds prior to hydrogenation.[61] Thus, methyl levulinate (Me-LA) hydrogenation in methanol was examined showing similar catalyst performance (Table 2, entry 2). LA conversion under solvent-free conditions, 12 bar H_2, and 25 °C was also possible, however with low productivity (TOF 7.0 h^{-1}), whereas achievement of significant efficiency required 190 °C reaction temperature (TOF 536 h^{-1}, Table 2, entry 3). Considerable activity decay after four catalyst reuses was observed, irrespectively of the temperature.

Table 2. Representative Data for Recent One-Pot Syntheses of GVL by Heterogeneous Catalysts under Batch Conditions

	catalyst	substrate[a]	solvent	H-source	T (°C)	P_{H_2}[b] (bar)	conv.[c] (%)	sel.[d] (%)	TOF[e] (h^{-1})	ref
1	5% Ru/C	LA	H_2O	H_2	130	12	99.5	86.6	130	36
2	5% Ru/C	Me-LA	CH_3OH	H_2	130	12	97.8	89.4	128	36
3	5% Ru/C	LA	-	H_2	190	12	100	100	536	36
4	5% Ru/C	Me-LA	CH_3OH	H_2	130	35	95	91	56	62
5	6% Ru/OMC	LA	-	H_2	150	45	99.4	99.4	2351	64
6	5% Pd/CNT	LA	H_2O	H_2	200	60	57.6	97.7	53	66
7	5% Pd/SiO_2	LA	H_2O	H_2	180	90	97.3	99.2	148	68
8	5% Pd/MCM-41	LA	H_2O	H_2	240	60	99	97.3	54	69
9	0.3% $Ru_{0.7}Ni_{0.3}$/OMC	LA	-	H_2	150	45	96	97.9	2999	70
10	5% Ru/C + [BMIm-SH][HSO_4]	FAL	CH_3OH	H_2	130	35	99	68[f]	31	72
11	5% Ru/C + Amberlyst-70	LA	H_2O	H_2	70	5	98	99.5	327	74
12	1% Ru/graphite + HZSM-5	Me-LA	H_2O	H_2	70	30	99	98	325	81
13	5% Ru/C + Al-$NbOPO_4$	cellulose	H_2O	H_2	180	50	95[g]	60	-[h]	83
14	Zr-Beta + Al-MFI-ns	furfural	2-butanol[i]	2-butanol	120	-	87	89.7	1.8[l]	85
15	5% Ru/HAP	LA	H_2O	H_2	70	5	99	99	86	88
16	2% Ru/SPES	LA	H_2O	H_2	70	30	87.9	99	380	90
17	3% Pd/Nb_2O_5−C	Et-LA	H_2O	H_2	100	5	87	93	62	95
18	10% Ni/MoO_x-C	LA	-	H_2	140	8	100	97	20[m]	96
19	ZrO_2	Bu-LA	2-butanol	2-butanol	150	-	99.9	84.8	0.1[l]	99
20	0.8% Au/ZrO_2	LA	H_2O	FA	150	-	99	99	166	100
21	3% Au/ZrO_2	LA	H_2O	FA	150	-	100	97	131	101
22	20% Cu/ZrO_2	LA	H_2O	FA	200	-	100	100	4.8[n]	102
23	10% Ag - 20% Ni/ZrO_2	LA	H_2O	FA	220	-	79	99	29[p]	104

[a] LA, levulinic acid; Me-LA, methyl levulinate; FAL, furfuryl alcohol; Et-LA, ethyl levulinate; Bu-LA, butyl levulinate. [b] Dihydrogen pressure. [c] Substrate conversion. [d] Selectivity to GVL, as (mol GVL)/(mol substrate converted). [e] Turnover frequency, as (mol substrate converted)/(mol noble metal × h). Calculated from literature data at the conversion indicated and on bulk metal content. [f] Other products include Me-LA and 4-hydroxy methyl levulinate. [g] Based on carbon balance. [h] Not calculated. [i] In the presence of 5 wt % water. [l] Based on moles of Zr. [m] Based on moles of Ni. [n] Based on moles of Cu. [p] Based on moles of Ag.

Scheme 3. Proposed Mechanism for the Hydrogenation Reaction of LA over Heterogeneous Ru/C Catalyst. Adapted from Ref 63 (Copyright 2009 American Chemical Society)



Similar selectivity results were reported for the hydrogenation reaction of methyl levulinate by homemade 5% Ru/C under comparable conditions (Table 2, entry 4).[62] No loss of active species was responsible for the drop of catalytic activity, even though the amount of ruthenium leached in solution was not quantified.

The mechanism of the liquid-phase hydrogenation of LA to GVL by Ru/C catalysts was carefully investigated (Scheme 3).[63] It was proposed that in a first step H_2 and LA are chemisorbed on the Ru surface, followed by the heterolytic cleavage of the H−H bond and the transfer of one hydrogen to an intermediate species stabilized by the interaction with Ru. Transfer of the second H atom results in the formation of Ru-bonded 4-HVA, which rapidly dehydrates to GVL.

In order to produce stable supported catalysts, a strategy was recently developed, in which homogeneously dispersed RuNP were generated within the voids of an ordered mesoporous carbon (OMC), formed simultaneously by pyrolysis of appropriated precursors at 750 °C.[64] The procedure afforded confined ruthenium particles more firmly attached to carbon than those obtained by conventional techniques, which are usually prone to extensive leaching.[65] Indeed, the solvent-free hydrogenation of LA was achieved under 45 bar H_2 and 150 °C to give nearly constant GVL 99% yield over 21 reuses (Table 2, entry 5).

Analogous heterogeneous catalysts fabricated with different metals and/or supports were examined, with Ru/C usually displaying the best performances. Thus, methyl levulinate conversion showed to decrease in the order Ru > Pt > Pd using 5 wt % M/C under the same reaction conditions.[62] Results were in line with those reported for the hydrogenation of LA by 5 wt % Pd/C and Pd/CNT (CNT, multiwalled carbon nanotubes), wherein harder reaction conditions were needed compared to Ru (Table 2, entry 6).[66] Size and dispersion of MNP were justified for the observed activity trend.[67] Similarly, rates of hydrogenation of both methyl levulinate and LA were reported to follow the order Ru/C > $Ru/SiO_2 \geq Ru/Al_2O_3 > Ru/TiO_2$, that was attributed to the decreasing relative content of hydrogenation active Ru^0 species due to incomplete ruthenium reduction,[36] and to the surface area of the supports,[62] respectively.

According with the above findings, 5 wt % Pd/SiO_2[68] and 5 wt % Pd/MCM-41[69] catalysts required 90 bar H_2 @ 180 °C (Table 2, entry 7) and 60 bar H_2 @ 240 °C (Table 2, entry 8), respectively, to achieve full LA conversion and GVL selectivity. The Pd/SiO_2 catalyst could be reused after high-temperature H_2 treatment with a 5% conversion drop after three runs.

Strategies have been devised to improve the performance of the ruthenium catalysts' family. In one case, bimetallic species onto OMC were prepared with tuned composition Ru_xNi_{1-x} (x = 0.5−0.9), showing maximum productivity in the solventless hydrogenation of LA for 30% mol Ni content (Figure 3 and Table 2, entry 9).[70] The $Ru_{0.7}Ni_{0.3}$/OMC catalyst could be reused with 13% GVL yield loss after six cycles, whereas $Ru_{0.9}Ni_{0.1}$/OMC was more stable and could be recycled up to 15 times without a significant activity drop. It was suggested that the introduction of Ni species into Ru/C enhances its catalytic performance due to a stronger metal−support interaction (SMSI),[71] resulting in an improved embedding and in a better dispersion of MNP in the carbonaceous matrix.

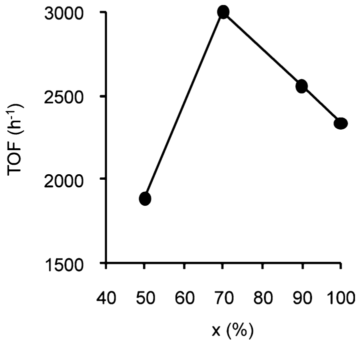


Figure 3. Solvent-free LA to GVL conversion by 0.3 wt % Ru_xNi_{1-x}/OMC catalysts (x = 0.5−0.9). Reaction conditions: 45 bar H_2, 150 °C. TOF calculated on overall conversion of ca. 98% per mole Ru (except x = 50%, conversion 45%). Data from ref 70.

3.2. Supported Metal Catalysts with Strong Soluble Acid Additives. Use of heterogeneous mixtures of supported metal catalysts and strong protic acid solutions, e.g., H_2SO_4, have been reported in one-pot multistep organic synthesis, particularly in the transformation of polysaccharides to liquid hydrocarbon fuels and of vegetable oils to low-molecular weight oxygenates, wherein the intrinsic acidity of the metal sites does not allow for the depolymerization/dehydration steps to be achieved under acceptable temperatures.[11b,23a]

The combination of carbon-supported metals and sulfonic acid-functionalized ionic liquids was recently reported to allow for the direct, single-pot catalytic conversion of furfuryl alcohol (FAL) to GVL in alcoholic solvents.[72] It was demonstrated that the process goes through the Brønsted acid-catalyzed alcoholysis of FAL to levulinic ester, followed by its metal-catalyzed hydrogenation (Scheme 1). Indeed, experiments without acids failed in the conversion of FAL. Under optimized conditions, full conversion of FAL with 68% GVL selectivity was achieved after 5 h using [BMIm-SH][HSO_4][73] and 5% Ru/C (mol ratio 10:1) at 130 °C and 35 bar H_2 in methanol (Table 2, entry 10). The procedure adopted was actually two-step because the alcoholysis reaction was carried out under N_2, which was replaced by H_2 after the changeover period. Use of initial hydrogenation conditions was possible too; however, low GVL selectivity was observed due to competitive ring hydrogenation of FAL to tetrahydrofurfuryl alcohol. GVL yield was much lower using other metals (Rh, Re, Pd, Ir) in the presence of the same ionic liquid. Use of Ru/C + H_2SO_4 was also examined, resulting in poor GVL yield because of deactivation of Ru catalyst due to sulfur leaching from sulfuric acid. The combined Ru/C–ionic liquid catalyst could be recycled three times by an evaporation-extraction protocol showing consistent conversion but significant selectivity decrease.

