

Special Collection

# Closing the Gap: Towards a Fully Continuous and Self-Regulated Kolbe Electrosynthesis

 Patrick Drögemüller,<sup>[a, c]</sup> Tobias Stobbe,<sup>[a]</sup> and Uwe Schröder<sup>\*[b, c]</sup>

In this article, we address the transition of the Kolbe electrolysis of valeric acid (VA) to *n*-octane as an exemplary electrosynthesis process from a batch reaction to a continuous, self-regulated process. Based on a systematic assessment of chemical boundary conditions and sustainability aspects, we propose a continuous electrosynthesis including a simple product separation and electrolyte recirculation, as well as an online-pH-controlled VA feeding. We demonstrate how essential performance parameters such as product selectivity (*S*) and coulombic efficiency (CE) are significantly improved by the transition from

batch to a continuous process. Thus, the continuous and pH-controlled electrolysis of a 1 M valeric acid, starting pH 6.0, allowed a constantly high selectivity of around 47% and an average Coulomb efficiency about 52% throughout the entire experimental duration. Under otherwise identical conditions, the conventional batch operation suffered from lower and strongly decreasing performance values ( $S_{n\text{-octane}, 60\text{min}} = 10.4\%$ ,  $S_{n\text{-octane}, 240\text{min}} = 1.3\%$ ;  $CE_{n\text{-octane}, 60\text{min}} = 7.1\%$ ,  $CE_{n\text{-octane}, 240\text{min}} = 0.5\%$ ). At the same time, electrolyte recirculation significantly reduces wastes and limits the use of electrolyte components.

## Introduction

The interest in electro-organic synthesis (EOS) has grown enormously in the last decade.<sup>[1]</sup> Having been a niche discipline for almost 120 years of oil and coal abundance, it is experiencing a renaissance in the context of the urging transition of the energy and chemistry sector towards a renewable basis.<sup>[2–5]</sup> While petrochemical processes usually involve the functionalization of non-polar hydrocarbons – which are often exergonic reactions<sup>[6,7]</sup> – renewable feedstocks such as biogenic chemicals are usually highly functionalized and polar and need to be defunctionalized.<sup>[8]</sup> The latter properties make biogenic chemicals ideally suited for electrochemical syntheses – offering the opportunity to use renewable electricity as driving force for the required chemical conversions. Hereby, using electrosynthesis

allows following major rules of green chemistry, such as rule 1 (waste avoidance by use of electrons immaterial agents), rule 3 (replacement of hazardous chemicals like oxidizing/reducing agents), rule 5 (safer solvents – when water is used as reaction medium), rule 6 (energy efficiency)<sup>[9,10]</sup> and rule 7 (use of renewable feedstocks)<sup>[8]</sup> These advantages make electrosyntheses appear sustainable *per se*<sup>[11]</sup> and may lead to insufficient engagement with boundary conditions of sustainable processes. Thus, although referring to the principles of green chemistry, the overwhelming number of fundamental studies on electrosynthesis, especially of biogenic raw materials, do not consequently address them in their implementation, focusing on certain advantages and avoiding addressing conflicts or linked disadvantages. Besides the design of the often-used H-cells, which prevents minimized cell voltages, the concentration levels of the feedstocks in the mmol range and their decrease during electrochemical batch processes lead to a poor coulombic efficiency and thus low energy efficiency. This may even make the syntheses seem unjustly uneconomical and unsustainable. Other important challenges are the usually not considered product separation, which means further energy consumption, as well as the resulting wastes of the electrolyte solutions, which not only carry high salt and acid loads, but also contain organic residues that require costly disposal.

In this article we close this gap by means of an exemplary Kolbe reaction and propose a continuous electrosynthesis process that combines a constant high efficiency of the electrosynthesis with integrated product separation and recirculation of the electrolyte solutions. The production of *n*-octane from valeric acid (VA) serves as a model reaction to demonstrate how boundary conditions are affected by reactor configuration and operation mode. We show how electro-organic can be performed under industrially relevant, as well as sustainable conditions, by choosing appropriate framework condition and by balancing the operational parameters. Hereby, we discuss different process strategies and highlight advan-

[a] P. Drögemüller, T. Stobbe  
Institute of Environmental and Sustainable Chemistry  
Technische Universität Braunschweig  
Hagenring 30, 38106 Braunschweig (Germany)

[b] Prof. Dr. U. Schröder  
Institute of Biochemistry  
University of Greifswald  
Felix-Hausdorff-Str. 4, 17489 Greifswald (Germany)  
E-mail: uwe.schroeder@uni-greifswald.de

[c] P. Drögemüller, Prof. Dr. U. Schröder  
Cluster of Excellence SE2A-Sustainable and Energy-Efficient Aviation  
Technische Universität Braunschweig  
Braunschweig (Germany)

Supporting information for this article is available on the WWW under <https://doi.org/10.1002/cssc.202300973>

This publication is part of a Special Collection highlighting "The Latest Research from our Board Members". Please visit the Special Collection at [chemsuschem.org/collections](https://chemsuschem.org/collections).

