Room-Temperature Asymmetric Transfer Hydrogenation of Biomass-Derived Levulinic Acid to Optically Pure $\gamma$-Valerolactone Using a Ruthenium Catalyst

Vaishali S. Shende,† Amol B. Raut,† Prathamesh Raghav,† Ashutosh A. Kelkar,‡ and Bhalchandra M. Bhanage*†

†Department of Chemistry, Institute of Chemical Technology, Mumbai 400019, India
‡Chemical Engineering and Process Development Division, CSIR-National Chemical Laboratory, Pune 411008, India

Supporting Information

ABSTRACT: This study presents a first report on ruthenium-catalyzed asymmetric transfer hydrogenation (ATH) of levulinic acid (LA) to chiral $\gamma$-valerolactone (GVL). ATH of LA has been explored with Noyori’s chiral catalyst (Ru–TsDPEN) in methanol solvent. Efficacy of ATH reaction of LA was investigated under different reaction conditions such as temperature, catalyst, and hydrogen donor concentration. The effect of various organic tertiary bases along with formic acid (FA) as a hydrogen donor was studied, and N-methylpiperidine with FA (1:1 molar ratio) was revealed as an efficient hydrogen donor for ATH of LA to GVL furnishing chiral GVL with complete conversion and 93% enantiomeric excess (ee). This operationally simple and mild ATH protocol was tested for practical applicability of ATH of LA obtained from biomass waste (rice husk and wheat straw) and furnished chiral GVL with 82% ee.

INTRODUCTION

Petrochemical feedstock is a major pillar for the synthesis of different chemicals and is playing a crucial role in today’s economy. Depletion of fossil resources is increasing day by day which imposes the development of new routes to synthesize chemicals and fuels from renewable resources such as biomass. Several industrially feasible methods have been developed in this perspective to generate new platform chemicals from biomass.1−13 One of the most favorable approaches to produce value-added chemicals is the selective biomass conversion.14−19 Several important platform chemicals are obtained through this route, for example, 5-hydroxymethyl furfural, succinic acid, levulinic acid (LA), $\gamma$-valerolactone (GVL), and so forth. Among them, GVL has been identified as a potential green biofuel since long,20 and it is used for various applications. Literature reveals that a variety of catalysts and different systems have been developed for LA hydrogenation to GVL21 but the study regarding hydrogenation of LA to obtain optically active GVL remains unexplored. Utilization of enantiopure GVL as a beneficial chiral precursor might be tested in the synthesis of various fine chemicals and other valuable intermediates like chiral 5-methyl-3-methylenedihydrofuran-2-(3H)-one, pentane-1,4-diol, and its derivatives, unsaturated esters, chiral ionic liquids, and so forth.22,23 Optically active (S)-GVL has been used to synthesize various pharmaceutical compounds such as the aggregation pheromone of Gnathotrichus sulcatus (S)-(−)-sulcatol, a cyclodepsipeptide of marine origin, geodiamolide A, and the antihypertensive WS75624B, the antileukemic steganacin (Figure 1).24−27 Apart from its pharmaceutical applications, optically pure GVL bearing the properties of good salvation could also be utilized as a non-hazardous and renewable chiral reaction medium for asymmetric synthesis.28 With the successful demonstration of chiral ionic liquids in the area of
asymmetric synthesis, applications of chiral 4-hydroxyvalerate-based ionic liquids derived from chiral GVL as a solvent for chiral induction are also proposed.