3.3. Mixtures of Supported Metals and Solid Acids Catalysts. It is clear that processes requiring strong soluble acid additives involve serious environmental issues and tedious workup of the reaction solutions. A most convenient approach would be the replacement of soluble acids by solid, insoluble ones. The easier method to achieve this is the use of mechanical mixtures of insoluble acids and supported metal catalysts.

An instructive example was reported for the one-pot conversion of LA using a mixture of commercial 5 wt % Ru/C and strongly acidic sulfonated resin Amberlyst-70.[74] An impressive one order magnitude increase of Ru/C activity was observed upon addition of Amberlyst-70 (2.3 equiv). Importantly, this allowed for the process to be efficiently carried out in water under unusual mild conditions, i.e., 5 bar H_2 and 70 °C (Table 2, entry 11). It was shown that the presence of the Brønsted solid acid cocatalyst not only promotes the cyclization reaction of 4-HVA but also accelerates the ruthenium-mediated hydrogenation step. This was elegantly demonstrated by parallel hydrogenation experiments of simple ketones by Ru/C either in the presence or in the absence of the acidic resin. Such a cooperative effect of proton acid sites has also been described for other supported-metal catalyzed reactions, including Pd-hydroxylation,[75] Ru-hydrogenolysis,[76] and Pd-hydrogenation.[77] The mixed heterogeneous catalyst could be recovered and reused with neither major efficiency decay nor leaching of ruthenium in solution over five cycles. Other solid acid cocatalyst were tested, including Amberlyst-15, niobium phosphate and niobium oxide, the latter containing both strong Brønsted acid sites and medium-strong Lewis acid sites.[78] Amberlyst-70 showed to be the most effective, which was related to the high strength of the acid sites due to the presence of chlorine atoms in its structure.[79] However, an accurate comparison of cocatalysts in terms of LA conversion was complicated because of the different amount of acids employed. No direct relation of the solid acid used with GVL selectivity was apparent.

Similarly, use of a mixture Ru/graphite and strongly Brønsted acidic HZSM-5 zeolite[80] showed to be extremely beneficial in the hydrogenation reaction of methyl levulinate, compared to Ru/graphite catalyst alone. Full conversion to GVL was achieved under 70 °C and 30 bar H_2 (TOF 325 h^{-1}) using 1 wt % Ru/graphite and one equivalent weight amount of zeolite (Table 2, entry 12).[81] It was demonstrated that methyl levulinate is hydrogenated to methyl 4-hydroxylevulinate over supported ruthenium sites and further dealcoholization to GVL proceed over the acid sites. Other types of zeolites and solid acids in the proton form were examined, showing that enhancement of GVL formation rate was dependent from the strength of the solid acid and, for zeolites sharing the same structure, proportional to the number of acid sites (Figure 4).[82]

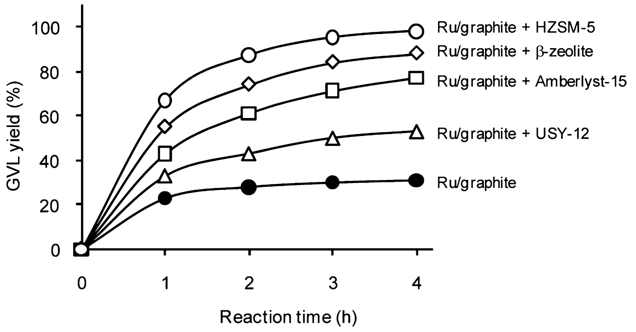


Figure 4. GVL yield over 1% Ru/graphite (●) and mixture of 1% Ru/graphite and equivalent weight amount of USY-12 (Δ), Amberlyst-15 (□), *β*-zeolite (◇), HZSM-5 (○). Substrate methyl levulinate, H_2 30 bar, temperature 70 °C, water. Adapted from ref 81 (Copyright 2014 Elsevier).

Interestingly, the mixture Ru/graphite + HZSM-5 performed better than the corresponding ruthenium catalyst supported onto HZSM-5. This finding was attributed to the smaller size and better accessibility of RuNP onto graphite (1.3 nm, located on graphite surfaces) rather than onto HZSM-5 (2.6 nm, micropores of zeolite).

An interesting one-pot, two step conversion of cellulose to GVL in 57% yield was reported using commercial 5% Ru/C in conjunction with 10:1 aluminum-doped mesoporous niobium phosphate (Al-$NbOPO_4$) as solid acid catalyst.[83] The procedure involved treatment of 5 wt % cellulose solution at 180 °C for 24 h under N_2, followed by further 12 h reaction time under 50 bar H_2 at the same temperature, without separation of LA intermediate (Table 2, entry 13). The optimal high temperature was required in this case to achieve maximum hydrolysis yield, while minimizing humins byproduction (Scheme 1). The water-tolerant Al-$NbOPO_4$ was selected to accelerate LA formation, due to the high amount of acid sites (ca.1 mmol g^{-1}) and to the coexistence of Lewis and Brønsted acidity.[84]

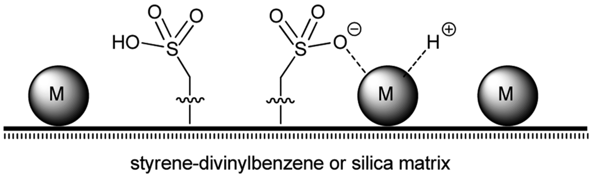
A peculiar mixed heterogeneous catalysts was described by Román-Leshkov and co-workers. In their approach, the conversion of furfural to GVL in one-pot was achieved through a domino sequence of MPV reductions and Brønsted acid-catalyzed ring-opening reactions.[85] The hydrogen transfer steps (furfural to FAL and LA to 4-HVA) are bring about by the zirconium ion Lewis acid sites of Zr-Beta zeolite catalyst using 2-butanol as hydrogen donor (Scheme 1). The hydrolytic step (FAL to LA) is promoted by an aluminosilicate solid acid with MFI topology and nanosheet morphology (Al-MFI-ns). The butyl furfuryl ether and butyl levulinate byproducts formed in the presence of 2-butanol undergo the same catalytic pathway. Under optimal reaction conditions, i.e., 1% mol % Zr + 6% mol Brønsted acid and 120 °C, GVL was obtained in 78% yield from a 5 wt % furfural solution (Table 2, entry 14). Other solid Brønsted acids were screened, including Al-Beta, Amberlyst-70, Al-MCM-41, and Al-MFI, which all resulted in lower GVL yields. Despite the use of the organic solvent and the relatively high temperature required to speed up the hydrogen transfer reaction to LA, the method is economically advantageous, because it avoids the use of precious metals or high H_2 pressures. The catalyst could be reused after calcination at 550 °C with no metal leaching in solution detected.

It is worth mentioning that the hydrogenation of a neutralized aqueous solution of bioderived LA was recently reported using a mixture of Ru/C and niobium oxide cocatalyst under mild conditions (5 bar H_2, 70 °C) to provide GVL in 16.6 wt % yield based on the starting weight of dry biomass.[86]

3.4. Bifunctional Catalysts. The above-mentioned examples clearly illustrate that the potential of supported metal catalysts for the conversion of renewables to GVL under mild conditions is greatly improved by the combined used with strong (solid) acids. A straightforward approach to more economic and efficient heterogeneous catalyst is therefore the immobilization of metal catalysts onto solid acid supports, hence to have both active sites on one single material. A variety of metals and support materials have been investigated to this purpose, with ruthenium metal usually demonstrating a superior performance.

Thus, 5 wt % MNP (Ru, Pt, Pd, Ni) on hydroxyapatite (HAP), a naturally occurring mineral containing both acid (10 ÷ 20 μmol g^{-1}) and basic sites,[87] were tested in the hydrogenation reaction of LA.[88] Catalyst efficiency was in the order Ru > Pt ≥ Pd > Ni, with GVL obtained in 99% yield and selectivity using Ru/HAP under 70 °C and 5 bar H_2 (Table 2, entry 15). Catalytic activity showed to be slightly dependent from the temperature and to decay by ca. 10% over five consecutive reuses. Interestingly, the acidity of HAP significantly increased upon incorporation of RuNP, which was ascribed to the presence of unreduced ruthenium species. A similar effect was previously reported for PtNPs catalyst onto sulfonated mesoporous silica used in one-step hydrogenation/esterification reactions of aldehydes.[89] In that case, the enhancement of acidity was attributed to the formation of acidic $[Pt_n{-}H]^+$ adducts (Scheme 4).

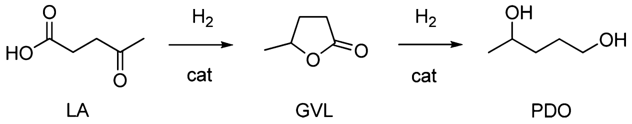
Scheme 4. Proposed Formation of $[M_n{-}H]^+$ Adducts (M = Pd, Pt) over Bifunctional, Sulfonated Catalysts onto Solid Supports (Silica, Amberlyst). Adapted from Ref 77 (Copyright 2008 Wiley-VCH Verlag GmbH & Co.) and Ref 89 (Copyright 2010 Elsevier)



A bifunctional catalysts based on 2 wt % RuNP onto cross-linked sulfonic poly(ether sulfone) (SPES) was used in the same reaction as above, providing slightly better results under comparable conditions (70 °C, 30 bar H_2, TOF 380 h^{-1}, Table 2, entry 16).[90] A comparative study was carried out using various supports showing that SPES not only performs better than carbon and SiO_2 in the order but also that the bifunctional catalyst is more active than a mixture of the supported metal and Amberlyst-15 catalysts. The high catalytic efficiency of Ru/SPES was attributed to the swelling of the polymer in reaction solvent and to the high density of the acid sites (3.8 mmol g^{-1}).