© 2023 The Authors. ChemSusChem published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution Non-Commercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

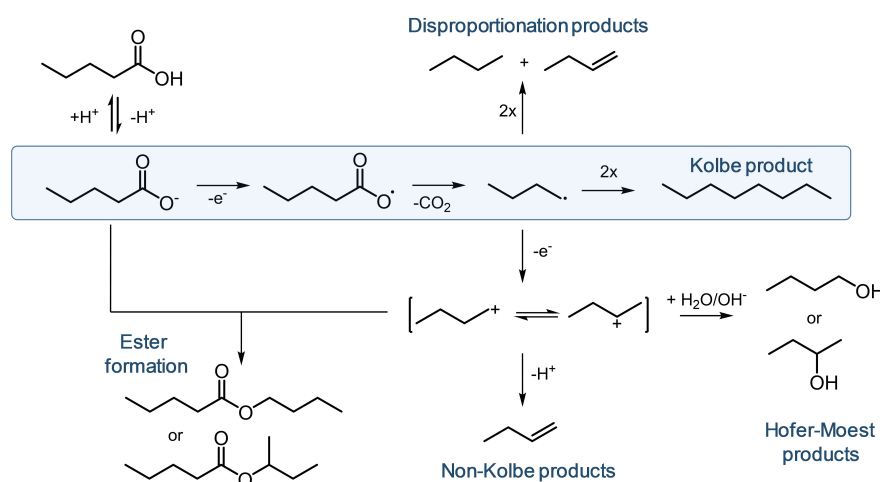
tages and potential disadvantages. To establish a systematic approach and also for didactic reasons, we will first provide a discussion on relevant framework conditions that apply to Kolbe electrolysis and similar electroorganic reactions and that should be taken into account for selective, energy-efficient and scalable electrosynthesis according to the rules of green chemistry.

The Kolbe reaction has often been performed using methanol-based electrolyte solutions. However, not only their high electric conductivity and the sustainability and non-toxicity of water as a solvent make aqueous electrolytes a promising reaction environment for electroorganic syntheses. Using aqueous electrolyte solutions also offers an elegant product separation opportunity. Thus, the products of electrochemical transformations (e.g., hydrogenations, hydrodeoxygenations, decarboxylations) of polar biogenic compounds are often significantly less polar than their precursors, leading to a reduced solubility and therefore the option to achieve a separation of the insoluble product phase (liquid or solid) from the electrolyte phase.<sup>[8,12–14]</sup> Kolbe reactions are generally performed at slightly acidic pH values.<sup>[15]</sup> This pH range can be understood as a compromise between the necessary acidic reaction conditions to avoid the Hofer-Moest-reaction<sup>[16]</sup> (see Scheme 1) on the one hand and the required deprotonation of the carboxylic group for a sufficiently high carboxylate concentration. Since  $pK_a$  values of typical, unsubstituted aliphatic acids are around 4.7–4.9 (e.g.,  $pK_a, \text{valeric acid} = 4.84$ ),<sup>[17]</sup> the reaction pH is often set to about 5.5. The advantage of a pH value above the  $pK_a$  value is a considerably enhanced solubility of the organic acids, as for example from 0.23 M VA in pure water<sup>[18]</sup> to 1 M at a pH of 5.5.<sup>[12]</sup>

Further process variables are educt concentration and current density. There are one specific and several general reasons to use high educt concentrations for the Kolbe reaction. Specifically for the Kolbe reaction, and to be considered in combination with a high current density, high educt concentrations allow to produce a sufficient density of radicals at the electrode surface to favor the recombination reaction towards the coupling product – against e.g., the Non-Kolbe product

formation (See Scheme 1).<sup>[15]</sup> More generally, high precursor concentrations also allow to efficiently suppressing side reactions like the oxidative (oxygen evolution reaction, OER) or reductive (hydrogen evolution reaction, HER) water decomposition (See Figure SI 1). They also offer a higher product formation rate and simplify separation of the product phase (see above). Current density values define the reaction rates according to Faradays law. High current densities also have been observed to improve the coupling rates to a certain extent.<sup>[14,15]</sup> Own preliminary experiments indicated significant positive effects up to  $100 \text{ mA cm}^{-2}$  and almost negligible improvements at a further increase to  $400 \text{ mA cm}^{-2}$  for initial 1 M carboxylate solutions. This is comparable to the latest publications.<sup>[14]</sup> As high temperatures are known to decrease radical stability, it is recommended to perform Kolbe coupling at moderate temperatures.<sup>[15]</sup> Depending on the reactor's electrical resistance, the required high currents cause joule heating and are likely to change the temperature.<sup>[19]</sup> Temperature control is recommended to ensure constant values.

Not only the physico-chemical process conditions, but also the reactor setup strongly impacts the performance and efficiency of electrochemical syntheses. Thus, the great majority of studies concerning electroorganic syntheses utilize batch reactors, i.e., conventional stirred glass flask based electrochemical cells (often separated into anode and cathode compartment) containing a fixed amount of educt dissolved in a respective electrolyte solution. Besides sharing the typical disadvantages of batch systems like, e.g., transient chemical conditions, specific electrochemical disadvantages are a sub-optimal ration of electrode surface to reactor volume and generally unnecessarily large cell voltages, caused by large distances between anode and cathode. Most importantly, however, the inherent decrease of the educt concentration during a batch conversion can lead to a considerable increase of side reactions such as HER or OER – drastically reducing the coulombic efficiency and thus the energy efficiency of the process. Flow-through reactors overcome this limitation and can be operated with a precise reaction control. The simplest and most flexible configuration is the parallel plate config-



**Scheme 1.** Schematic illustration of the competing reaction pathways for the anodic valeric acid oxidation. The desired Kolbe coupling is highlighted.