Various catalytic processes have been investigated for the conversion of LA to GVL with homogeneous and heterogeneous catalyst systems. However, the asymmetric reduction of LA to enantiomerically pure GVL has been demonstrated in very few articles. Recently, Osawa and Tanabe reported the asymmetric hydrogenation of LA to chiral GVL with the use of the \((\text{R,R})\)-tartaric acid-NaBr-modified nickel catalyst; however, the enantioselectivity obtained was moderate [60% enantiomeric excess (ee)]. Mika et al. demonstrated direct asymmetric hydrogenation of biomass-derived LA to chiral \((\text{S})\)-GVL using the SEGPHOS ligand-modified ruthenium catalyst with 82% enantioselectivity. Optically active \(\gamma\)-substituted \(\gamma\)-lactone synthesis was reported by Karnik et al. from \((\text{S})\)-menthyl or \((\text{S})\)-bornyl esters of 4-carboxylates by sodium borohydride reduction with very moderate yield and enantioselectivity of \((\text{S})\)-GVL. Enzymatic reduction often results in excellent enantioselectivity of the products. Hiltchen et al. investigated a chemoenzymatic reduction reaction of LA to obtain \((\text{S})\)-GVL in good yields and ee (\(\sim 90\%\)). Enantioselective hydrogenation of LA esters has been performed in few research articles with ruthenium as a catalyst. Vinogradov et al. suggested asymmetric hydrogenation of LA with the \(\text{Ru-BINAP-HCl}\) catalyst system in ethanol, pertaining to the GVL in optical purity up to 99% ee. Mineral acid is necessary for ester hydrolysis, and it also presented with the release of HCl from the reaction mixture. This is a critical problem from environmental safety concern as aqueous HCl is corrosive in nature. Jacobs et al. reported the reduction of alkyl levulinate to its hydroxy esters with Baker’s yeast which upon hydrolysis furnished \((\text{S})\)-GVL in 73% yield. Though there are few reports of asymmetric hydrogenation of LA to GVL, asymmetric transfer hydrogenation (ATH) of LA in the presence of chiral ligands has not been explored till date. ATH is a very efficient method to obtain chiral compounds under mild reaction conditions. ATH is one of the most competent strategies for hydrogenation of prochiral compounds because of its operational ease and prevention of the use of perilous hydrogen gas and the pressure vessels.

Herein, we investigated ATH of LA by using various chiral metal complexes to obtain optically active GVL. Among various chiral catalysts, \(\text{RuCl-}(\text{R,R})\)-TsDPEN was found to be the best catalyst leading to chiral GVL in 97% yield and 93% ee.

# RESULTS AND DISCUSSION

To begin this study, we have performed ATH of LA to optically active GVL with different chiral catalysts (Scheme 1). In this study, we have used commercially available and most successful catalysts reported for ATH reactions based on the platinum group metals with a variety of chiral chelating ligands and donor atoms such as nitrogen and oxygen (Figure 2).

ATH reaction was performed with an azeotropic mixture of formic acid (FA) and triethylamine (TEA) as a hydrogen donor, that is, FA/TEA (5:2) and methanol as a solvent. It was observed that the LA was successfully converted to GVL with the use of tosylated diamine ligands in the presence of Ru, Rh, and Ir catalysts (Table 1). ATH of LA to GVL proceeded in very good yield of 99 and 64% ee within 48 h reaction time using the Ru-TsDPEN catalyst (Table 1, entry 1). With catalyst 2, conversion of LA was 99% but with very low enantioselectivity 36% was observed (Table 1, entry 2). Tethered catalyst complex 3 was effective in producing GVL with complete consumption of

### Table 1. Screening of Various Chiral Catalysts for ATH of LA to GVL

| entry | catalyst | time (h) | conv (%) | ee (%) |
|-------|----------|----------|----------|--------|
| 1     | 1        | 24       | 99       | 64     |
| 2     | 2        | 24       | 59       | 36     |
| 3     | 3        | 24       | 98       | 39     |
| 4     | 4        | 24       | 68       | 2      |
| 5     | 5        | 24       | 99       | 62     |
| 6     | 6        | 24       | 99       | 9      |
| 7     | 7        | 24       | 99       | 6      |
| 8     | 1 (in situ) | 24   | 99       | 54     |
| 9     | 8        | 24       | 29       | 36     |

*Reaction conditions: LA: 0.5 mmol, MeOH: 1.5 mL, catalyst: 0.005 mmol, FA/TEA (5:2): 0.5 mL, temp: RT.*
LA but provided chiral GVL with only 39% ee (Table 1, entry 3). Ru–benzene complex 4 was moderately active in converting the LA to GVL with 68% conversion and only 2% ee (Table 1, entry 4). With catalyst 3, conversion was good (99%) and moderate ee value (62%) was observed (Table 1, entry 5). Catalysts 6 and 7 with Rh and Ir metals were found to be active in hydrogenating LA to GVL with 99% conversion (Table 1, entry 9), but ee values were very low (6–9%) as compared to the Ru catalyst precursor.