In the course of their studies on the synthesis of 1,4-pentanediol (PDO) by catalytic hydrogenation of LA, Pinel et al. recently reported high rates of intermediate GVL formation using mono- (Ru, Pd, Pt) and bimetallic (with Re) catalysts immobilized onto carboxylated carbon (C_{ox}) (Scheme 5).[91]

Scheme 5. Catalytic Hydrogenation of LA to PDO



The Ru catalyst (2.1 wt % Ru) was the most efficient, resulting in complete conversion to GVL within few minutes under 160 °C and 150 bar H_2. In contrast, under the same reaction conditions, 2.7% Pd/C_{ox} and 4.1% Pt/C_{ox} catalysts exhibited a much lower activity. Similar performances were observed for the bimetallic catalysts based on Ru, whereas using the Pd−Re and Pt−Re catalysts, the reaction rate significantly increased compared to the monometallic parent catalyst. The highest GVL yield (85%) was obtained in the presence of 2.8% Ru−3.9% Re/C. However, it must be noted that drastic conditions were adopted in this case to achieve fast conversion of GVL to PDO.

Besides the use of functional groups, other methods have been developed to introduce acid sites in a carbon matrix, including doping with acidic metal oxides to produce inorganic−carbon hybrid materials.[92] For instance, the hydrothermal stability of the strong solid acid niobium oxide can be significantly improved by fabrication of Nb_2O_5-carbon nanocomposites used in several condensation and hydrolytic processes.[93,94] The incorporation of MNP onto such hybrids led to effective bifunctional catalysts for ethyl levulinate hydrogenation under mild conditions.[95] The optimized catalyst 3 wt % Pd onto 10% niobia-doped carbon showed acceptable GVL productivity in water under 100 °C and 5 bar H_2 (Table 2, entry 17). It was highlighted that the bifunctional catalyst Pd/Nb_2O_5−C is the most active in the series Pd/Nb_2O_5−C > mixture Pd/C + Nb_2O_5/C > Pd/C ≫ Pd/Nb_2O_5 under the same reaction conditions. This synergistic effect between Pd and niobia on carbon was justified in terms of stronger metal−support interaction resulting in the stabilization of well-dispersed PdNP. Catalyst activity decreased by 6% after five reuses.

Similarly, a series of non-noble metals (Ni, Co, Cu, Fe) on metal oxides (Mo, V, W)-doped carbon was tested in the solvent-free hydrogenation of LA. The study revealed invariably higher conversion rates for bifunctional catalysts compared to the corresponding oxide-free systems, and the best combination

Table 3. Selected Data for Recent Catalytic Conversions of LA to GVL under Continuous Flow Conditions

	catalyst	reactor type	solvent	H-source	T (°C)	P_{H_2}[a] (bar)	conv.[b] (%)	sel.[c] (%)	TOF[d] (h^{-1})	STY[e] (kg l^{-1} h^{-1})	ref
1	5% Ru/C	packed-bed	H_2O	H_2	140	10	97.1	99	84	1.54	111
2	5% Ru/C	packed-bed	PG[f]	H_2	200	13.8	62	96	35	0.05	112
3	5% Ru/C + Amberlyst-70	packed-bed	H_2O	H_2	50	24	92	88[g]	80	0.36	114
4	0.85% Ru/Dowex	packed-bed	H_2O	H_2	70	7	97	99	117	0.12	116
5	Zr-Beta	packed-bed	2-propanol	2-propanol	150	-	99	99	0.74[h]	-[i]	118
6	15% Ru_3Re_4/C	packed-bed	H_2O	FA	150	35	80	95	12	-[i]	37a

[a] Dihydrogen pressure. [b] Substrate conversion. [c] Selectivity to GVL, as (mol GVL)/(mol substrate converted). [d] Turnover frequency, as (mol substrate converted)/(mol noble metal × h). Calculated from literature data at the average conversion value indicated and on bulk metal content. [e] Space-time-yield, as (kg $_{GVL}$)/(liter reactor volume x h). Calculated from literature data at the average conversion and selectivity values indicated. [f] PG, propyl guaiacol. [g] 4-HVA byproduct. [h] Based on moles of Zr. [i] Not calculated.

of Ni/MoO_x-C (10 wt % Ni, 7 wt % Mo) afforded full conversion at 140 °C and 8 bar H_2 (Table 2, entry 18).[96] Nevertheless, catalyst activity was not only lower than that of conventional noble metal catalysts but also dramatically decreased in the presence of water.

A number of inventive bifunctional catalyst, namely, for the MPV and CHT reduction-based process, used zirconium oxide as support. This was mainly due to the amphoteric nature of ZrO_2 (acidic sites 0.3 mmol g^{-1})[97] and to the Lewis acid property of the zirconium sites.[98] Indeed, even in the absence of immobilized metals, zirconia showed to be able to catalyze the MPV hydrogen transfer reaction from alcohols to butyl levulinate to give GVL, wherein the Lewis acid sites were the active centers. A modest productivity was observed at 150 °C using 2-butanol as hydrogen source, and transesterification byproducts were detected (Table 2, entry 19).[99]

Immobilization of AuNP onto zirconia turned out to improve the catalytic properties of ZrO_2. Thus, 0.8 wt % Au/ZrO_2 (Au 1.8 nm) was found to catalyze the conversion of 1:1 LA/FA to GVL, via hydrogenation of LA where H_2 was generated in situ by metal-mediated FA decomposition.[100] Good productivity (TOF 166 h^{-1}) and 99% GVL selectivity were observed at 150 °C under base-free conditions, whereas activity significantly decreased at lower temperatures (Table 2, entry 20). Notably, concentrated aqueous solution of LA (50 wt %) could be used as substrate, which simulates the original bioderived feeds. No LA conversion was observed in the absence of gold or using Au/C, although other zirconia-supported noble metals (Pd, Pt, Ru) were far less effective. This latter finding was attributed to catalyst poisoning by CO formed in consequence of FA dehydration reaction. In the event that external H_2 was used as hydrogen source, achievement of comparable performance required 40 bar H_2 pressure, whereas the catalytic activity was in the order Ru/ZrO_2 > Pt/ZrO_2 > Au/ZrO_2 ≥ Pd/ZrO_2, in that case. Similar results were obtained in a more recent work in which Au/ZrO_2 catalysts with different gold content were tested.[101] Use of the optimal 3 wt % Au/ZrO_2 catalyst confirmed that LA conversion using FA as a hydrogen source is strongly dependent on reaction temperature, with 130 °C being the lower limit to achieve efficient FA decomposition (Table 2, entry 21). The catalyst could be reused with 10% GVL yield loss over five consecutive runs.

Conversion of LA/FA mixtures to GVL by zirconia-supported non-noble metals was also possible, albeit at higher metal content and temperature required for the selective decomposition of FA.[102] A modest catalytic activity (TOF 4.8 h^{-1}) was indeed observed using 20 wt % Cu/ZrO_2 at 200 °C in water (Table 2, entry 22). The catalyst could be reused after high temperature H_2 treatment, with no Cu leaching in solution detected. In contrast to the above-described, for Au/ZrO_2, use of 40 bar H_2 instead of FA as hydrogen source, resulted in better catalyst efficiency (TOF 11.9 h^{-1}). Analogous results were reported in methanol solution.[103]

In order to maintain the performance of zirconia-supported catalyst without detriment of cost effectiveness, a strategy was devised on the basis of appropriate combinations of noble and non-noble metals. Accordingly, bimetallic Ag–Ni NP onto ZrO_2 (10 wt % Ag, 20 wt % Ni) provided higher GVL yield (78%), compared to the corresponding monometallic Ag (22%) and Ni (34%) catalysts, in the conversion of LA/FA in water at 220 °C (Table 2, entry 23).[104]

A series of bimetallic catalysts derived from hydrotalcite with a high loading of non-noble metals (Fe, Cr, Cu) was also reported for the hydrogenation of LA, which required very harsh conditions (200 °C, 70 bar H_2).[18,105]

4. FLOW APPLICATIONS

Compared to conventional batch operations, catalysis under continuous flow usually offers considerable advantages in terms of space-time-yield (STY, up to 1–2 order of magnitude greater), purification, environmental impact, automation and energy consumption.[106] Examples of continuous conversion of LA to GVL have been described in the literature. However, they have been rarely achieved with high yields for long time-on-stream at low energy expenses, i.e. under operating temperature below 100 °C and H_2 pressure (if used) below 10 bar.[16b,22,107] Representative data for recent LA to GVL conversions under continuous flow conditions are reported in Table 3, in which productivities are reported both as TOF and STY.

Earlier studies on the hydrogenation of 90 wt % aqueous solution of LA using 1 wt % Pt/TiO_2 or 0.8 wt % Pt/SiO_2 required 200 °C and 40 bar H_2 to achieve an initial catalyst productivity in the range 1.8–6.5 mol_{GVL} g_{Pt}^{-1} h^{-1} (TOF 300–1300 h^{-1}), which significantly decreased with time.[108,109] Conversion of 50 wt % aqueous LA by 5 wt % Ru/C under 150 °C and 35 bar H_2 resulted in lower GVL yield (ca. 1 mol_{GVL} g_{Ru}^{-1} h^{-1}, TOF 100 h^{-1}), showing ca. 25% activity loss after 106 h operation time.[110] The catalytic activity was partially restored after high-temperature H_2 treatment.

Similar results were more recently reported using a commercial flow reactor packed with 5% Ru/C and 0.1 M LA aqueous feed. A productivity of 0.83 mol_{GVL} g_{Ru}^{-1} h^{-1} was obtained under 10 bar H_2 and 140 °C, without additives (Table 3, entry 1).[111] The catalyst was stable over 3 h on stream use.

Much lower catalytic efficiency was observed using the analogous Pd/C system.