uration in a filter-press type reactor, with modules to be easily exchanged. This reactor type can be scaled up in a straightforward manner by enlarging the electrode plates in a "size-out" approach. Today, many micro-flow reactors are presented to be easily scaled up.<sup>[14,20,21]</sup> The perspective given is the addition of an arbitrary number of compartments in a "numbering-up" approach, which is rather a "scale-out" than a "scale-up".<sup>[21,22]</sup> In principle, numbering-up can be used to enable large production quantities. It avoids the complications caused by size-up but, based on higher reactor complexity, brings its own challenges, such as the increasing susceptibility to failure and potentially higher equipment costs. Size-up of microreactors contradicts their fundamental concept, as it would mean increasing the diameter of the electrolyte guiding channels. Increasing the channel length is strictly limited by pressure drop, resulting in uneven reaction conditions along the channels and increasing energy consumption by pumps. Even scale-out approaches of micro-flow reactors are still susceptible concerning clogging and gas evolution. In huge stacks, identifying affected or damaged modules would require disproportionate usage of sensors. For the named reasons, microflow reactors are potentially unsuitable for the large-scale application of Kolbe electrolysis. By using a simple parallel plate geometry, these problems are avoided. The electric field between the parallel plate electrodes can be considered almost ideal. Equal potential distributions simplify the prediction of reactor behavior, and constant ambient pressure enhances energy efficiency while avoiding operational risks.

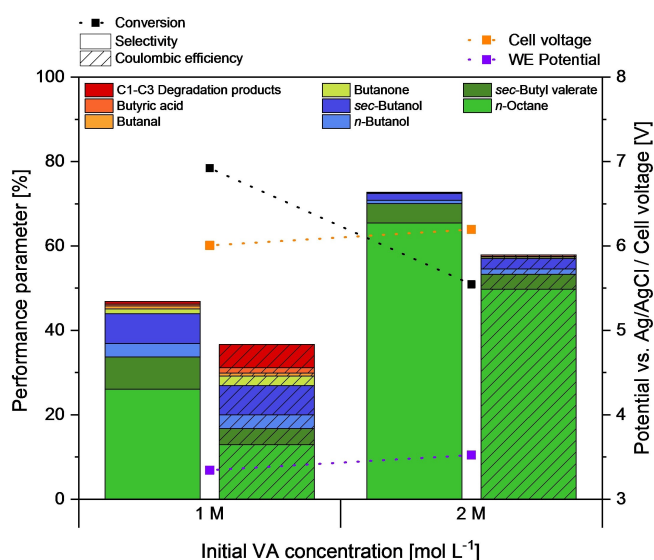
## Results & Discussion

The following sections will first discuss the Kolbe electrolysis performed under classical batch conditions and then propose two different options for a fully continuous operation including an automatic product separation and electrolyte recycling. We will discuss advantages and disadvantages of the different approaches by means of performance parameters and operation conditions.

### Batch operation

For the batch operations, the valeric acid containing electrolyte solutions were pumped in a loop between the reservoir vessel and the electrochemical flow cell (Scheme 2A) without any further precursor addition or chemical adjustment. The occurring water-insoluble product phase was constantly removed/separated by using a custom-made vertical gravity separator (Scheme 2B). The products were sampled either at the end of the electrochemical conversion (Figure 1) or regularly after certain time segments (results presented in Figure 2).

To illustrate the intrinsic phenomena of batch operations in electrosynthesis, the Kolbe reaction was performed under common conditions for Kolbe electrolysis in aqueous medium at two different concentrations of starting material. The results of these experiments are presented in Figure 1.



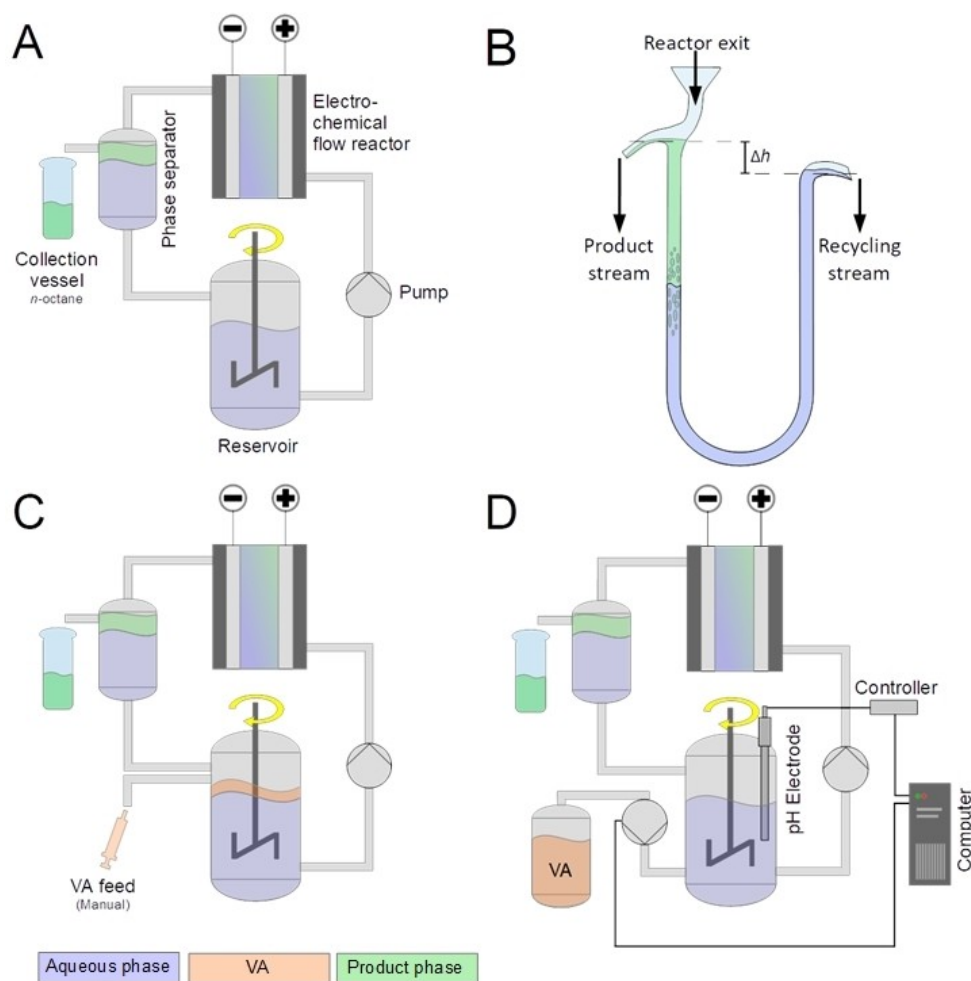
**Figure 1.** Impact of the starting concentration of VA of the performance parameters of the Kolbe electrolysis during batch operation (Starting pH 5.5,  $A_{\text{anode}} = 10 \text{ cm}^2$ ,  $i_{\text{electrolysis}} = 1 \text{ A}$ ,  $t_{\text{electrolysis}} = 240 \text{ min}$ ;  $V_{\text{flow}} = 10 \text{ mL min}^{-1}$ )