It is demonstrated in earlier results that asymmetric reduction reaction of aliphatic ketones results in a lower enantioselectivity value as compared to aromatic ketones, and enantioselectivity is governed by vicinal functional groups around the carbonyl group. It is presented in the previous reports that activity and enantioselectivity differed when reaction was performed with in situ generated and preformed catalyst complexes.50 Hence, ATH of LA was tested with in situ generated and preformed complexes.

To our surprise, the enantioselectivity value was dramatically influenced, giving GVL with 66% ee with preformed catalyst complex 1 and with in situ generated complex furnished GVL with 54% ee (Table 1, entry 1 and 8). ATH of LA was also performed with the in situ generated ruthenium complex using a [Ru(p-cymene)Cl]2 catalyst precursor and (1S,2S)-TsCYDN 8 as a ligand, but the reduction product formed was low (29%) and enantioselectivity was very poor (36%) (Table 1, entry 9). To gain more insight on the enantioselectivity pattern, ATH of LA was performed under different reaction conditions. Among all the catalysts screened, the catalyst 1 was found to be active and hence further optimization of LA to GVL was performed with this catalyst with FA/TEA as a hydrogen donor.

It was previously reported in the literature that conversion of LA to chiral GVL proceeds through a hydroxy-pentanoic acid intermediate, and the 18O-labeled study of (LA to chiral GVL) proceeds through a hydroxy-pentanoic acid with FA/TEA as a hydrogen donor. Optimization of LA to GVL was performed with this catalyst.

Enantioselectivity was slightly affected with the use of different solvents for ATH of LA reaction. Polar solvents such as AcCN, dimethylformamide, and alcoholic solvents were found to be the effective solvents for ATH reactions and resulted in nearly 72% ee value. As stated in our earlier publication, methanol could act as a co-solvent and increase the yield and enantioselectivity of ATH reaction, thereby improving the stability of the catalyst.53,54 Hence, we performed ATH of LA in different solvents at room temperature (RT) (Figure 3). ATH of LA reaction under neat conditions proceeded with low conversion, and no enantioselectivity was observed. A possible reason for the low conversion under neat reaction conditions could be the increased acidity of the reaction mixture which hampers the active form of the ruthenium catalyst. Further in the investigation of the solvent screening, different polar, apolar, protic solvents were screened for ATH reaction of LA with catalyst 1, and it was observed that reaction proceeded with complete conversion and excellent ee of 64% in methanol solvent. As stated in our earlier publication, methanol could act as a co-solvent and increase the yield and enantioselectivity of ATH reaction, thereby improving the stability of the catalyst.53

ATH of LA was not effective in dimethyl sulfoxide solvent and led to only 12% conversion with no ee determined. Enantioselectivity was slightly affected with the use of different solvents for ATH of LA reaction. Polar solvents such as AcCN, dimethylformamide, and alcoholic solvents were found to be the effective solvents for ATH reactions and resulted in nearly 99% conversion with a moderate to good (55–72%) ee value.

Temperature of the reaction impacts enantioselectivity in asymmetric reactions as it affects polarity, viscosity, and diffusivity. Consequently, the study of reaction temperature on activity and enantioselectivity was demonstrated for ATH of LA reaction (Figure 4). Usually, ATH reactions are performed from RT to 60 °C temperature because further increase in
Remarkably, ATH reaction proceeded well with the FA/TEA value of 0.5 mL in conversion; however, enantioselectivity was decreased. ATH of LA to GVL and it is seen that high catalyst loading leads to increased enantioselectivity and conversion and 78% ee. The result obtained confirmed that high catalyst loading leads to increased enantioselectivity and activity. When 0.5 mmol LA was subjected under ATH reaction conditions with 0.01 mmol of catalyst 1, complete conversion was detected with GVL formation in 78% enantioselectivity in 18 h reaction time. This confirms that high catalyst loading leads to increased enantioselectivity and activity as there is an increase in the number of catalytic sites available for the substrates to undergo transfer hydrogenation reaction.