The conversion of LA to GVL using an organic stream containing 1:1 LA: FA (2.0 M) in propyl guaicol and a 5 wt % Ru/C packed bed flow reactor was achieved under 200 °C and 13.8 bar H_2 (Table 3, entry 2).[112] There were multiple reason for choice of propyl guaicol as solvent: (i) it is obtainable by catalytic depolymerization of lignin, (ii) it has a high partition coefficients for extraction of FA and LA from aqueous solutions containing mineral acids (i.e., from the acid-catalyzed hydrolysis solution of cellulose), (iii) its boiling point is higher than that of GVL, so that the final product can be separated by distillation. In this case, GVL was obtained with 94% selectivity at 82% LA conversion (0.33 $\mathrm{mol_{GVL}\ g_{Ru}^{-1}\ h^{-1}}$), with significant contamination (3.6%) by propyl guaicol hydrogenation products. These latter could be suppressed using a bimetallic $RuSn_4/C$ catalyst instead, which showed good stability for 80 h time-on-stream, even though the GVL production rate decreased by 80%.

Using the Ru_xSn_y/C system, similar results were obtained for the hydrogenation of LA in 2-*sec*-butyl-phenol (SBP) solvent.[113] At the optimal catalyst composition Ru_1Sn_1/C, stable activity and 100% selectivity of LA hydrogenation versus SBP hydrogenation was observed under 35 bar H_2 and 180 °C (0.14 $\mathrm{mol_{GVL}\ g_{metal}^{-1}\ h^{-1}}$), although with lower rates compared to Ru/C. Significant Sn leaching in the SBP phase was observed using the $RuSn_4/C$ system.

A careful analysis of the kinetic of aqueous-phase 0.1 M LA hydrogenation over 5 wt % Ru onto 45−90 μm carbon particles was recently carried out.[114] It was demonstrated that the acid-catalyzed 4-HVA ring closure step is the kinetic bottleneck in GVL formation below 70 °C. Hence, an increase of the reaction temperature improves GVL selectivity. However, this is an inefficient choice for increasing productivity, because pore diffusion quickly becomes rate controlling, resulting in a marginal enhancement of the hydrogenation rate upon increase in the reaction temperature. Thus, the additional investment in energy input is not conveniently recovered in terms of GVL yield. It was also shown that the rate of lactonization scales with proton concentration. Therefore, as previously described for batch setups, GVL yield could be improved by introducing an acidic cocatalyst to expedite ring closure. This was achieved using stacked beds of Ru/C and Amberlyst-15 solid acid to deliver GVL quite efficiently under 24 bar H_2 and 50 °C (0.7 $\mathrm{mol_{GVL}\ g_{Ru}^{-1}\ h^{-1}}$, Table 3, entry 3).

The sequential LA hydrogenation−intramolecular 4-HVA esterification at low temperature was elegantly facilitated using a bifunctional catalyst obtained by immobilization−reduction of ruthenium onto Dowex strong cation-exchange sulfonic acid resins (gel-type, 4.8 mmol g^{-1} acidic sites).[115] A productivity of 1.16 $\mathrm{mol_{GVL}\ g_{Ru}^{-1}\ h^{-1}}$ (TOF 117 h^{-1}, STY 0.12 kg l^{-1} h^{-1}, Table 3, entry 4) was obtained using a 0.85 wt % Ru content, 84 μm size catalyst beads, 70 °C and 7 bar H_2, with neither productivity decay nor metal leaching observed over 35 h continuous flow.[116] The superior performance of the Ru/Dowex catalyst was attributed to the favorable combination of well-defined acid and RuNP hydrogenation sites (2.9 nm) on the support, with the optimal resistance and swelling of the resin in water. Larger catalyst beads resulted in lower efficiency due to the internal (diffusive) mass-transfer limitations of gel-type resins.[117] This example shows that the efficient synthesis of GVL can be accomplished under continuous flow and very mild reaction conditions by a straightforward catalyst design using commercial materials, with no need of (acidic) additives, regeneration steps, or high loading of noble metals.

It is worth mentioning that the conversion of 5 wt % LA under continuous flow was conveniently achieved by MPV reduction from 2-propanol solvent, avoiding concurrent H_2 flow, using microporous Zr-Beta zeolite catalyst.[118] A steady productivity of 0.01 $\mathrm{mol_{GVL}\ g_{Zr}^{-1}\ h^{-1}}$ was estimated in the liquid phase during 10 h reaction time at 150 °C (Table 3, entry 5). The catalytic activity was ascribed to the Lewis acid properties of the zeolite which, on the other hand, was responsible for the deactivation of the catalyst due to the strong adsorption of substrate and product molecules. The activity could be recovered after calcination at 500 °C.

The reactive extraction of butyl levulinate to GVL in 95% yield from LA-, FA-, and H_2SO_4-containing feed was also reported over a dual-bed catalytic reactor packed with 10 wt % Pd/C and 5 wt % Ru/C under 35 bar H_2 and 170 °C.[119]

Use of other monometallic carbon-supported catalysts other than ruthenium have been described for the continuous hydrogenation of aqueous LA, although with low productivities under intensive conditions. Conversion and selectivity values higher than 99 and 90%, respectively, were observed under 30 bar of H_2 and 200 °C using 20 wt % molybdenum carbide onto carbon nanotubes.[120]

Notably, a bimetallic 15 wt % Ru_3Re_4/C catalyst was reported for the continuous conversion of a LA feed typical of decomposition of cellulose, i.e., 2.2 M LA and FA and 0.5 M sulfuric acid (Table 3, entry 6).[37a] Despite the relatively harsh conditions (150 °C, 35 bar) required to achieve a moderate productivity (0.02 $\mathrm{mol_{GVL}\ g_{metal}^{-1}\ h^{-1}}$), the catalysts showed to be significantly more active and resistant (up to 150 h time-on-stream) than conventional 5% Ru/C catalyst under the same experimental conditions, and also tolerant to sulfuric acid.

From the above studies, one can learn that higher TOF values for the conversion of LA to GVL may be found for batch compared to flow operations (Table 2 vs Table 3). However, the easier workup, the reduced energy and space consumption, the lower H_2 pressure in contrast to the H_2 static pressure required, and the enhanced catalysts' lifetime, because of the continuous removal of reaction products, compensates well the lower catalyst efficiency both in terms of overall process sustainability and $\mathrm{mol_{GVL}\ g_{metal}^{-1}}$ productivity.

5. CONCLUSIONS

Catalytic conversion of vegetable-biomass-derived substrates to GVL is possible by mean of a variety of catalysts and processes. However, to do so efficiently, high temperatures, organic solvents, additives, troublesome separation procedures, or the management of the relatively high hydrogen pressures are often required, which entail huge energy inputs and the emission of large amounts of waste. New materials and technologies that reduce resources and energy used are therefore desirable.

From this review, critical features affecting the performance of the existing catalysts can be appreciated. Homogeneous systems are usually very efficient; however, their use is restricted by stability, cost, reuse, and environmental drawbacks. On the other hand, activity and selectivity of heterogeneous catalysts are uncertain and regulated by subtle combinations of several factors, including swellability, grain size, surface area of the support, particle size and oxidation state of the supported metal, as well as its interactions with the solid matrix.

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Moreover, most catalysts rely on the use of noble metals and external hydrogen gas supply. These limitations have been elegantly circumvented by the implementation of MPV and CHT-based catalysts that, however, usually need high temperatures to provide acceptable productivities.

It has been demonstrated that the combined use of a strongly acidic catalyst and a hydrogenation metal significantly improves the LA to GVL conversion rate at low temperatures. With respect to rational design, it is clear that these dual systems are best-suited to bifunctional catalysts exhibiting hydrogenation functionality alongside acidity.[114] Table 4 lists significant structural parameters and activity data for the reported bifunctional catalysts enabling LA or LA esters conversion under mild conditions, i.e. $T < 100$ °C and $H_2 < 10$ bar. Both inorganic (HPA) and organic (SPES, Dowex, C) supports featured by different acidic sites (phosphate, sulfonic, Nb_2O_5) and textures have been reported in conjunction with various metals. Direct consequences on the overall catalytic performance at different levels can be inferred from the literature. For instance, it is expected that the presence of Ru of small particles size and a high acidic strength may facilitate the hydrogenation and dehydration steps, respectively, wherein the number of acid sites turn out to be crucial. The thermal stability of the support, arguably cross-linked polymers or inorganic oxides,[121] has importance in terms of long-term catalyst resistance. Other effects may be effective, although less predictable. For instance, the mutual influence of proton and metal sites on the acidic strength and acceleration of hydrogenation reaction as well as the SMSI for e.g. TiO_2 supports.[122] A ruthenium catalyst onto commercial acidic polymer has been recently described with good continuous flow productivity under unprecedented mild conditions,[116] showing that efficiency and low energy consumption can be joined using appropriate combinations of materials and reaction conditions. However, the lack of systematic studies hampers establishing a clear catalyst structure−activity relationship for this type of catalysts. Noticeably, bifunctional catalysts based on 0.1−0.3 wt % Pd-doped macroreticular Amberlyst resins are now commercialized by The Dow Chemical Company.[123]

Table 4. Selected Structural Parameters and Activity Data of Bifunctional Catalysts for LA to GVL Conversion under Mild Conditions

catalyst	NP size[a] (nm)	porosity[b]	acid sites[c] (mmol g^{-1})	TOF[d] (h^{-1})	ref
5% Ru/HAP	15	macro	0.015	86	88
2% Ru/SPES	3.0	-[e]	3.8	380[f]	90
0.85% Ru/Dowex	2.9	micro	4.8	117[g]	116
3% Pd/Nb_2O_5−C	1.7	meso	0.097	62	95

[a]MNP size. [b]Support porosity: macro >50 nm; meso 2 ÷ 50 nm; micro <2 nm.[43] [c]Measured density of acid sites. [d]Turnover frequency, as (mol substrate converted)/(mol noble metal × h). Calculated from literature data at 87−99% conversion. [e]Not measured. [f]Under 30 bar H_2 pressure. [g]Under continuous flow conditions.

In conclusion, there is still a long way to go to achieve the long-term sustainability of GVL production. Issues need to be solved related to catalyst stability, use of non-noble metals and conversion of concentrated aqueous solutions. Macroreticular supports or monolithic reactors may be beneficial for use in continuous flow processes.