The Kolbe electrolysis of the 1 M VA led to 78% VA conversion with a mean variation of  $\pm 0\%$  for the independent duplicates (residual VA concentration 0.22 M), hereby the selectivity of the *n*-octane formation,  $S_{n\text{-octane}}$  was  $26 \pm 0\%$ . As to be expected, by increasing the initial VA concentration at otherwise unchanged conditions (identical electrolysis time and current)  $S_{n\text{-octane}}$  increased to  $65 \pm 15\%$ . Despite the doubling of the initial concentration, the relative VA conversion was reduced from 78 to only  $51 \pm 4\%$  which, together with the significantly increased coulombic efficiency (from  $13 \pm 0\%$  to  $50 \pm 9\%$ ), clearly indicates suppression of water decomposition as the dominant side reaction of Kolbe reactions in aqueous media.<sup>[23]</sup>

Simply increasing the initial concentrations, however, does not solve the inherent problems of the batch reactions. Thus, even at the higher initial concentrations, the Coulomb efficiency as well as the selectivity would strongly decrease in the course of the electrolysis. Further restrictions arise from exceeding the critical micelle concentration (CMC) of VA (1.22 M), which leads to excessive foam formation,<sup>[24]</sup> as well as to problems to separate the product phase from the aqueous electrolyte solution. Only after falling below the CMC of VA in the course of the reaction, separation of the aqueous reaction solution and the organic product phase was possible. For these reasons, all further experiments were performed at a maximum VA concentration of 1 M.

By means of a differential analysis of important performance parameters, Figure 2 illustrates the course of the Kolbe batch process and the transient conditions that apply to the batch reaction.

Selectivities and CEs for the *n*-octane formation are low and decrease almost entirely from  $S = 10 \pm 1\%$  to  $1 \pm 0.2\%$  and  $\text{CE} = 7 \pm 0.2\%$  to  $3 \pm 0\%$  throughout the 4 h process, whilst side product formation increases. Thereby, more acidic starting pH



**Scheme 2.** Illustration of the main reactor setups used in this study. **A:** Batch setup using a continuous electrolyte flow (loop) between reservoir and electrochemical flow reactor; **B:** Phase separator for a continuous separation and collection of the organic product phase; **C:** Setup for a continuous reaction using an excess VA phase; **D:** Setup for a continuous reaction using an online pH-controlled VA feeding.

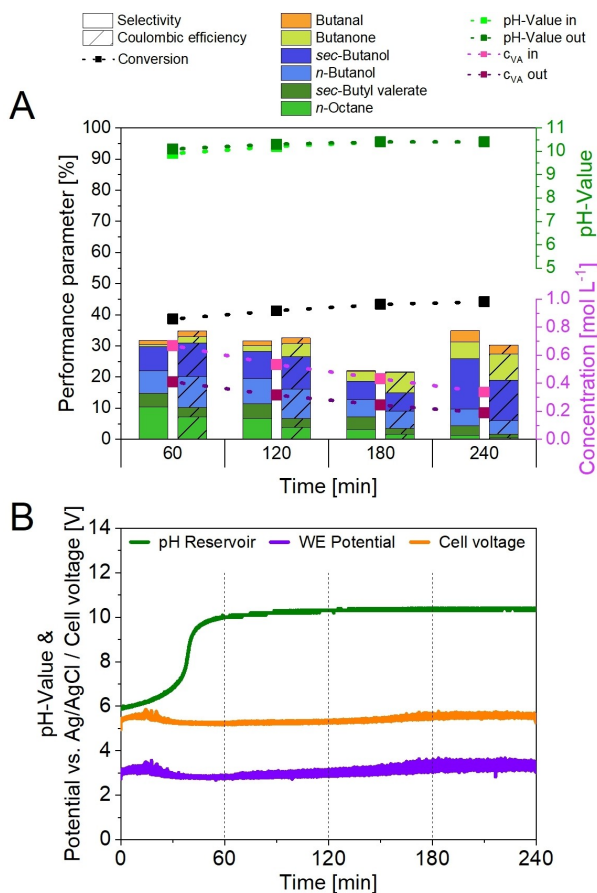
values (see also Figure S12) are beneficial and  $S_{n\text{-octane}}$  is almost doubled at pH 5.0 ( $18 \pm 1\%$ ) compared to pH 6.0 ( $10 \pm 1\%$ ). Meanwhile, the decrease of  $S_{n\text{-octane}}$  is independent from the initial pH value. Mean values for the hourly-determined selectivities and CEs and the respective standard deviations (SD) over the whole process duration can be used to quantify process quality and stability. The average  $S_{n\text{-octane}}$  under semi-batch condition for pH 6.0 over 4 h is 5.4% with a  $SD_{(n=4)}$  of 3.4%. The average  $CE_{n\text{-octane}}$  is 3.3% with  $SD_{(n=4)}$  of 2.5%. Both parameters display the inherent deterioration of reaction conditions during batch-like experiments. One of the reasons lies in the fast alkalization of the electrolyte (see Figure 2B) at less acidic starting pH values. The pH shift is caused by the loss of protons due to VA depletion combined with the cathodic hydrogen evolution reaction, HER. At a starting pH of 5, a tenfold concentration of protons is available in the system as compared to pH 6, and pH 5 is close to the  $pK_{a,VA}$  (4.86) and thus to the buffer point of the system. Both effects allow keeping the solution acidic for at least the first 2 h and neutral after 3 h, whereas at pH 6, the pH shifts forwards pH 10 within ca. 45 minutes. At these alkaline conditions, the formation of

