Unprecedented Catalytic Wet Oxidation of Glucose to Succinic Acid Induced by the Addition of *n*-Butylamine to a Ru^{III} Catalyst

Iunia Podolean,^[a] Cristina Rizescu,^[a] Camelia Bala,^[b] Lucian Rotariu,^[b] Vasile I. Parvulescu,^[a] Simona M. Coman,^{*[a]} and Hermenegildo Garcia^{*[c]}

A new pathway for the catalytic wet oxidation (CWO) of glucose is described. Employing a cationic Ru@MNP catalyst, succinic acid is obtained in unprecedently high yield (87.5%) for a >99.9% conversion of glucose, most probably through a free radical mechanism combined with catalytic didehydroxylation of vicinal diols and hydrogenation of the resulted unsaturated intermediate.

It is now unanimously accepted that the biomass transformation to platform molecules could provide a long-term solution to the industrial dependence on fossil carbon.^[1] In this respect, chemistry is challenging the development of efficient catalytic methods for such processes and succinic acid (SA) is among the targets.^[2] A potential starting material to obtain this compound is levulinic acid (LA) but most of the reported oxidative procedures of LA to SA raise immediate environmental concerns related to the use of stoichiometric inorganic oxidation reagents, high energy consumption, and the use of homogeneous catalysts.^[3]

In the last years many efforts have been devoted to develop oxidation systems using solid catalysts and environmentallybenign molecular oxygen as a sole oxidant. Not less important, the development of easily recoverable and recyclable heterogeneous catalysts has attracted considerable research interest.^[4]

Trying to give answers to these issues, not long ago we reported a cationic Ru-based catalyst (4 wt % Ru^{III}@MNP), developed by combining propylamine-functionalized silica-coated magnetic nanoparticles (MNP) with grafted cationic Ru.^[5,6] In

[a]	I. Podolean, C. Rizescu, V. I. Parvulescu, S. M. Coman Department of Organic Chemistry, Biochemistry and Catalysis Faculty of Chemistry University of Bucharest Bdul Regina Elisabeta 4-12, Bucharest 030016 (Romania) E-mail: simona.coman@chimie.unibuc.ro
[b]	C. Bala, L. Rotariu Department of Analytic Chemistry, Faculty of Chemistry University of Bucharest Bdul Regina Elisabeta 4-12, Bucharest 030016 (Romania)
[c]	H. Garcia Instituto Universitario de Tecnologia Quimica (CSIC-UPV) Universitat Politécnica de Valencia Avenida de los Naranjos S/N, 46022 Valencia (Spain) F-mail: haarcia@nim.uny.es

 Supporting Information and the ORCID identification number(s) for the author(s) of this article can be found under http://dx.doi.org/10.1002/ cssc.201600474. the presence of this catalyst, the oxidation of LA to SA takes place not only with high LA conversions (X = 59-79%), but also with high selectivities to SA (S = 96-98%).^[6] The same catalyst was proven to be highly efficient for the one-pot production of sorbitol and glycerol starting from cellulose even in the absence of an external hydrogen source.^[5] Extremely important, in both cases, the catalyst was easily separated from the product mixture by an external magnetic force making possible its repeated use without any deactivation under hydrothermal or oxidation conditions.

Nowadays, the selective oxidation of C6 sugar molecules (i.e., glucose and fructose) emerged as an extremely important area in oxidation chemistry.^[7] Following this route, it has been demonstrated that the oxidation of glucose may lead to the production of important chemicals, such as gluconic, glucuronic, glucaric, and 2-keto-D-gluconic acids.^[8] As a general rule, these liquid-phase oxidation reactions, producing the corresponding carbonyl compounds or carboxylic acids in high yields, were usually carried out at 20-80 °C and slightly basic pH (pH 7–9), mainly with air or oxygen, in aqueous medium and in the presence of supported Pt-group metals. However, since bi- and multimetallic catalysts are more efficient and less prone to deactivation than monometallic catalysts, Pt may be replaced with these systems.^[9] Another alternative might be the combination of monometallic catalysts with organic modifiers, such as nitrogen- and phosphorus-containing compounds, which may be simply added to the reaction mixture.^[10]

Encouraged by our previous results, here we report the simple development of an unprecedented highly active and selective system for the catalytic wet oxidation (CWO) of glucose to SA by combining 4 wt% Ru^{III}@MNP with *n*-butylamine as a strong nitrogenated ligand. This new system enables the transformation of glucose into 2,3-dihydroxybutanedioic acid and its forward didehydroxylation into SA, providing evidence for its practical application to produce oxygen-reduced compounds from biomass-derived materials.