Hopefully, GVL synthesis represents a case study whose solution could open up new perspectives for the one-pot conversion of renewable substrates to other high-added value chemicals, e.g., sorbitol, isosorbide, 1,6-hexanediol, 2,5-dimethylfuran, 1,2-propandiol.[124]

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Notes

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■ REFERENCES

(1) Horváth, I. T.; Mehdi, H.; Fabos, V.; Boda, L.; Mika, L. T. *Green Chem.* **2008**, *10*, 238−242.

(2) For recent reviews on GVL use, see: (a) Tang, X.; Zeng, X.; Li, Z.; Hu, L.; Sun, Y.; Liu, S.; Lei, T.; Lin, L. *Renew. Sust. Energy Rev.* **2014**, *40*, 608−620. (b) Gu, Y.; Jérôme, F. *Chem. Soc. Rev.* **2013**, *42*, 9550−9570. (c) Alonso, D. M.; Wettstein, S. G.; Dumesic, J. A. *Green Chem.* **2013**, *15*, 584−595.

(3) For recent examples, see: (a) Han, J.; Sen, S. M.; Alonso, D. M.; Dumesic, J. A.; Maravelias, C. T. *Green Chem.* **2014**, *16*, 653−661. (b) Al-Shaal, M. G.; Dzierbinski, A.; Palkovits, R. *Green Chem.* **2014**, *16*, 1358−1364. (c) Chan-Thaw, C. E.; Marelli, M.; Psaro, R.; Ravasio, N.; Zaccheria, F. *RSC Adv.* **2013**, *3*, 1302−1306. (d) Serrano-Ruiz, J. C.; Pineda, A.; Balu, A. M.; Luque, R.; Campelo, J. M.; Romero, A. A.; Ramos-Fernández, J. M. *Catal. Today* **2012**, *195*, 162−168. (e) Buitrago-Sierra, R.; Serrano-Ruiz, J. C.; Rodríguez-Reinoso, F.; Sepúlveda-Escribano, A.; Dumesic, J. A. *Green Chem.* **2012**, *14*, 3318−3324.

(4) For recent examples, see: (a) Raoufmoghaddam, S.; Rood, M. T. M.; Buijze, F. K. W.; Drent, E.; Bouwman, E. *ChemSusChem* **2014**, *7*, 1984−1990. (b) Van de Vyver, S.; Román-Leshkov, Y. *Catal. Sci. Technol.* **2013**, *3*, 1465−1479. (c) Chalid, M.; Heeres, H. J.; Broekhuis, A. A. *J. Appl. Polym. Sci.* **2012**, *123*, 3556−3564. (d) Rose, M.; Palkovits, R. *Macromol. Rapid Commun.* **2011**, *32*, 1299−1311.

(5) For recent examples, see: (a) Wang, D.; Hakim, S. H.; Alonso, D. M.; Dumesic, J. A. *Chem. Commun.* **2013**, *49*, 7040−7042. (b) Zeng, F. X.; Liu, H. F.; Deng, L.; Liao, B.; Pang, H.; Guo, Q. X. *ChemSusChem* **2013**, *6*, 600−603. (c) Du, X. L.; Bi, Q. Y.; Liu, Y. M.; Cao, Y.; He, H. Y.; Fan, K. N. *Green Chem.* **2012**, *14*, 935−939. (d) Bond, J. Q.; Alonso, D. M.; West, R. M.; Dumesic, J. A. *Langmuir* **2010**, *26*, 16291−16298.

(6) For recent examples, see: (a) Qi, L.; Mui, Y. F.; Lo, S. W.; Lui, M. Y.; Akien, G. R.; Horváth, I. T. *ACS Catal.* **2014**, *4*, 1470−1477. (b) Boissou, F.; Mühlbauer, A.; De Oliveira Vigier, K.; Leclercq, L.; Kunz, W.; Marinkovic, S.; Estrine, B.; Nardello-Rataj, V.; Jérôme, F. *Green Chem.* **2014**, *16*, 2463−2471. (c) Luterbacher, J. S.; Rand, J. M.; Alonso, M. D.; Han, J.; Youngquist, J. T.; Maravelias, C. T.; Pfleger, B. F.; Dumesic, J. A. *Science* **2014**, *343*, 277−280. (d) Gürbüz, E. I.; Gallo, J. M. R.; Alonso, D. M.; Wettstein, S. G.; Lim, W. Y.; Dumesic, J. A. *Angew. Chem., Int. Ed.* **2013**, *52*, 1270−1274. (e) Alonso, D. M.; Gallo, J. M. R.; Mellmer, M. A.; Wettstein, S. G.; Dumesic, J. A. *Catal. Sci. Technol.* **2013**, *3*, 927−931. (f) Alonso, D. M.; Wettstein, S. G.; Mellmer, M. A.; Gürbüz, E. I.; Dumesic, J. A. *Energy Environ. Sci.* **2013**, *6*, 76−80. (g) Strádi, A.; Molnár, M.; Óvári, M.; Dibó, G.; Richter, F. U.; Mika, L. T. *Green Chem.* **2013**, *15*, 1857−1862. (h) Duan, Z. Q.; Hu, F. *Green Chem.* **2012**, *14*, 1581−1583. (i) Wettstein, S. G.; Alonso, D. M.; Chong, Y.; Dumesic, J. A. *Energy Environ. Sci.* **2012**, *5*, 8199−8203.

(7) (a) Tanaka, S.; Fukuda, K.; Asada, T. (Kao Corp.). Patent No. EP1555261A1, 2005. (b) *Volatile components in food: Qualitative and quantitative data - Vol. III*; Maarse, H.; Visscher, C. A.; Willimsens, L.

C.; Nijssen, L. M.; Boelens, M. H., Ed.; 6th ed. Centraal Instituut Voor Voedingsonderzoek TNO: Zeist, The Netherlands, 1994. (c) Horman, I.; Cazenave, P. (Nestle SA). Patent No. CA1039563 A1, 1978.

(8) (a) Marinetti, L. J.; Leavell, B. J.; Jones, C. M.; Hepler, B. R.; Isenschmid, D. S.; Commissaris, R. L. *Pharmacol. Biochem. Be.* **2012**, *101*, 602−608. (b) Fábos, V.; Koczó, G.; Mehdi, H.; Boda, L.; Horváth, I. T. *Energy Envrion. Sci.* **2009**, *2*, 767−769. (c) EPA, Substance Registry Services http://iaspub.epa.gov/sor_internet/ (accessed Sept 3, 2014). (d) NIH, National Toxicology Program. https://www.erowid.org/chemicals/ghv/ghv_info2.shtml (accessed Sept 3, 2014).

(9) For research policies on renewables conversion, see: (a) *Promotion of the use of energy from renewable sources*; Directive 2009/28/EC of the European Parliament, 23 April 2009. (b) *Roadmap for Biomass Technologies in the United States*; U.S. Department of Energy: Washington DC, 2002. (c) *Kyoto protocol to the united nations framework convention on climate change*, United Nations, 1998, http://unfccc.int/resource/docs/convkp/kpeng.pdf. (d) *Energy for the future: renewable sources of energy*; European Commission, COM(97)599 final, November 26, 1997.

(10) For roadmaps and perspectives, see: (a) Sheldon, R. A. *Catal. Today* **2011**, *167*, 3−13. (b) Cheng, J. *Biomass to Renewable Energy Processes*; CRC Press: Boca Raton, 2010. (c) *Catalysis for Renewables*; Centi, G., van Santen, R. A., Eds.; Wiley-VCH: Weinheim, 2007. (d) Wettstein, S. G.; Alonso, D. M.; Gürbüz, E. I.; Dumesic, J. *A Curr. Op. Chem. Eng.* **2012**, *1*, 218−224.

(11) For recent reviews on vegetable biomass conversion, see: (a) Deuss, P. J.; Barta, K.; de Vries, J. G. *Catal. Sci. Technol.* **2014**, *4*, 1174−1196. (b) Climent, M. J.; Corma, A.; Iborra, S. *Green Chem.* **2014**, *16*, 516−547. (c) Sheldon, R. A. *Green Chem.* **2014**, *16*, 950−963. (d) Gallezot, P. *Chem. Soc. Rev.* **2012**, *41*, 1538−1558. (e) Alonso, D. M.; Wettstein, S. G.; Dumesic, J. A. *Chem. Soc. Rev.* **2012**, *41*, 8075−8098. (f) Tuck, C. O.; Pérez, E.; Horváth, I. T.; Sheldon, R. A.; Poliakoff, M. *Science* **2012**, *337*, 695−699. (g) Kobayashi, H.; Ohta, H.; Fukuoka, A. *Catal. Sci. Technol.* **2012**, *2*, 869−883. (h) Ruppert, A. M.; Weinberg, K.; Palkovits, R. *Angew. Chem., Int. Ed.* **2012**, *51*, 2564−2601. (i) Centi, G.; Lanzafame, P.; Perathoner, S. *Catal. Today* **2011**, *167*, 14−30. (l) Serrano-Ruiz, J. C.; Luque, R.; Sepúlveda-Escribano, A. *Chem. Soc. Rev.* **2011**, *40*, 5266−5281. (m) Van de Vyver, S.; Geboers, J.; Jacobs, P. A.; Sels, B. F. *ChemCatChem.* **2011**, *3*, 82−94. (n) Corma, A.; Iborra, S.; Velty, A. *Chem. Rev.* **2007**, *107*, 2411−2502.

(12) For studies on single steps, see: (a) Chen, J.; Zhao, G.; Chen, L. *RSC Adv.* **2014**, *4*, 4194−4202. (b) van Putten, R. J.; van der Waal, J. C.; de Jong, E.; Rasrendra, C. B.; Heeres, H. J.; de Vries, J. G. *Chem. Rev.* **2013**, *133*, 1499−1597. (c) Hu, L.; Zhao, G.; Hao, W.; Tang, X.; Sun, Y.; Lin, L.; Liu, S. *RSC Adv.* **2012**, *2*, 11184−11206. (d) Lange, J. P.; van der Heide, E.; van Buijtenen, J.; Price, R. *ChemSusChem* **2012**, *5*, 150−166. (e) Lincai, P.; Lu, L.; Hui, L.; Qiulin, Y. *Appl. Energy* **2011**, *88*, 4590−4596. (f) Mascal, M.; Nikitin, E. B. *Green Chem.* **2010**, *12*, 370−373. (g) Girisuta, B.; Janssen, L. P. B. M.; Heeres, H. J. *Ind. Eng. Chem. Res.* **2007**, *46*, 1696−1708.