alcohols and their successive oxidation products increases and dominates the product spectrum.

Depending on the used flow rate and thus the degree of VA conversion, alkaline conditions can be reached well within a single pass of the flow reactor, with the initial conditions accounting only for a negligible proportion of conversion. This may explain why Harnisch et al. could not find the initial pH to affect electrolysis outcome (the final pH was not determined).<sup>[25]</sup>

The limited overall selectivities (comprising all measured liquid reaction products) for all initial pH value can be attributed to losses by non-Kolbe and disproportionation reactions, resulting in the formation of butane and butene as gaseous products,<sup>[26]</sup> which were not quantified in this study. The product phase composition is further affected by the ratio of *n*-octane to butyl esters. The esters increase the polarity of the organic phase and therefore the amount of water capable to dissolve within. GC/MS sample indicates that water content can reach up to 50 wt.-% when organic phase's molar composition reaches 30 mol.-% of ester content versus 70 mol.-% *n*-octane.





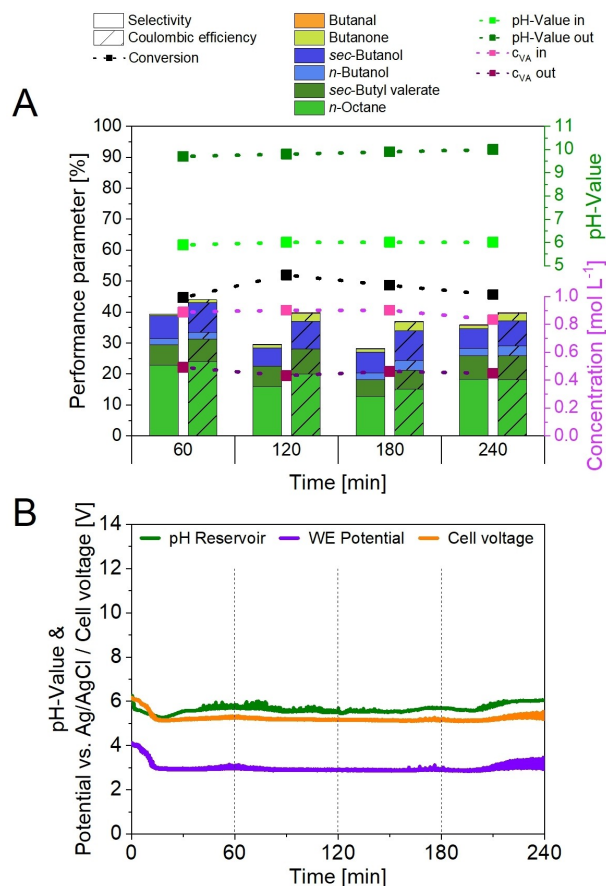
**Figure 2. A:** Analysis of the performance parameters of the Kolbe electrolysis of a 1 M VA solution at different stages of a batch reaction. The starting pH was 6.0 (see Figure S12 for pH 5.0 and 5.5 results). The product phase was continuously separated and samples were taken after 60, 120, 180 and 240 minutes of operation. **B:** Development of pH within the reactor feed, working electrode potential and cell voltage during the batch electrolysis. “in” and “out” values represent parameters measured at the inlet and the outlet of the electrochemical flow reactor, respectively. ( $A_{\text{anode}} = 10 \text{ cm}^2$ ,  $i_{\text{electrolysis}} = 1 \text{ A}$ ,  $v_{\text{flow}} = 10 \text{ mL min}^{-1}$ ).

### Continuous operation using excess valeric acid

To avoid the negative effects of the transient conditions of the batch reaction, constant and uniform reactant concentrations and pH values must be maintained within the system. This also implies flow reactor retention times that are short enough to avoid excessive substrate turnover within a single run. For an only moderately soluble acid such as valeric acid (with a solubility ranging from 0.23 M in pure water<sup>[18]</sup> to 1 M at a 5.5) an obvious opportunity is to operate the reaction system at constant VA concentration is using an excess of VA, whereby undissolved VA serves as a reservoir and dissolves successively in the electrolyte solution when the solution concentration falls below the saturation limit due to substrate conversion. Hereby, the slightly lower gravimetric density of VA as compared to water ( $\rho_{\text{VA}, 25^\circ\text{C}} = 0.934 \text{ g cm}^{-3}$  versus ( $\rho_{\text{H}_2\text{O}, 25^\circ\text{C}} = 0.993 \text{ g cm}^{-3}$ )<sup>[17]</sup>) allows the aqueous solution in the reservoir to be overlaid with VA. For our experiments the same setup was used as in the batch experiments, but with an additional port for dosing VA