Developed as a benign method for the mineralization of the organic pollutants contained in wastewaters, CWO recently became a routine way to convert lignin into aromatic aldehydes^[11] or glucose into gluconic acid.^[12]

Blank experiments carried out under CWO conditions (T= 180°C, 10 atm of O₂) led to moderate reaction rates (conversion of 12%) and to a non-selective broad distribution of products. Among these, the most important was glycolic acid (se-

ChemPubSoc Europe

lectivity of 28.4%), but several lactones, hexoses, and glucose isomers were also identified as by-products.

In the presence of 4 wt% Ru^{III}@MNP catalyst, the CWO of glucose (see the Experimental Section) took place with an unexpected selectivity of 62.7% to SA, for a conversion of glucose of 100%, in only 1.5 h. Lower molecular mass carboxylic acids, such as lactic, glycolic, and glyceric acid, constituted the difference. Small amounts of solid brown products were also formed, most probably through glucose caramelization.

Unfortunately, during the catalyst recycling tests, even if the catalyst remained highly active, a decreased selectivity to SA of about 20% per catalytic cycle was observed. After the third recycle, the selectivity in SA was only 20.8% (Figure 1).



Figure 1. Catalytic performance of 4 wt% Ru^{III}@MNP upon recycling in the CWO of glucose. Note that, besides SA, the reaction mixture contained a wide distribution of products, the major ones with selectivity lower than 10% being lactic, glycolic, and glyceric acids.

In LA oxidation, under similar reaction conditions, the same catalyst was recyclable for several catalytic runs without noticeable activity or selectivity decay.^[6] This behavior suggested that Ru^{III} species are strongly coordinated and that this interaction may prevent the leaching of the active species. Indeed, characterization of the fresh and spent catalyst through diffuse reflectance infrared Fourier transform (DRIFT) and inductively couled plasma atomic emission spectroscopy (ICP-OES) spectroscopy, confirmed the chemical integrity of the catalyst. During recycling, the amount of leached Ru in the reaction products was negligible (< 0.01 ppm, as detected from ICP-OES analysis), whereas the DRIFT spectra evidenced the presence of the characteristic bands assigned to the hydrochloride $-C-NH_3^+CI^-$ species (i.e., 1859, 1557, and 1426 cm⁻¹) also in the spent catalyst.^[6]

These results might suggest that the catalyst deactivation is caused by the created acidic pH, in which case the non-dissociated carboxylic acids would be very strongly adsorbed on catalyst. As consequence, the active catalyst sites would be blocked, the selective reaction would be poisoned, and the over-oxidation processes would be favored.^[13]

Indeed, the analysis of the reaction products indicated an increase in the yields of the low molecular mass carboxylic acids (i.e., lactic, glycolic, and glyceric acids) in the successive runs that was accompanied in the elemental analysis of the spent 4 wt% Ru@MNP catalysts by an accumulation of organic compounds (Table 1).

Table 1. Elemental analysis of fresh and spent 4 wt $\%~\text{Ru}^{\text{III}}\text{@}\text{MNP}$ catalyst.				
Catalyst	N [%]	C [%]	H [%]	
Fresh Spent ^[a]	0.303 0.393	1.387 3.538	0.578 1.757	
[a] 3 rd cycle.				