(13) For recent examples of MPV reductions, see: (a) Wise, N. J.; Williams, J. M. J. *Tetrahedron Lett.* **2007**, *48*, 3639−3641. (b) Corma, A.; Domine, M. E.; Valencia, S. *J. Catal.* **2003**, *215*, 294−304.

(14) For recent examples of CTH reductions, see: (a) Tang, X.; Chen, H.; Hu, L.; Hao, W.; Sun, Y.; Zeng, X.; Lin, L.; Liu, S. *Appl. Catal. B. Environ.* **2014**, *147*, 827−834. (b) Yi, G.; Zhang, Y. G. *ChemSusChem* **2012**, *5*, 1383−1387.

(15) Electrocatalytic reduction methods have also been reported, see: Xin, L.; Zhang, Z.; Qi, J.; Chadderdon, D. J.; Qiu, Y.; Warsko, K. M.; Li, W. *ChemSusChem* **2013**, *6*, 674−686.

(16) For sustainability issues in biomass conversion, see: (a) *Sustainable catalytic conversions of renewable substrates* themed issue; Bruijnincx, P. C. A.; Román-Leshko Y., Eds.; *Catal. Sci. Technol.* **2014**. (b) *Sustainable Catalysis: Challenges and Practices for the Pharmaceutical and Fine Chemical Industries*, Dunn, P. J., Hii, K. K., Krische, M. J., Williams, M. T., Eds.; Wiley: Weinheim, 2013.

(17) (a) Sheldon, R. A.; Arends, I.; Hanefeld, U. *Green Chemistry and Catalysis*; Wiley-VCH: Weinheim, 2007. (b) *Green Chemistry: Theory and Practice*; Anastas, P. T., Warner, J. C., Eds.; Oxford University Press: Oxford, 1998.

(18) Yan, K.; Chen, A. *Fuel* **2014**, *115*, 101−108.

(19) Dahl, J. A.; Maddux, B. L. S.; Hutchison, J. E. *Chem. Rev.* **2007**, *107*, 2228−2269.

(20) (a) Gritzner, G.; Kreysa, G. *Pure Appl. Chem.* **1993**, *65*, 1009−1020. (b) Pletcher, D.; Walsh, F. *Industrial Electrochemistry*; Springer: London, U.K., 1990; p 83.

(21) Wiles, C.; Watts, P. *Green Chem.* **2014**, *16*, 55−62.

(22) Dach, R.; Song, J. J.; Roschangar, F.; Samstag, W.; Senanayake, C. H. *Org. Process Res. Dev.* **2012**, *16*, 1697−1706.

(23) For benefits of one-pot vs sequential processes, see: (a) Li, H.; Bhadury, P. S.; Riisager, A.; Yang, S. *Catal. Sci. Technol.* **2014**, *4*, 4138−4168. (b) Wu, Z.; Ge, S.; Ren, C.; Zhang, M.; Yip, A.; Xu, C. *Green Chem.* **2012**, *14*, 3336−3343. (c) Hayes, D. J.; Fitzpatrick, S.; Hayes, M. H. B.; Ross, J. R. H. *Biorefineries − Industrial Processes and Products*; Wiley-VCH Verlag GmbH: Weinheim, 2008, 139−164.

(24) For recent examples of GVL catalytic synthesis in separate reaction units, see: Molinari, V.; Antonietti, M.; Esposito, D. *Catal. Sci. Technol.* **2014**, *4*, 3626−3630.

(25) (a) Lucarelli, C.; Vaccari, A. *Green Chem.* **2011**, *13*, 1941−1949. (b) *Heterogenized Homogeneous Catalysts for Fine Chemicals Production*; Barbaro, P., Liguori, F., Eds.; Springer: London, 2010. (c) Pugin, B.; Blaser, H. U. *Top. Catal.* **2010**, *53*, 953−962. (d) *Catalyst Separation, Recovery and Recycling; Chemistry and Process Design*; Cole-Hamilton, D. J., Tooze, R. P., Eds.; Springer: Dordrecht, 2006. (e) *Fine Chemicals Through Heterogeneous Catalysis*; Sheldon, R. A., van Bekkum, H., Eds.; Wiley-VCH: Weinheim, 2001.

(26) Sen, S. M.; Alonso, D. M.; Wettstein, S. G.; Gürbüz, E. I.; Henao, C. A.; Dumesic, J. A.; Maravelias, C. T. *Energy Environ. Sci.* **2012**, *5*, 9690−9697.

(27) Luo, W.; Deka, U.; Beale, A. M.; van Eck, E. R. H.; Bruijnincx, P. C. A.; Weckhuysen, B. M. *J. Catal.* **2013**, *301*, 175−186.

(28) For recent reviews on GVL synthesis, see: (a) Climent, M. J.; Corma, A.; Iborra, S.; Sabater, M. J. *ACS Catal.* **2014**, *4*, 870−891. (b) Démolis, A.; Essayem, N.; Rataboul, F. *ACS Sustainable Chem. Eng.* **2014**, *2*, 1338−1352. (c) Zhang, J.; Wu, S. B.; Li, B.; Zhang, H. D. *ChemCatChem.* **2012**, *4*, 1230−1237. (d) Sen, S. M.; Henao, C. A.; Braden, D. J.; Dumesic, J. A.; Maravelias, C. T. *Chem. Eng. Sci.* **2012**, *67*, 57−67. (e) Wright, W. R. H.; Palkovits, R. *ChemSusChem* **2012**, *5*, 1657−1667.

(29) Upare, P. P.; Lee, J. M.; Hwang, D. W.; Halligudi, S. B.; Hwang, Y. K.; Chang, J. S. *J. Ind. Eng. Chem.* **2011**, *17*, 287−292.

(30) (a) Ragauskas, A. J.; Williams, C. K.; Davison, B. H.; Britovsek, G.; Cairney, J.; Eckert, C. A.; Frederick, W. J.; Hallett, J. P.; Leak, D. J.; Liotta, C. L.; Mielenz, J. R.; Murphy, R.; Templer, R.; Tschaplinski, T. *Science* **2006**, *311*, 484−489. (b) Bozell, J. J.; Moens, L.; Elliott, D. C.; Wang, Y.; Neuenscwander, G. G.; Fitzpatrick, S. W.; Bilski, R. J.; Jarnefeld, J. L. *Resour. Conserv. Recycl.* **2000**, *28*, 227−239.

(31) For potentials of LA, see: (a) Selva, M.; Gottardo, M.; Perosa, A. *ACS Sustainable Chem. Eng.* **2013**, *1*, 180−189. (b) Bozell, J. J. *Green Chem.* **2010**, *12*, 525−728. (c) Werpy, T.; Petersen, G. *Top Value Added Chemicals from Biomass. Vol. I: Results of Screening for Potential Candidates from Sugars and Synthesis Gas*; U.S. Department of Energy, Energy Efficiency and Renewable Energy, 2004. (d) Patel, A. D.; Serrano-Ruiz, J. C.; Dumesic, J. A.; Anex, R. P. *Chem. Eng. J.* **2010**, *160*, 311−321.

(32) (a) Fitzpatrick, S. W. (Biofine Technologies LLC). U.S. Patent No. US2010234638A1, 2010. (b) Hayes, D. J.; Fitzpatrick, S.; Hayes, M. H. B.; Ross, J. R. H. In *Biorefineries-Industrial Processes and Products: Status Quo and Future Directions; The Biofine Process − Production of Levulinic Acid, Furfural, and Formic Acid from Lignocellulosic Feedstocks*; Kamm, B., Gruber, P. R., Kamm, M., Eds.; Wiley: Weinheim, 2008. (c) Zeitsch, K. J. *The Chemistry and Technology of Furfural and Its Many By-Products*, 1st ed.; Elsevier: Amsterdam, 2000, Vol. *13*, pp 150−155. (d) Fitzpatrick, S. W. (Biofine Inc.) U.S. Patent No. US5608105, 1997.

(33) (a) Rackemann, D. W.; Doherty, W. O. S. *Biofuel Bioprod. Bior.* **2011**, *5*, 198−214. (b) Horvat, J.; Klaic, B.; Metelko, B.; Sunjic, V. *Tetrahedron Lett.* **1985**, *26*, 2111−2114.

(34) (a) Wettstein, S. G.; Bond, J. Q.; Alonso, D. M.; Pham, H. N.; Datye, A. K.; Dumesic, J. A. *Appl. Catal. B. Environ.* **2012**, *117−118*, 321−329. (b) Du, X. L.; Bi, Q. Y.; Liu, Y. M.; Cao, Y.; Fan, K. N. *ChemSusChem* **2011**, *4*, 1838−1843. (c) Alonso, D. M.; Wettstein, S. G.; Bond, J. Q.; Root, T. W.; Dumesic, J. A. *ChemSusChem* **2011**, *4*, 1078−1081. (d) Ayoub, P. M. (Shell International Research Maatschappij B. V., The Netherlands). Patent No. WO2005070867A1, 2005.

(35) (a) Gong, Y.; Lin, L.; Yan, Z. *Bioresources* **2011**, *6*, 686−699. (b) Starodubtseva, E. V.; Turova, O. V.; Vinogradov, M. G.; Gorshkova, L. S.; Ferapontov, V. A. *Russ. Chem. Bull.* **2005**, *54*, 2374−2378.

(36) Al-Shaal, M. G.; Wright, W. R. H.; Palkovits, R. *Green Chem.* **2012**, *14*, 1260−1263.

(37) (a) Braden, D. J.; Henao, C. A.; Heltzel, J.; Maravelias, C. T.; Dumesic, J. A. *Green Chem.* **2011**, *13*, 1755−1765. (b) Osada, M.; Hiyoshi, N.; Sato, O.; Arai, K.; Shirai, M. *Energy Fuels* **2008**, *22*, 845−849.