into the reservoir with a syringe to maintain an approximately 5 mm thick VA layer on top of the electrolyte solution (see Scheme 2C). The range of the studied initial pH values was relatively small and was determined by the respective VA solubility. Thus, a minimum pH of 5.0 was necessary to reach a concentration of 0.8 M, whereas at pH values above pH 6.0, the solubility becomes too high to maintain a reproducible concentration and a stable acid phase. Stirring of the reactor must be slow (max. 100 RPM) and the flow rate through the electrochemical cell must be low (max.  $1 \text{ mL min}^{-1}$ ) to maintain mechanical stability of the layered electrolyte-VA phases within the reservoir and to avoid the formation of emulsions. By these limitations, VA concentration can be maintained between 0.7 M and 0.9 M, slightly below and above the initially targeted concentration of 0.8 M.

After 1 h of the continuous operation (Figure 3) a  $S_{n\text{-octane}}$  of  $23 \pm 2\%$  and  $CE_{n\text{-octane}}$  of  $24 \pm 0\%$  were achieved, which represent a considerable improvement compared to the respective data of the batch operation ( $S_{n\text{-octane}} = 10 \pm 1\%$  and  $CE_{n\text{-octane}} = 7 \pm 0.2\%$ ) (Figure 2). Yet, the process stability – indicated by a standard deviation of 3.4% for a  $S_{n\text{-octane}}$  mean



**Figure 3. A:** Analysis of the performance parameters of a continuous Kolbe electrolysis using an overlaid saturated VA solution. The starting pH was 6.0 (see Figure S13 for pH 5.0 and 5.5 results). Product samples were taken after 60, 120, 180 and 240 minutes of operation. **B:** Development of pH within reactor feed, working electrode potential and cell voltage during the batch electrolysis. “in” and “out” values represent parameters measured at the inlet and the outlet of the electrochemical flow reactor, respectively. ( $A_{\text{anode}} = 10 \text{ cm}^2$ ,  $i_{\text{electrolysis}} = 1 \text{ A}$ ,  $v_{\text{flow}} = 1 \text{ mL min}^{-1}$ ).

value of 17.5% for over the entire process duration – is relatively poor, especially due to the pH-dependence of the VA solubility. Further, the slow flow rate (1 mLmin<sup>-1</sup>, as compared to 10 mLmin<sup>-1</sup> for the batch experiment) and thus long hydraulic retention time lead to an average VA conversion of 50% during a single pass, intrinsically connected with a significant pH shift towards alkaline values within the electrochemical cell (see Figure 3A). Despite the less transient conditions in these experiments, the selectivity of *n*-octane formation decreases over time, with the respective CEs showing a similar trend, yet less pronounced. These changes might be due to increasing carbonate concentrations during the Kolbe process as recently described as a negative factor for the acetic acid coupling.<sup>[27]</sup> Carbonate formation is based on the cleavage of one molecule of CO<sub>2</sub> per molecule carboxylic acid in combination with an alkaline solution pH. The resulting carbonate/bicarbonate equilibrium stabilizes the solution pH at a value around 10 (see Figure 1A and B and Figure 2A) and side reactions like the butanol formation prevail. The solution is reconditioned when the alkaline recirculation stream comes into contact with the re-saturated solution below the VA phase (Scheme 2B). Here, the carbonate-bicarbonate system shifts towards H<sub>2</sub>CO<sub>3</sub> formation ( $pK_{a_1}(\text{H}_2\text{CO}_3) = 6.35^{[28]}$ ) – the latter decomposing to release gaseous CO<sub>2</sub> (visible in the form of gas bubbles rising within the reservoir). This offers the opportunity to not only restore the needed VA acid concentration but, at the same time, to remove the disadvantageous carbonate without any additional energetic or operative effort. Such a need was already emphasized by Nordkamp et al., however, without proposing a practical solution.<sup>[27]</sup> Also Baumgarten et al. observed a negative impact while re-saturating carboxylate during a Kolbe electrolysis.<sup>[14]</sup> Adding neutralized (via addition of KOH) carboxylate instead of the acid itself, however leads to a further increased carbonate concentration with every re-saturation – enhancing negative effects on the Kolbe electrolysis. This problem is avoided by re-dosing the acid itself. It is possible that unimpeded escape of the carbon dioxide was limited in this experiment due to the overlaying VA phase, which led to deterioration of the Kolbe electrolysis over the duration of the experiment.

Summarizing this experimental approach, the continuous operation using excess VA significantly improved the Kolbe electrolysis. Yet, negative aspects are:

- the unstable VA concentrations due to the pH dependence of the VA solubility,
- slow flow rates to prevent a mixing / emulsion formation of VA layer and aqueous phase. The resulting long hydraulic retention times lead to a high degree of VA conversion during a single pass – connected with an inherent pH increase and increasing side reactions and
- a possibly hindered CO<sub>2</sub> release of the system.