In accordance with literature reports,^[14] for an oxidation reaction, the addition of a base facilitates the alcohol group dehydrogenation by H abstraction, favors desorption of produced carboxylic acids, and protects the catalysts against deactivation. However, experiments carried out in the presence of NaOH failed. In the presence of NaOH, only insoluble highmolecular-weight compounds commonly named "caramels" were identified, in agreement with reports showing their production by controlled heating of carbohydrates with different reagents, such as sodium hydroxide, sodium sulphite, or ammonium chloride.^[15]

When replacing NaOH by *n*-butylamine ($pK_a = 10.8$) glucose was almost totally transformed, in only 1.5 h, to a mixture of succinic, glyceric, glycolic, lactic, and 3-hydroxypropanoic (3-HPA) acids, with selectivities of 11.5, 15.8, 25.0, 2.6, and 2.8%, respectively. Besides these carboxylic acids, 36% from the reaction products was constituted by lactones, known to be highly unstable in the aqueous conditions where they can undergo further oxidation to the corresponding diacids, presumably through the intermediacy of the hydroxyacids.^[16]

In this way, the formation of SA can be reasonably explained. It is likely that lactic, glycolic, and glyceric acids are formed via the already proposed mechanism of the glucose alkaline degradation including an enediol intermediate mechanism and successive enolization, β -elimination, and rearrangement steps.^[17] Nevertheless, under the CWO conditions, hydroxy radicals are produced from the dissociation and oxidation of water (i.e., $H_2O \rightarrow OH + H$; $H_2O + O_2 \rightarrow OH + HO_2$). Hydroperoxy radicals can also be formed from the oxidation of water (i.e., $H_2O + O_2 \rightarrow OH + HO_2$) and hydrogen peroxide by its recombination (i.e., $2 HO_2 \rightarrow H_2O_2 + O_2$).^[13] Although the hydroperoxy radicals are less reactive than the hydroxy radicals, at high concentrations they could play an important role. These radicals together with the free oxygen can attack at the reducing end group, resulting in the opening of the glycosidic ring and the formation of carboxylic acids. Moreover, in the presence of the *n*-butylamine, these strong oxidizing species can cause carbon-carbon bond cleavages increasing the reaction rate of the CWO and the concentration of the glucose alkaline degradation products. Such behavior is fully consistent with literature reports.^[18] No oxidation products of amine were found in

www.chemsuschem.org



the reaction products. This could be owing to the complete mineralization of the amine and/or its protonation. It can be reasonably assumed that protonated amine would be better protected from oxidation compared to neutral basic amine (Figure S1 in the Supporting Information).

Surprisingly, the mixture of high amounts of *n*-butylamine with the Ru^{III}-based catalyst (i.e., *n*-butylamine to glucose molar ratio of 0.5 and *n*-butylamine to Ru molar ratio of 12.5) exerted a strong synergic effect in CWO process (Figure 2). Thus a selectivity of 87.9% to SA was obtained by adding



Figure 2. The effect of *n*-butylamine on the catalytic performance of the fresh and spent $4 \text{ wt} \% \text{ Ru}^{III} @\text{MNP}$ catalyst in the oxidation of glucose.

n-butylamine to the fresh catalyst (by comparing with 62.7% SA, in the absence of *n*-butylamine, Figure 1) and a selectivity of 73.1% to SA by adding in the second run *n*-butylamine to a catalyst that was used without *n*-butylamine in the first run (in comparison with 43% SA, obtained in the second catalytic cycle again in the absence of *n*-butylamine, Figure 1). This selectivity to SA at almost complete glucose conversion is remarkable and, as far as we know, it has never been previously reported from glucose.

In a moderate alkaline media, glucose is isomerized to fructose, resulting in an equilibrium mixture of the two sugars. However, it seems that the mechanism of the CWO of glucose does not involve its isomerization to fructose as the first step of reaction. Neither the presence of fructose as intermediate nor of its derivative-products has been evidenced.

Based on these considerations, a plausible pathway of the CWO of glucose to the unexpected SA product might involve a two-step mechanism: a concerted heterogeneous-homogeneous free radical mechanism leading to 2,3-dihydroxybutanedioic (tartaric acid) and oxalic acids that is also in accordance to a previous report,^[17] followed by disproportionation of 2,3-dihydroxybutanedioic acid to fumaric and 2,3-dioxosuccinic acids (Scheme 1) that is quite similar to the diol-disproportionation reported by Arceo et al.^[19] The 2,3-





Scheme 1. Possible reaction pathways for SA formation through a heterogeneous-homogeneous free radical mechanism to 2,3-dihydroxybutanedioic acid (tartaric acid), followed by its disproportionation to fumaric acid.