(38) (a) Deng, L.; Li, J.; Lai, D. M.; Fu, Y. X.; Guo, Q. *Angew. Chem., Int. Ed.* **2009**, *48*, 6529−6532. (b) Mehdi, H.; Fabos, V.; Tuba, R.; Bodor, A.; Mika, L. T.; Horvath, I. T. *Top. Catal.* **2008**, *48*, 49−54.

(39) Stankiewicz, A. I.; Moulijn, J. A. *Chem. Eng. Prog.* **2000**, 22−34.

(40) (a) Choudhary, V.; Mushrif, S. H.; Ho, C.; Anderko, A.; Nikolakis, V.; Marinkovic, N. S.; Frenkel, A. I.; Sandler, S. I.; Vlachos, D. G. *J. Am. Chem. Soc.* **2013**, *135*, 3997−4006. (b) Chambon, F.; Rataboul, F.; Pinel, C.; Cabiac, A.; Guillon, E.; Essayem, N. *Appl. Catal. B. Environ.* **2011**, *105*, 171−179. (c) Shimizu, K.; Furukawa, H.; Kobayashi, N.; Itaya, Y.; Satsuma, A. *Green Chem.* **2009**, *11*, 1627−1632. (d) Suganuma, S.; Nakajima, K.; Kitano, M.; Yamaguchi, D.; Kato, H.; Hayashi, S.; Hara, M. *J. Am. Chem. Soc.* **2008**, *130*, 12787−12793.

(41) (a) Bond, J. Q.; Alonso, D. M.; Wang, D.; West, R. M.; Dumesic, J. A. *Science* **2010**, *327*, 1110−1114. (b) Heeres, H.; Handana, R.; Chunai, D.; Rasrendra, C. B.; Girisuta, B.; Heeres, H. J. *Green Chem.* **2009**, *11*, 1247−1255.

(42) Vargaftik, M. N.; Kozitsyna, N. Y.; Cherkashina, N. V.; Rudyi, R. I.; Kochubei, D. I.; Novgorodov, B. N.; Moiseev, I. I. *Kinet. Catal.* **1998**, *39*, 740−757.

(43) IUPAC. *Manual of Symbols and Terminology for Physicochemical Quantities and Units - Appendix II., Pure Appl. Chem.* **1976**, *46*, 71−90.

(44) (a) Conley, B. L.; Pennington-Boggio, M. K.; Boz, E.; Williams, T. J. *Chem. Rev.* **2010**, *110*, 2294−2312. (b) Blum, Y.; Reshef, D.; Shvo, Y. *Tetrahedron Lett.* **1981**, *22*, 1541−1544.

(45) Fábos, V.; Mika, L. T.; Horváth, I. T. *Organometallics* **2014**, *33*, 181−187.

(46) Qi, L.; Horváth, I. T. *ACS Catal.* **2012**, *2*, 2247−2249.

(47) Deng, J.; Wang, Y.; Pan, T.; Xu, Q.; Guo, Q. X.; Fu, Y. *ChemSusChem* **2013**, *6*, 1163−1167.

(48) Ortiz-Cervantes, C.; García, J. J. *Inorg. Chim. Acta* **2013**, *397*, 124−128.

(49) Tukacs, J. M.; Király, D.; Strádi, A.; Novodarszki, G.; Eke, Z.; Dibó, G.; Kégl, T.; Mika, L. T. *Green Chem.* **2012**, *14*, 2057−2065.

(50) (a) Delhomme, C.; Schaper, L. A.; Zhang-Preße, M.; Raudaschl-Sieber, G.; Weuster-Botz, D.; Kühn, F. E. *J. Organomet. Chem.* **2013**, *724*, 297−299. (b) Chalid, M.; Broekhuis, A. A.; Heeres, H. J. *J. Mol. Catal. A: Chem.* **2011**, *341*, 14−21.

(51) Tukacs, J. M.; Novák, M.; Dibób, G.; Mika, L. T. *Catal. Sci. Technol.* **2014**, *4*, 2908−2912.

(52) Geilen, F. M. A.; Engendahl, B.; Harwardt, A.; Marquardt, W.; Klankermayer, J.; Leitner, W. *Angew. Chem., Int. Ed.* **2010**, *49*, 5510−5514.

(53) Li, W.; Xie, J. H.; Lin, H.; Zhou, Q. L. *Green Chem.* **2012**, *14*, 2388−2390.

(54) The term *bifunctional catalyst* refers to the conventional nomenclature adopted for catalysts having differentiated metal and acid sites. For recent reviews, see: (a) Barbaro, P.; Liguori, F.; Linares, N.; Moreno-Marrodan, C. *Eur. J. Inorg. Chem.* **2012**, 3807−3823. (b) Li, P.; Yamamoto, H. *Top. Organomet. Chem.* **2011**, *37*, 161−184. (c) Climent, M. J.; Corma, A.; Iborra, S. *Chem. Rev.* **2011**, *111*, 1072−1133. (d) Serrano-Ruiz, J. C.; West, R. M.; Dumesic, J. A. *Annu. Rev. Chem. Biomol. Eng.* **2010**, *1*, 79−100.

(55) An alternative definition of bifunctional catalyst was proposed referring to supported single-site metal catalysts exhibiting both hydrogenation and Lewis acidity activities, see reference 60.

(56) For recent reviews on solid acid catalysts, see: (a) Ciriminna, R.; Demma Carà, P.; Lopez-Sanchez, J. A.; Pagliaro, M. *ChemCatChem.* **2014**, *6*, 3053−3059. (b) Gupta, P.; Paul, S. *Catal. Today* **2014**, *236*, 153−170. (c) Shimizu, K.; Satsuma, A. *Energy Environ. Sci.* **2011**, *4*, 3140−3153. (d) Macht, J.; Carr, R. T.; Iglesia, E. *J. Catal.* **2009**, *264*, 54−66. (e) Corma, A.; García, H. *Chem. Rev.* **2003**, *103*, 4307−4365.

(57) See, e.g.: (a) Nie, Y.; Jaenicke, S.; Chuah, G. K. *Chem.—Eur. J.* **2009**, *15*, 1991−1999. (b) Mertens, P.; Verpoort, F.; Parvulescu, A. N.; De Vos, D. *J. Catal.* **2006**, *243*, 7−13.

(58) (a) Zhou, H.; Song, J.; Fan, H.; Zhang, B.; Yang, Y.; Hu, J.; Zhu, Q.; Han, B. *Green Chem.* **2014**, *16*, 3870−3875. (b) Geboers, J.; Wang, X.; Bruno de Carvalho, A.; Rinaldi, R. *J. Mol. Catal. A: Chem.* **2014**, *106−115*, 388−389. (c) Yang, Z.; Huang, Y. B.; Guo, Q. X.; Fu, Y. *Chem. Commun.* **2013**, *49*, 5328−5330. (d) Di Mondo, D.; Ashok, D.; Waldie, F.; Schrier, N.; Morrison, M.; Schlaf, M. *ACS Catal.* **2011**, *1*, 355−364.

(59) Manzer, L. E. *Appl. Catal. A: Gen.* **2004**, *272*, 249−256.

(60) Scotti, N.; Dangate, M.; Gervasini, A.; Evangelisti, C.; Ravasio, N.; Zaccheria, F. *ACS Catal.* **2014**, *4*, 2818−2826.

(61) Saravanamurugan, S.; Van Buu, O. N.; Riisager, A. *ChemSusChem* **2011**, *4*, 723−726.

(62) Hengne, A. M.; Biradar, N. S.; Rode, C. V. *Catal. Lett.* **2012**, *142*, 779−787.

(63) Yan, Z.; Lin, L.; Liu, S. *Energy Fuels* **2009**, *23*, 3853−3858.

(64) Yang, Y.; Sun, C.; Ren, Y.; Hao, S.; Jiang, D. *Sci. Rep. UK* **2014**, *4*, Article no. 4540 DOI: 10.1038/srep04540.

(65) Xiong, K.; Zhang, Y. H.; Li, J. L.; Liew, K. Y. *J. Energy Chem.* **2013**, *22*, 560−566.

(66) Yan, K.; Lafleur, T.; Liao, J. *J. Nanopart. Res.* **2013**, *15*, 1906−1913.

(67) Du, X.; Liu, Y.; Wang, J.; Cao, Y.; Fan, K. *Chin. J. Catal.* **2013**, *34*, 993−1001.

(68) Yan, K.; Lafleur, T.; Wu, G.; Liao, J.; Ceng, C.; Xie, X. *Appl. Catal. A: Gen.* **2013**, *468*, 52−58.

(69) Yan, K.; Lafleur, T.; Jarvis, C.; Wu, G. *J. Clean. Prod.* **2014**, *72*, 230−232.

(70) Yang, Y.; Gao, G.; Zhang, X.; Li, F. *ACS Catal.* **2014**, *4*, 1419−1425.

(71) Zhou, W. P.; Lewera, A.; Larsen, R.; Masel, R. I.; Bagus, P. S.; Wieckowski, A. *J. Phys. Chem. B* **2006**, *110*, 13393−13398.

(72) Hengne, A. M.; Kamble, S. B.; Rode, C. V. *Green Chem.* **2013**, *15*, 2540−2547.

(73) BMIm-SH = 1-Butyl sulfonic acid, 3-methyl imidazolium.

(74) Raspolli Galletti, A. M.; Antonetti, C.; De Luise, V.; Martinelli, M. *Green Chem.* **2012**, *14*, 688−694.

(75) (a) Laufer, W.; Niederer, J. P. M.; Hoelderich, W. F. *Adv. Synth. Catal.* **2002**, *34*, 1084−1089. (b) Miller, T.; Mojet, B. L.; Ramaker, D. E.; Koningsberger, D. C. *Catal. Today* **2000**, *62*, 101−114.

(76) Miyazawa, T.; Koso, S.; Kunimori, K.; Tomishige, K. *Appl. Catal., A* **2007**, *318*, 244−251.