### Continuous operation using pH-controlled VA feeding

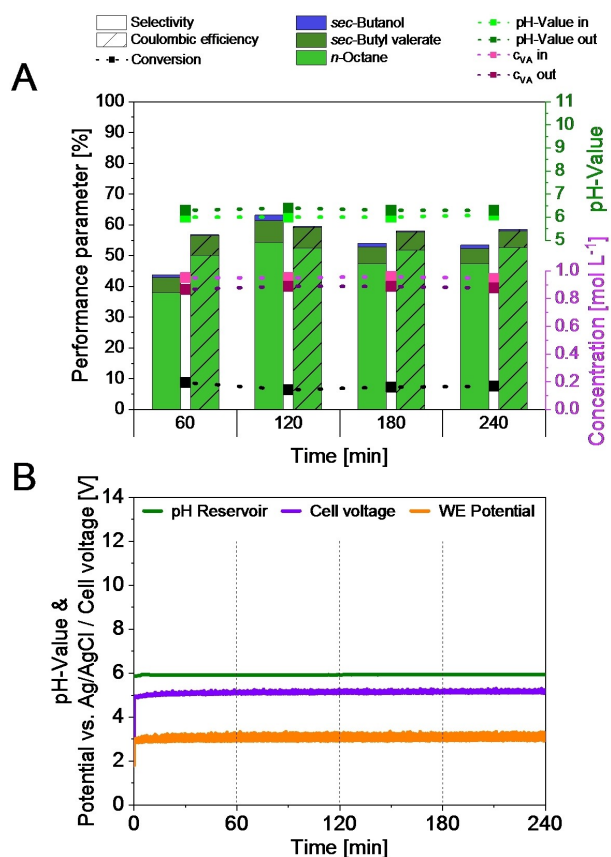
To overcome the limitations described in the previous section, the use of a sub-saturation level of the starting material in

combination with a suitable process control strategy are necessary. Considering a stoichiometric relationship between the described pH increase and the VA consumption within an undivided reactor, we propose an automatic, pH based, online control and VA feeding strategy to maintain stationary chemical conditions for a continuous Kolbe electrolysis under permanent recirculation of the aqueous electrolyte solution. For this purpose, a pH electrode is inserted into the reservoir (Scheme 2D) for online (in time) pH monitoring. The obtained pH information was used to control a pump, dosing pure VA into the reservoir. This real-time analysis meets rule 11 of green chemistry and is superior to conventional (e.g., HPLC) probing in terms of speed, effort, and cost. It allows immediate response and it is not limited to measurement duration.

By avoiding the VA phase covering the electrolyte the restriction on flow rate and potential pH range are eliminated. Shorter residence times are enabled that allow limiting the total turnover during a single pass through the electrochemical flow cell, thus maintaining stable and well-defined chemical conditions, indicated by constant values and low changes in pH during one pass of the reactor. For this operation mode only, single experiments was performed and process stability was monitored over the course of the experiment, as deviations were negligible for duplicates of self-stabilized operation mode. Therefore, no deviations are be provided for the respective data.

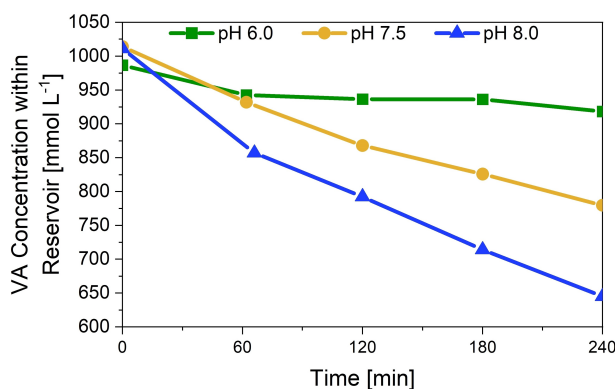
Figure 4 depicts the outcome of such a continuous operation. A flow rate of 10 mLmin<sup>-1</sup> was chosen to ensure the VA conversion not to exceed 10% within a single pass through the electrochemical cell. Consequently, the pH shift during the pass remains below 0.3 pH units and the average change in valeric acid concentration is down to 71 mmolL<sup>-1</sup> ( $SD_{(n=4)} = 8 \text{ mmolL}^{-1}$ ) over the course of the experiment. Both, the high carboxylate concentration and the low pH favor the *n*-octane formation and suppress side reactions like the alcohol and esters formation. With an average  $S_{n\text{-octane}}$  of 47% ( $SD_{(n=4)} = 6\%$ ) and an average  $CE_{n\text{-octane}}$  of 53% ( $SD_{(n=4)} = 1\%$ ), the Kolbe electrolysis now shows a very stable performance throughout the duration of the experiment. Especially the alcohol formation (Hofer Moest pathway) was suppressed efficiently. No significant accumulation of alcohols could be observed in the aqueous electrolyte phase, and ultimately no subsequent oxidation products can be found. It indicates an efficient suppression of side reactions except for butane/butene formation. This also means a cleaner product phase, less effort during workup, and fewer changes in electrolyte composition, to favor long-term recirculation. The lower pH values in addition with the opportunity of a more intense mixing of the reservoir solution also lead to a visibly enhanced outgassing of CO<sub>2</sub>, thus further supporting the Kolbe electrolysis.

By increasing the initial pH from 6.0 to above 7 (See Figure S14),  $S$  and  $CE$  of *n*-octane decrease significantly and side-product formation increases. Now, the pH changes measurably during a single reactor pass, which is a typical effect for pH-natural conditions, in which pH values are easily affected. Further, the VA concentration level in the system decreases throughout 4 h experimental duration. The effect is more



**Figure 4.** A: Analysis of the performance parameters of a continuous Kolbe electrolysis using pH-controlled VA feeding. The starting pH was 6.0 (see Figure SI4 for pH 5.0 and 5.5 results). The product phase was continuously separated and samples were taken after 60, 120, 180 and 240 minutes of operation. B: Development of pH, working electrode potential and cell voltage during the batch electrolysis. "in" and "out" values represent parameters measured at the inlet and the outlet of the electrochemical flow reactor, respectively. ( $A_{\text{anode}} = 10 \text{ cm}^2$ ,  $i_{\text{electrolysis}} = 1 \text{ A}$ ,  $v_{\text{flow}} = 10 \text{ mL min}^{-1}$ )

pronounced the more alkaline the starting pH is (Figure 5). This observation can be ascribed to an increasing accumulation of bicarbonate in the system when the reaction is conducted at a pH above the  $pK_a$  value of the  $\text{H}_2\text{CO}_3/\text{HCO}_3^-$  system ( $pK_a = 6.36$ ).