Variation of the FA and TEA ratio afforded with remarkable improvement in activity for ATH of imines and ketones. Furthermore, use of different organic bases along with FA as a hydrogen donor for ATH reactions was found to have strong influence on the enhancement in activity and enantioselectivity of the desired product. In our earlier work for ATH of imines, we have reported that FA in combination with various organic bases works as an efficient hydrogen donor and resulted in high yields and enantioselectivity in short reaction time. To shed more light into the effect of various organic bases with FA as a hydrogen donor, we screened ATH reaction of LA with few different organic bases (Table 3).

![Table 3. Effect of Base in Combination with FA for ATH of LA](media)

The influence of catalyst concentration on enantioselectivity was checked for ATH reaction (Figure 5). Remarkable improvement in enantioselectivity was obtained from 63 to 74% ee when catalyst concentration was increased from 0.0025 to 0.0075 mmol, respectively. Further increase in catalyst concentration up to 0.01 mmol provided the GVL in 99% conversion and 78% ee. The result obtained confirms that high catalyst loading leads to increased enantioselectivity and activity. When 0.5 mmol LA was subjected under ATH reaction conditions with 0.01 mmol of catalyst 1, complete conversion was detected with GVL formation in 78% enantioselectivity in 18 h reaction time. This confirms that high catalyst loading leads to increased enantioselectivity and activity as there is an increase in the number of catalytic sites available for the substrates to undergo transfer hydrogenation reaction.
TEA. An equivalent ratio of FA with the base for ATH reaction of LA resulted in increased enantioselectivity and activity. Cyclic amines with FA were screened for ATH of LA with a 1:1 ratio and 0.01 mmol of Ru catalyst 1 and 1 mmol of LA. Cyclic secondary amines with FA afforded the reduction of LA with full conversion; however, enantioselectivity was comparable with the TEA and in the range of 68–69%. Surprisingly, enantioselectivity was improved significantly to 82% with N-methylpyrrolidine and 93% with N-methylpiperidine. For example, ATH of LA was performed with (1:1 molar ratio) FA/N-methylpiperidine at 30 °C and 1 mmol of Ru catalyst 1, and full conversion of LA was obtained with 93% ee value in 16 h reaction time. With this protocol in hand, activity of the catalyst 1 was investigated for increased substrate concentration from 0.5 to 2 mmol of LA (Figure 6). The TON value and conversion decreased as LA concentration increased; however, enantioselectivity was maintained from 93 to 85%. Reaction proceeded well with the use of FA/N-methylpiperidine (1:1) hydrogen donor, and 93% conversion was obtained with 85% ee for 2 mmol of LA in 36 h reaction time.

Various esters of LA have been screened under optimized reaction conditions of ATH reaction (Table 4). All esters were hydrogenated with good yields; however, enantioselectivity for esters decreased marginally as per the chain length of the ester group of the LA increased and it was low as compared to ATH of LA. It was also observed that the stereochemical result of these reductions was not changed by variation of the ester group.

Table 4. ATH of Levulinate Esters Using Catalyst 1

| entry | substrate (−R) | conv (%) | ee (%) |
|-------|----------------|----------|--------|
| 1     | methyl         | 96       | 85     |
| 2     | ethyl          | 94       | 82     |
| 3     | propyl         | 94       | 83     |
| 4     | butyl          | 92       | 81     |

“Reaction conditions: RuCl(p-cymene) [(R,R)-Ts-DPEN]: 0.005 mmol, MeOH: 1.5 mL, FA/N-methylpiperidine (molar ratio 1:1): 0.5 mL, substrate: 0.5 mmol, temp: 30 °C.”

Thus, a new effective catalyst system is demonstrated for ATH of LA to chiral GVL, and the concentration–time (C−T) profile was generated (Figure 7). This developed methodology asymmetrically reduces the LA under very mild reaction conditions and with very efficient hydrogen donor FA/N-methylpiperidine.