(77) Seki, T.; Grundwaldt, J. D.; van Vegten, N.; Baiker, A. *Adv. Synth. Catal.* **2008**, *350*, 691−705.

(78) (a) Carniti, P.; Gervasini, A.; Biella, S.; Auroux, A. *Catal. Today* **2006**, *118*, 373−378. (b) Tanabe, K.; Okazaki, S. *Appl. Catal. A: Gen.* **1995**, *133*, 191−218. (c) Alberti, G.; Costantino, U. *J. Mol. Catal.* **1984**, *27*, 235−250.

(79) Dow Products Website. www.dow.com/products/product/amberlyst-70 (accessed October 1, 2014).

(80) Lermer, H.; Draeger, M.; Steffen, J.; Unger, K. K. *Zeolites* **1985**, *5*, 131−134.

(81) Nadgeri, J. M.; Hiyoshi, N.; Yamaguchi, A.; Sato, O.; Shirai, M. *Appl. Catal. A: Gen.* **2014**, *470*, 215−220.

(82) Haw, J. F. *Phys. Chem. Chem. Phys.* **2002**, *4*, 5431−5441.

(83) Ding, D.; Wang, J.; Xi, J.; Liu, X.; Lu, G.; Wang, Y. *Green Chem.* **2014**, *16*, 3846−3853.

(84) Nowak, I.; Ziolek, M. *Chem. Rev.* **1999**, *99*, 3603−3624.

(85) Bui, L.; Luo, H.; Gunther, W. R.; Román-Leshkov, Y. *Angew. Chem., Int. Ed.* **2013**, *52*, 8022−8025.

(86) Raspolli Galletti, A. M.; Antonetti, C.; Ribechini, E.; Colombini, M. P.; Nassi o Di Nasso, N.; Bonari, E. *Appl. Energy* **2013**, *102*, 157−162.

(87) (a) Carniti, P.; Gervasini, A.; Tiozzo, C.; Guidotti, M. *ACS Catal.* **2014**, *4*, 469−479. (b) Lamonier, C.; Lamonier, J. F.; Aellach, B.; Ezzamarty, A.; Leglise, J. *Catal. Today* **2010**, *164*, 124−130.

(88) Sudhakar, M.; Lakshmi Kantam, M.; Swarna Jaya, V.; Kishore, R.; Ramanujachary, K. V.; Venugopal, A. *Catal. Commun.* **2014**, *50*, 101−104.

(89) Tang, Y.; Miao, S.; Shanks, B. H.; Zheng, X. *Appl. Catal., A* **2010**, *375*, 310−317.

(90) Yao, Y.; Wang, Z.; Zhao, S.; Wang, D.; Wu, Z.; Zhang, M. *Catal. Today* **2014**, *234*, 245−250.

(91) Corbel-Demailly, L.; Ly, B. K.; Minh, D. P.; Tapin, B.; Especel, C.; Epron, F.; Cabiac, A.; Guillon, E.; Besson, M.; Pinel, C. *ChemSusChem* **2013**, *6*, 2388−2395.

(92) (a) Drisko, G. L.; Sanchez, C. *Eur. J. Inorg. Chem.* **2012**, 5097−5105. (b) *Hybrid Materials: Synthesis, Characterization, and Applications*; Kickelbick, G., Ed.; Wiley-VCH: Weinheim, 2007.

(93) Xiong, H.; Pham, H. N.; Datye, A. K. *J. Catal.* **2013**, *302*, 93−100.

(94) (a) Xiong, H.; Wang, T.; Shanks, B. H.; Datye, A. K. *Catal. Lett.* **2013**, *143*, 509−516. (b) Tanabe, K. *Catal. Today* **2003**, *78*, 65−77.

(95) Ye, F.; Zhang, D.; Xue, T.; Wang, Y.; Guan, Y. *Green Chem.* **2014**, *16*, 3951−3957.

(96) Shimizu, K.; Kannoa, S.; Kon, K. *Green Chem.* **2014**, *16*, 3899−3903.

(97) (a) Gürbüz, E. I.; Kunkes, E. L.; Dumesic, J. A. *Appl. Catal., B* **2010**, *94*, 134−141. (b) Tanabe, K.; Yamaguchi, T. *Catal. Today* **1994**, *20*, 185−197. (c) Yamaguchi, T. *Catal. Today* **1994**, *20*, 199−217.

(98) (a) Chuah, G. K.; Jaenicke, S.; Zhu, Y. Z.; Liu, S. H. *Curr. Org. Chem.* **2006**, *10*, 1639−1654. (b) Zhu, Y.; Liu, S.; Jaenicke, S.; Chuah, G. *Catal. Today* **2004**, *97*, 249−255. (c) Zhao, Y.; Li, W.; Zhang, M.; Tao, K. *Catal. Commun.* **2002**, *3*, 239−245.

(99) Chia, M.; Dumesic, J. A. *Chem. Commun.* **2011**, *47*, 12233−12235.

(100) Du, X. L.; He, L.; Zhao, S.; Liu, Y. M.; Cao, Y.; He, H. Y.; Fan, K. N. *Angew. Chem., Int. Ed.* **2011**, *50*, 7815−7819.

(101) Son, P. A.; Nishimura, S.; Ebitani, K. *RSC Adv.* **2014**, *4*, 10525−10530.

(102) Yuan, J.; Li, S. S.; Yu, L.; Liu, Y. M.; Cao, Y.; He, H. Y.; Fan, K. N. *Energy Environ. Sci.* **2013**, *6*, 3308−3313.

(103) Hengne, A. M.; Rode, C. V. *Green Chem.* **2012**, *14*, 1064−1072.

(104) Hengne, A. M.; Malawadkar, A. V.; Biradar, N. S.; Rode, C. V. *RSC Adv.* **2014**, *4*, 9730−9736.

(105) Yan, K.; Liao, J.; Wu, X.; Xie, X. *RSC Adv.* **2013**, *3*, 3853−3856.

(106) For recent reviews on continuous flow catalysis, see: (a) Vaccaro, L.; Lanari, D.; Marrocchi, A.; Strappaveccia, G. *Green Chem.* **2014**, *16*, 3680−3704. (b) Newman, S. G.; Jensen, K. F. *Green Chem.* **2013**, *15*, 1456−1472. (c) Anderson, N. G. *Org. Process Res. Dev.* **2012**, *16*, 852−869. (d) Wegner, J.; Ceylan, S.; Kirschning, A. *Adv. Synth. Catal.* **2012**, *354*, 17−57. (e) Irfan, M.; Glasnov, T. N.; Kappe, C. O. *ChemSusChem* **2011**, *4*, 300−316.

(107) *Sustainable Industrial Processes*; Cavani, F., Centi, G., Perathoner, S., Trifirò, F., Eds.; Wiley-VCH: Weinheim, 2009.

(108) Lange, J. P.; Price, R.; Ayoub, P. M.; Louis, J.; Petrus, L.; Clarke, L.; Gosselink, H. *Angew. Chem., Int. Ed.* **2010**, *49*, 4479−4483.

(109) Ayoub, P. M.; Lange, J. P. (Shell International Research Maatschappij B. V., The Netherlands). Patent No. WO 2008142127A1, 2008.

(110) Serrano-Ruiz, J. C.; Wang, D.; Dumesic, J. A. *Green Chem.* **2010**, *12*, 574−577.

(111) Tukacs, J. M.; Jones, R. V.; Darvas, F.; Dibó, G.; Lezsák, G.; Mika, L. T. *RSC Adv.* **2013**, *3*, 16283−16287.

(112) Azadi, P.; Carrasquillo-Flores, R.; Pagán-Torres, Y. J.; Gürbüz, E. I.; Farnood, R.; Dumesic, J. A. *Green Chem.* **2012**, *14*, 1573−1576.

(113) Wettstein, S. G.; Bond, J. Q.; Alonso, D. M.; Pham, H. N.; Datye, A. K.; Dumesic, J. A. *Appl. Catal. B. Environ.* **2012**, *117−118*, 321−329.

(114) Abdelrahman, O. A.; Heyden, A.; Bond, J. Q. *ACS Catal.* **2014**, *4*, 1171−1181.

(115) (a) Gelbard, G. *Ind. Eng. Chem. Res.* **2005**, *44*, 8468−8498. (b) DOW Product Data Sheet, Form No. 177-01509-904..

(116) Moreno-Marrodan, C.; Barbaro, P. *Green Chem.* **2014**, *16*, 3434−3438.

(117) Moreno Marrodan, C.; Berti, D.; Liguori, F.; Barbaro, P. *Catal. Sci. Technol.* **2012**, *2*, 2279−2290.

(118) Wang, J.; Jaenicke, S.; Chuah, G. K. *RSC Adv.* **2014**, *4*, 13481−13489.

(119) Gürbüz, E. I.; Alonso, D. M.; Bond, J. Q.; Dumesic, J. A. *ChemSusChem* **2011**, *4*, 357−361.

(120) Mai, E. F.; Machado, M. A.; Davies, T. E.; Lopez-Sanchez, J. A.; Teixeira da Silva, V. *Green Chem.* **2014**, *16*, 4092−4097.

(121) Kralik, M.; Corain, B.; Zecca, M. *Chem. Papers* **2000**, *54*, 254−264.

(122) Linares, N.; Hartmann, S.; Galarneau, A.; Barbaro, P. *ACS Catal.* **2012**, *2*, 2194−2198.

(123) Dow Water and Process Solutions. http://www.dowwaterandprocess.com/en/products/a/amberlyst_ch28 (accessed December 28, 2014).

(124) (a) Kobayashi, H.; Fukuoka, A. *Green Chem.* **2013**, *15*, 1740−1763. (b) Zhang, J.; Li, J. B.; Wu, S. B.; Liu, Y. *Ind. Eng. Chem. Res.* **2013**, *52*, 11799−11815. (c) Nakagawa, Y.; Tomishige, K. *Catal. Sci. Technol.* **2011**, *1*, 179−190. (d) Karinen, R.; Vilonen, K.; Niemelä, M. *ChemSusChem* **2011**, *4*, 1002−1016.

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