dioxosuccinic acid is, however, not stable in a strong oxidizing environment, where it can be transformed in oxalic acid under the action of hydroxyl radicals. Accordingly, the key step in the process would be the catalytic conversion of tartaric acid into SA (Scheme 2). To provide support to this mechanistic proposal and, particularly to the activity of 4 wt% Ru^{III}@MNP as dehy-



Scheme 2. Possible reaction pathway for the reduction of fumaric acid to SA.

droxylation/reduction catalyst, two control experiments were made: i) tartaric acid was transformed under the same reaction conditions in the presence of 4 wt% Ru^{III}@MNP and *n*-butylamine, and ii) mixed fumaric acid with water and *iso*-propanol (or small amounts of glucose) was treated under the same reaction conditions in the presence of 4 wt% Ru^{III}@MNP and *n*butylamine. It was observed an almost complete disappearance of tartaric acid (over 98% conversion) in just 30 min reaction and the formation of SA in 48% selectivity, accompanied



by glycolic acid (38% selectivity, experiment i). Moreover, treating fumaric acid with aqueous *iso*-propanol, SA was formed with a selectivity of 48.4%, along of lactic acid (15.6%), hydroxypropionic acid (2.8%), glycolic acid (5.5%), oxalic acid (5.8%), maleic acid (6.0%), and methylsuccinic acid (16%, Figure S3). Interestingly enough, in the presence of small amounts of glucose, 26.4% of SA was found in the reaction products (Figure S4). Attempts to detect the presence of tartaric and fumaric acids in the reaction mixture at short reaction times failed, indicating that these proposed intermediates should be highly reactive under the reaction conditions. The Supporting Information provides detailed information of the stability of SA under CWO conditions in the presence of 4wt% Ru^{III}@MNP as well as the reaction of tartaric and fumaric acid (Figure S1–S4).

Oxalic acid is a typical reducing agent and its conjugate base, oxalate $(C_2O_4^{2-})$, is a chelating agent for metal cations. Alternatively, Ru^{III} species could catalyze the oxalic acid decomposition, which produces H₂ and CO₂, in accordance to previous reports.^[20] However, this approach is less probable under CWO conditions. It is likely that under the conditions of CWO, molecular hydrogen is not even formed, but the acceptorless dehydrogenation of keto-alcohols or hydroxy-acids intermediates affords di-ketones or keto-acids and causes the fumaric acid reduction to SA. A closely related approach is the so hydrogen equivalents borrowed from the substrate (i.e., glucose) are temporarily stored at the Ru^{IV} sites, and instead of being released, are used for reduction of the formed fumaric acid. Both mechanisms are possible (see the Supporting Information), but it is difficult to establish the involvement degree of each at this stage of research.

SA is a refractory acid, having a low reactivity in CWO conditions. Imamura²³ already reported that at 220 °C and 30 bars O_2 SA can be removed in a proportion of only 8% in 2 h of degradation reaction. Accordingly, once formed its additional degradation is difficult to be achieved (Figure S1).

Comparative cyclic voltamograms (CV) of RuCl₃ and RuCl₃– butylamine systems suggest the role of Ru^{IV} in this reaction. Ru^{IV} is a better –OH ions remover (Scheme 1) than Ru^{III}.

Figure 3 shows the CVs for RuCl₃ (2.0 mм in aqueous solution) and RuCl₃/n-butylamine (2.0 mm/2.5-25 mm) when a reversed potential (E_{λ}) of 1400 mV was applied. The scan started in a positive direction with respect to the system potential at rest ($E_{i=}0$ V). For RuCl₃ solution, the oxidation peak from + 1163 mV can be attributed to Ru^{III}/Ru^{IV} couple. The reduction process occurs at +796 mV, showing that process is not reversible. Because *n*-butylamine did not show any electrochemical activity in the working potential range, the peak recorded for RuCl₃-butylamine has to be assigned to the Ru^{III}/Ru^{IV} couple. A decrease of the oxidation peak intensity of Ru^{III}/Ru^{IV} (+1163 mV) can be observed after adding 2.5-7.5 mм n-butylamine. Interestingly, increasing the added volume of *n*-butylamine to 12.5 mm led to a secondary oxidation peak at a potential of +539 mV, which can be assigned to the oxidation of a Ru^{III}-mono butylamine complex. This shift is generated by the electron donor ability of *n*-butylamine ligand facilitating the oxidation of the Ru^{III} at lower potentials compared to



Figure 3. CV traces of the 2 mm RuCl₃ aqueous solution and 2 mm RuCl₃ aqueous solution with different amounts of *n*-butylamine.