![Figure 6. Effect of LA concentration on activity of ATH of LA. Reaction conditions: [RuCl(p-cymene)((R,R)-Ts-DPEN)]: 0.005 mmol, MeOH: 1.5 mL, FA/N-methylpiperidine (molar ratio 1:1): 0.5 mL, temp: 30 °C.]

![Figure 7. C−T profile for ATH of LA to chiral GVL using catalyst 1. Reaction conditions: RuCl(p-cymene)((R,R)-Ts-DPEN): 0.005 mmol, MeOH: 1.5 mL, FA/N-methylpiperidine (molar ratio 1:1): 0.5 mL, LA: 0.5 mmol, temp: 30 °C.]

This simple and effective ATH protocol was successfully demonstrated for ATH of biomass-derived LA using FA/N-methylpiperidine hydrogen donor using catalyst 1. D-Fructose (4 gm) was converted to LA based on literature reports31,52 and 1.0 g LA was obtained; 1 mmol of LA was subjected to ATH reaction with 0.0075 mmol of the Ru catalyst 1 in 1 mL MeOH and 1:1 FA/N-methylpiperidine (0.5 mL) as a hydrogen donor (Scheme 3). Complete conversion of LA was obtained with 82% enantioselectivity for chiral GVL after 18 h reaction time. Mika et al. have also demonstrated the direct transformation of LA obtained from a “real” biomass to optically active GVL by asymmetric hydrogenation with a good enantioselectivity value.11 Following the same protocol, we treated the real biomass waste including rice husk and wheat straw with 2 M H2SO4 at 170 °C for 8 h. After the workup process,46 the obtained brown colored LA was consequently reduced under optimized ATH reaction conditions (Scheme 4). (Cat 1: 0.0075 mmol, LA: 1 mmol, 1:1 FA/N-methylpiperidine: 0.5 mL, MeOH: 1 mL, temp 30 °C). GVL with 78% enantioselectivity was obtained with full conversion of LA in 18 h reaction time. Thus, based on the results obtained, it can be stated that the current ATH protocol is highly effective and operationally simple in transformation of biomass-derived LA to enantioselective GVL with 93% enantioselectivity.

**CONCLUSIONS**

Thus, we have demonstrated an efficient and simple process for ATH of LA in methanol with F/B as the H-donor and a Ru–TsDPEN catalyst system and obtained optically active GVL in 98% yield and 93% enantioselectivity. Optimization of different reaction parameters was performed for ATH of LA to GVL: such as temperature, solvent effect, hydrogen donors, catalyst, and ligand concentration to get optimized reaction conditions. Further increment in activity was obtained with the use of different bases with FA as the H donor. To the best of our understanding, this study presents the first report of producing chiral (R)-GVL by ATH of LA using a ruthenium catalyst system.
catalyst precursor (Ru–TsDPEN) and obtained chiral GVL in 93% ee with 99% conversion. Practical applicability of the current methodology was shown on ATH of biomass-derived LA to GVL and obtained GVL in 78–82% ee.

## EXPERIMENTAL SECTION

All reactions were performed in oven-dried Schlenk flask. ee analysis of chiral GVL was performed by gas chromatography (GC) using a chiral column, and yield was determined by GC–mass spectrometry analysis. LA, chiral catalyst precursors were purchased from Sigma-Aldrich and used as received. Solvents were obtained from Merck Ltd. and used as received.

**Experimental Procedure for ATH of LA.** A Schlenk flask containing a magnetic stirring bar was charged with catalyst 1 [Ru(β-cymene)Cl(1,2,5)-TsDPEN] (0.0075 mmol) in 1 mL MeOH and LA (1 mmol). The reaction was started with the addition of (1:1 molar ratio) FA/N-methylpiperidine (0.5 mL). The reaction mixture was stirred at 30 °C for the time indicated, then basified with 0.5 M Na2CO3 solution, and extracted with dichloromethane (3 mL × 2 mL). The organic phase was dried over Na2SO4, and solvent was removed under reduced pressure. Conversion was determined on GC using HP-5 column, and enantioselectivity was determined on GC using β-DEX 225 (L × L.D. 30 m × 0.25 mm, d 0.25 μm).

## ASSOCIATED CONTENT

**Supporting Information**

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.9b03424.

Experimental procedure for ATH of LA and NMR and GC spectra of chiral GVL (PDF)

## AUTHOR INFORMATION

**Corresponding Author**

*E-mail: bm.bhanage@gmail.com.

**ORCID**

Bhalchandra M. Bhanage: 0000-0001-9538-3339

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

Authors are thankful for funding from Department of Science and Technology under BRICS-ICP-Bio grant and V.S.S. thanks to SERB, DST India for National Postdoctoral Fellowship programme.

## REFERENCES

1. Jin, X.; Yin, B.; Xia, Q.; Fang, T.; Shen, J.; Kuang, L.; Yang, C. Catalytic Transfer Hydrogenation of Biomass-Derived Substrates to Value-Added Chemicals on Dual Functional Catalysts: Opportunities and Challenges. ChemSusChem 2019, 12, 71–92.
2. Anastas, P. T.; Warner, J. C. Green Chemistry: Theory and Practice; Oxford University Press: New York, 1998; pp 1–135.
3. Introduction to Chemicals from Biomass; Clark, J. H., Deswarte, P., Eds.; John Wiley & Sons: Chichester, 2008; pp 77–101.
4. The Biology of Biomass; Blackwell, Chichester, 2011; pp 275–309.
5. Morales, M.; Quintero, J.; Conejeros, R.; Aroca, G. Life cycle assessment of lignocellulosic bioethanol: Environmental impacts and energy balance. Renewable Sustainable Energy Rev. 2015, 42, 1349–1361.
6. Gellen, F. M. A.; Engendahl, B.; Harwardt, A.; Marquardt, W.; Klankermayer, J.; Leitner, W. Selective and Flexible Transformation of Biomass-Derived Platform Chemicals by a Multifunctional Catalytic System. Angew. Chem., Int. Ed. 2010, 49, 5510–5514.
7. Besson, M.; Gallezot, P.; Pinet, C. Conversion of Biomass into Chemicals over Metal Catalysts. Chem. Rev. 2014, 114, 1827–1870.
8. Farrán, A.; Cai, C.; Sandoval, M.; Xu, Y.; Liu, J.; Hernáiz, M. J.; Linhardt, R. J. Green solvents in carbohydrate chemistry: from raw materials to fine chemicals. Chem. Rev. 2015, 115, 6811–6853.
9. Clark, J. H.; Deswarte, F. Introduction to Chemicals from Biomass; John Wiley & Sons Inc.: U.K., 2015; pp 89–143.
10. Xue, Z.; Liu, Q.; Wang, J.; Mu, T. Valorization of levulinic acid over non-noble metal catalysts: challenges and opportunities. Green Chem. 2018, 20, 4391–4408.
11. Mika, L. T.; Cséfálay, E.; Németh, Á. Catalytic Conversion of Carbohydrates to Initial Platform Chemicals: Chemistry and Sustainability. Chem. Rev. 2018, 118, 505–613.
12. Xie, C.; Song, J.; Wu, H.; Hu, Y.; Liu, H.; Zhang, Z.; Zhang, P.; Zhan, B.; Han, B. Ambient Reductive Amination of Levulinic Acid to Pyrrolidones over Pt Nanocatalysts on Porous TiO2 Nanosheets. J. Am. Chem. Soc. 2019, 141, 4002–4009.
13. Liu, C.; Wu, S.; Zhang, H.; Xiao, R. Catalytic oxidation of lignin to valuable biomass-based platform chemicals: A review. Fuel Process. Technol. 2019, 191, 181–201.
14. Ni, M.; Leung, D. Y. C.; Leung, M. K. H.; Sumathy, K. An overview of hydrogen production from biomass. Fuel Process. Technol. 2006, 87, 461–472.
15. Ramli, N. A. S.; Amin, N. A. S. Hydrolysis of cellulose and oil palm biomass in ionic liquid to reducing sugar for levulinic acid production. Fuel Process. Technol. 2014, 128, 490–498.