RuCl₃. Even larger added volumes (25 mM) shifted the oxidation peak from +1163 to +1244 mV that may correspond to the formation of a Ru-bis-butylamine adduct. The observed shift can be assigned to a higher steric hindrance of the Ru^{III} cation in this new environment. Consecutively, a shift of the Ru^{III}/Ru^{IV} oxidation peak was observed. Higher concentrations of *n*-butylamine (e.g., >5 mM) also corresponded to the absence of any reduction counter-peak on back scanning, also confirming the high stability of the in situ produced oxidized Ru^{IV}-bis-amine adduct.

Based on these measurements, one may assume that the role of *n*-butylamine in this reaction is twofold: it provides a steric stability of the Ru species and stabilizes the Ru^{IV} that appears to be the active catalytic species.

In summary, Ru^{IV}-bis-amine adducts afford a new catalytic system for the wet oxidation (CWO) of glucose to succinic acid. The pathway follows a two-step mechanism involving both the free radicals from homogeneous phase and the catalytic active sites from solid phase. The addition of *n*-butylamine provides access to unprecedented high selectivities to succinic acid for a total conversion of glucose by changing the oxidation potential of the Ru species. None of the active intermediates (tartaric or fumaric acids) could be identified even at low conversions. However, further studies of the mechanism and investigation of other substrates and N-additives are in progress.

Experimental Section

Activity tests in batch mode were carried out by adding to a solution of 90 mg (0.5 mmol) glucose in 10 mL of water, 50 mg of 4 wt % Ru^{III}@MNP (0.02 mmol Ru) catalyst. After closing, the reactor was pressured at 10 bars with molecular oxygen and heated up to 180 °C, under stirring (1200 rpm), for 1–2 h. The same catalytic experiments were done by using 0.25 mmol of *n*-butylamine as promoter. After reaction, the oxygen was released and the catalyst was magnetically recovered by placing a permanent magnet on the reactor wall, and the products were separated by distillation under vacuum. The recovered products were silylated, diluted with 1 mL of toluene and analyzed by gas chromatography–flame ionization detector (GC–FID) chromatography (GC-Shimadzu appara-



tus). The identification of the products was made using a GC-MS Carlo Erba Instruments QMD 1000 equipped with a Factor Four VF-5HT column.

The CV measurements were carried out with an Autolab PGSTAT 12 potentiostat/galvanostat (Metrohm, AG, Herisau, Switzerland) and the Nova 1.11.2 software was used to collect and process the experimental data. A three-electrode system was used with a glassy carbon working electrode (3 mm diameter), an Ag/AgCl electrode 3 m KCl reference electrode, and a Pt wire as auxiliary electrode. All the potentials are reported to the Ag/AgCl reference electrode. The potential was swept between 0 and + 1400 mV with a scan rate of 50 mV s⁻¹. CV was used to describe the potential range of work. The initial rest potential ($E_{i=0}$ V) was increased in a positive direction up to various potentials limits (E_{i}), where the sweep direction was reversed.

Acknowledgements

The work was supported by the strategic grant POSDRU/159/1.5/ S/137750, Project "Postdoctoral programme for training scientific researchers" co-financed by the European Social Foundation within the Sectorial Operational Program Human Resources Development 2007–2013. Prof. Simona Coman kindly acknowledges UEFISCDI for financial support (project PN-II-PT-PCCA-2013-4-1090, Nr. 44/2014). Also, we thank Prof. Curt Reimann for critical reading and helpful suggestions related to manuscript preparation.

Keywords: biomass conversion · heterogeneous catalysis · oxidation · ruthenium · succinic acid

- B. Kamm, Angew. Chem. Int. Ed. 2007, 46, 5056-5058; Angew. Chem. 2007, 119, 5146-5149.
- [2] X. Hu, C. Z. Li, Green Chem. 2011, 13, 1676-1679.
- [3] S. K. Pandey, S. P. S. Yadav, M. Prasad, J. Prasad, Asian J. Chem. 1999, 11, 203–206.