16. Liguori, F.; Moreno-Marrodan, C.; Barbaro, P. Environmentally Friendly Synthesis of γ-Valerolactone by Direct Catalytic Conversion of Renewable Sources. ACS Catal. 2015, 5, 1882–1894.
(17) Park, M.-R.; Kim, H. S.; Kim, S.-K.; Jeong, G.-T. Thermochemo-
chemical conversion for production of levulinic and formic acids from
glucosamine. Fuel Process. Technol. 2018, 172, 115–124.
(18) Pradhan, P.; Mahajan, S. M.; Arora, A. Production and utiliza-
tion of fuel pellets from biomass: A review. Fuel Process. Technol.
2018, 181, 215–332.
(19) Rahman, M. M.; Liu, R.; Cai, J. Catalytic fast pyrolysis of bi-
mass over zeolites for high quality bio-oil—A review. Fuel Process.
Technol. 2018, 180, 32–46.
(20) Galletti, A. M. R.; Antonetti, C.; Ribechini, E.; Colombini, M. P.;
Nassi o Di Naso, N.; Bonari, E. From giant reed to levulinic acid
and gamma-valerolactone: A high yield catalytic route to valeric
biofuels. Appl. Energy 2013, 102, 157–162.
(21) Osatiahtiani, A.; Lee, A. F.; Wilson, K. Recent advances in the
production of γ-valerolactone from biomass-derived feedstocks
via heterogeneous catalytic transfer hydrogenation. J. Chem. Technol.
Biotechnol. 2017, 92, 1125–1135.
(22) Fegyverneki, D.; Orha, L.; Láng, G.; Horváth, I. T. Gamma-
valerolactone-based solvents. Tetrahedron 2010, 66, 1078–1081.
(23) Strádi, A.; Molnár, M.; Óvári, M.; Dibó, G.; Richter, F. U.;
Mika, L. T. Rhodium-catalyzed hydrogenation of olefins in γ-
valerolactone-based ionic liquids. Green Chem. 2013, 15, 1857–1862.
(24) Mori, K. Synthesis of optically active forms of sulcatol: The
aggregation phenomenon in the scolytid beetle, Gnathotrichus sulcatus.
Tetrahedron 1975, 31, 3011–3012.
(25) Tomioka, K.; Ishiguro, T.; Koga, K. First asymmetric total
synthesis of (+)-steganacin determination of absolute stereochemistry.
Tetrahedron Lett. 1980, 21, 2973–2976.
(26) White, J. D.; Amedio, J. C. Total synthesis of geodiamolide A, a
novel cyclodepsipeptide of marine origin. J. Org. Chem. 1989, 54,
736–738.
(27) Stangeland, E. L.; Sammakia, T. Use of Thiazoles in the
Halogen Dance Reaction: Application to the Total Synthesis of
WS75624 B. J. Org. Chem. 2004, 69, 2381–2385.
(28) Reichardt, C.; Thomas, W. Solvents and Solvent Effects in
Organic Chemistry, 3rd ed.; Wiley VCH; Weinheim, Germany, 2003;
p. 509–548.
(29) Tulasi, S. K.; Lorenz, H.; Hilbert, L.; Edelmann, F. T.; Seidel-
Morgenstern, A. Potential of Chiral Solvents for Enantioselective
Crystallization. 1. Evaluation of Thermodynamic Effects. Cryst.
Growth Des. 2008, 8, 3408–3414.
(30) Tulasi, S. K.; Lorenz, H.; Seidel-Morgenstern, A. Potential of
Chiral Solvents for Enantioselective Crystallization. 2. Evaluation
of Kinetic Effects. Cryst. Growth Des. 2009, 9, 2387–2392.
(31) Li, W.; Xie, J.-H.; Lin, H.; Zhou, Q.-L. Highly efficient
hydrogenation of biomass-derived levulinic acid to γ-valerolactone
caused by iridium pincer complexes. Green Chem. 2012, 14, 2388–
2390.
(32) Deng, J.; Wang, Y.; Pan, T.; Xu, Q.; Guo, Q.-X.; Fu, Y.