- [4] P. T. Anastas, L. B. Bartlett, M. M. Kirchhoff, T. C. Williamson, *Catal. Today* 2000, 55, 11–22.
- [5] A. Negoi, I. T. Trotus, O. Mamula Steiner, M. Tudorache, V. Kuncser, D. Macovei, V. I. Parvulescu, S. M. Coman, *ChemSusChem* 2013, *6*, 2090–2094.
- [6] I. Podolean, V. Kuncser, N. Gheorghe, D. Macovei, V. I. Parvulescu, S. M. Coman, Green Chem. 2013, 15, 3077–3082.
- [7] H. Van Bekkum in Carbohydrates as Organic Raw Materials (Ed.: F. W. Lichtenthaler), Wiley-VCH, Weinheim, 1991, pp. 298.
- [8] A. Corma, S. Iborra, A. Velty, Chem. Rev. 2007, 107, 2411-2502.
- M. Besson, P. Gallezot in *Fine Chemicals through Heterogeneous Catalysis*, (Eds.: R. A. Sheldon, H. van Bekkum), Wiley-VCH, Weinheim, 2001, pp. 491.
- [10] T. Mallat, C. Brönnimann, A. Baiker, Appl. Catal. A 1997, 149, 103-112.
- [11] P. C. Rodrigues Pinto, E. A. Borges da Silva, A. E. Rodrigues, Ind. Eng. Chem. Res. 2011, 50, 741-748.
- [12] P. Gallezot, Catal. Today 1997, 37, 405–418.
- [13] S. Roy, M. Vashishtha, A. K. Saroha, J. Eng. Sci. Technol. Rev. 2010, 3, 95– 107.
- [14] T. Mallat, A. Baiker, Chem. Rev. 2004, 104, 3037-3058.
- [15] J. M. De Bruijn, Starch/Staerke 1987, 39, 23-28.
- [16] A. B. Smith, III, R. M. Scarborough, Jr., Synth. Commun. 1980, 10, 205– 211.
- [17] H. Peng, Y. Sun, J. Zhang, L. Lin, BioResources 2010, 5, 616-633.
- [18] M. Comotti, C. Della Pina, R. Matarrese, M. Rossi, Angew. Chem. Int. Ed. 2004, 43, 5812–5815; Angew. Chem. 2004, 116, 5936–5939.
- [19] E. Arceo, J. A. Ellman, R. G. Bergman, J. Am. Chem. Soc. 2010, 132, 11408–11409.
- [20] C. Fellay, P. J. Dyson, G. Laurenczy, Angew. Chem. Int. Ed. 2008, 47, 3966–3968; Angew. Chem. 2008, 120, 4030–4032.
- [21] G. R. M. Dowson, M. F. Haddow, J. Lee, R. L. Wingad, D. F. Wass, Angew. Chem. Int. Ed. 2013, 52, 9005–9008; Angew. Chem. 2013, 125, 9175– 9178.
- [22] S. A. Hamid, M. Haniti, C. L. Allen, G. W. Lamb, A. C. Maxwell, H. C. Maytum, A. J. A. Watson, J. M. J. Williams, J. Am. Chem. Soc. 2009, 131, 1766–1774.
- [23] S. Imamura, Ind. Eng. Chem. Res. 1999, 38, 1743-1753.

Received: April 12, 2016 Revised: May 17, 2016 Published online on

COMMUNICATIONS

I. Podolean, C. Rizescu, C. Bala, L. Rotariu, V. I. Parvulescu, S. M. Coman,* H. Garcia*



Unprecedented Catalytic Wet Oxidation of Glucose to Succinic Acid Induced by the Addition of *n*-Butylamine to a Ru^{III} Catalyst



SA with $Ru + BuNH_2$: Glucose is converted in 87.5% selectivity to succinic acid at complete conversion under catalytic wet oxidation conditions using Ru^{III} supported on aminopropyl-functionalized silica-coated magnetic nanoparticles as the catalyst and *n*-butylamine as the base. The addition of *n*-butylamine provides access to unprecedented high selectivities to succinic acid for a total conversion of glucose by changing the oxidation potential of the Ru species.

© 2016 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim **K** These are not the final page numbers!