Conversion of Carbohydrate Biomass to γ-Valerolactone by using
Water-Soluble and Reusable Iridium Complexes in Acidic Aqueous
Media. ChemSusChem 2013, 6, 1163–1167.
(33) Omoruyi, U.; Paje, S.; Hallett, J.; Miller, P. W. Homogeneous
Catalyzed Reactions of Levulinic Acid: To γ-Valerolactone and
Beyond. ChemSusChem 2016, 9, 2037–2047.
(34) Wright, W. R. H.; Palkovits, R. Development of Heterogenous
Catalysts for the Conversion of Levulinic Acid to γ-Valerolactone.
ChemSusChem 2012, 5, 1657–1667.
(35) Ennaert, T.; Van Aelst, J.; Dijkmans, J.; De Clercq, R.;
Schutwyser, W.; Musselier, M.; Verboekend, D.; Sels, B. F. Potential
and challenges of zeolite chemistry in the catalytic conversion of biomass.
Chem. Soc. Rev. 2016, 45, 584–611.
(36) Sudarsanam, P.; Zhong, R.; Van den Bosch, S.; Coman, S. M.;
Parvulescu, V. I.; Sels, B. F. Functionalised heterogeneous catalysts for
sustainable biomass valorisation. Chem. Soc. Rev. 2018, 47, 8349–
8402.
(37) Ohkuma, T.; Kitamura, M.; Noyori, R. Enantioselective
synthesis of 4-substituted γ-lactones. Tetrahedron Lett. 1990, 31,
5509–5512.
(38) Jacobs, H.; Berryman, K.; Jones, J.; Gopal, A. Bakers’ Yeast
Reductions of Alkyl Levulinate: Synthesis of (R)-(+) and (S)-(−)
methylbutyrolactones. Synth. Commun. 1990, 20, 999–1010.
(39) Karrer, A. V.; Patil, S. T.; Patnekar, S. S.; Senwalla, A.
A convenient route to optically active γ-substituted γ-lactones. New J.
Chem. 2004, 28, 1420–1422.
(40) Starodubtseva, E. V.; Turova, O. V.; Vinogradov, M. G.;
Gorskhova, L. S.; Ferapontov, V. A. Enantioselective hydrogenation
of levulinic acid esters in the presence of the Ru15-BINAP-HCl catalytic
system. Russ. Chem. Bull. 2005, 54, 2374–2378.
(41) Gött, K.; Liese, A.; Ansorge-Schumacher, M.; Hilterhaus, L.
A chemo-enzymatic route to synthesise (S)-γ-valerolactone from
levulinic acid. Appl. Microbiol. Biotechnol. 2013, 97, 3865–3873.
(42) Tukacs, J. M.; Fridding, B.; Dibó, G.; Székely, E.; Mika, L. T.
Direct asymmetric reduction of levulinic acid to gamma-valerolactone:
synthesis of a chiral platform molecule. Green Chem. 2015, 17, 5189–
5195.
Hydrogenation, a Practical Synthesis of Optically Enriched N-Propyl Pantolactam. *J. Org. Chem.* **2009**, *74*, 1411−1414.

(58) Kuzma, M.; Václavík, J.; Novák, P.; Přech, J.; Januščák, J.; Červený, J.; Pečaček, J.; Šot, P.; Vilhanová, B.; Matoušek, V.; Goncharova, I. I.; Urbanová, M.; Kačer, P. New insight into the role of a base in the mechanism of imine transfer hydrogenation on a Ru(II) half-sandwich complex. *Dalton Trans.* **2013**, *42*, 5174−5182.

(59) Shende, V. S.; Shingote, S. K.; Deshpande, S. H.; Kelkar, A. A. Asymmetric Transfer Hydrogenation of Cyclic Imines in Water with a Versatile Hydrogen Donor Formic Acid/N-Methylpiperidine: Rapid Access to Highly Enantioselective Amines. *ChemistrySelect* **2016**, *1*, 2221−2224.

(60) Szabolcs, Á.; Molnár, M.; Dibó, G.; Mika, L. T. Microwave-assisted conversion of carbohydrates to levulinic acid: an essential step in biomass conversion. *Green Chem.* **2013**, *15*, 439−445.