**Figure 5.** Changes of feed concentration for pH-regulated concentration control at different initial pH levels of 1 M VA solutions during 4 h process. Condition as in Figure 4 and Figure SI4.

Not only that the removal of  $\text{CO}_2$  is now inhibited, its transformation into bicarbonate also limits the applicability of a pH-controlled VA dosing, since the bicarbonate contributes to the acidic pH.

These observations show that for an efficient conduction of the Kolbe electrolysis, a relatively narrow pH range has to be ensured: The pH should be above the  $pK_a$  of the organic acid to ensure a sufficient solubility of the acid in the aqueous and a sufficient carboxylate concentration, but it should not be above the  $pK_a$  value of the  $\text{H}_2\text{CO}_3/\text{HCO}_3^-$  system in order to prevent bicarbonate accumulation.

## Conclusions

The transfer of electrochemical syntheses from batch to continuous operation allows the target reactions to be carried out efficiently, sustainably and at the same time in a scalable and thus industrially relevant manner. The proposed precise reaction control helped to suppress the water decomposition as a main disadvantage of this green solvent, thus avoiding inevitable decrease in Coulomb efficiencies in the course of a batch electro-synthesis. Overcoming this limitation allowed to fully exploit the advantages of water in continuous operation via a simple and efficient product separation and removal – allowing immediate electrolyte recirculation and reuse. Educt concentrations above 1.22 M and optimized turnover with respect to pH changes that causes decrease below CMC holds out the prospect of a functional process with  $S_{n\text{-octane}} > 70\%$ .

Our design for a continuous and self-regulated electro-synthesis process addresses key rules of green chemistry and improves the synthesis with respect to rule 1 (waste prevention) by enhanced  $S$  and electrolyte recycling and rule 6 (energy efficiency) by enhanced  $CE$ , passive product separation and electrolyte reconditioning. Finally, by applying rule 11 (online monitoring) an elegant and simple way of control the continuous process becomes possible.

The proposed process can also be envisioned to be coupled with the fluctuating electricity supply from wind power of photovoltaics. Hereby, the computer-controlled approach can automatically react to increased or decreased electricity levels. Production can be carried out between 75 and 600  $\text{mA/cm}^2$  by adapting residence time via flow rate to keep conversion per turnover and thus the reaction conditions, constant. The product composition is likely to be unaffected within this region, but energy consumption is affected by load of the pumps.

## Materials and Experimental Setup

### Chemicals

All chemicals in this study, except sec-butyl valerate, were of analytical grade and were used without further purification. Aqueous solutions were made with deionized water. VA (99%, Alfa Aesar) and potassium carbonate ( $\geq 99$ , Carl Roth) were used to prepare solutions for electrolysis. Further chemicals were used as



analytical standards: *n*-Octane (95%, Fisher Scientific), *sec*-butyl valerate (68.5%, self-made), *n*-butyl valerate ( $\geq 98\%$ , SIGMA-ALDRICH), *n*-butanol ( $\geq 99.5\%$ , Carl Roth), *sec*-butanol (99.5%, SIGMA-ALDRICH), butyl aldehyde (99%, Fluka), butanone ( $\geq 99.7\%$ , SIGMA-ALDRICH), butyric acid (99%, SIGMA-ALDRICH), propionic acid (99%, SIGMA-ALDRICH), acetic acid (99.8%, SIGMA-ALDRICH), formic acid (98%, Carl Roth), *n*-hexane ( $\geq 97\%$ , SIGMA-ALDRICH), potassium carbonate ( $\geq 99$ , Carl Roth). The preparation of *sec*-butyl valerate was done by esterification reaction and azeotropic distillation using VA, *sec*-butanol, sodium bicarbonate ( $\geq 99$ , Carl Roth), toluene sulfonic acid (97%, Alfa Aesar), and trichloromethane ( $\geq 99.8\%$  Carl Roth).

### Electrochemical reactor and periphery

All reactions were carried out in MicroFlowCell® (ELECTROCELL®, Denmark), equipped with PTFE flow frames (ELECTROCELL®, Denmark), platinized titanium plate electrodes 9.5×4.5×1 mm with  $1.5 \pm 0.2 \mu\text{m}$  Pt (99.9%) by HTE-Method (Umicore Galvanotechnik, Germany). Pristine gaskets were cut from 2000×1200×1 mm Viton® (Technikplaza GmbH, Germany). The geometrical surface area of the working electrode was 10 cm<sup>2</sup> (defined by a 3×3.33 cm window cut into the gasket). Since separating diaphragms between anode and cathode compartment would increase the internal resistance of the electrochemical cell and also constitute an important cost factor in large-scale applications, we decided to work in a membrane-less system. For the performed (anodic) Kolbe electrolysis of valeric acid this is not a problem, since the only possible cathodic reaction in the aqueous environment is the hydrogen evolution reaction. Notably, on a large scale, such membrane-less operation must assure a complete suppression of the anodic oxygen evolution reaction in order to avoid the generation of explosive gas mixtures.

All experiments were carried out galvanostatically. The currents were applied using a SP300 potentiostat equipped with 2 A, +/−30 V booster board (BioLogic, France). Potentials were measured using a leak free Ag/AgCl/3.4 M KCl capillary reference electrode (Innovative Instruments, USA). The reactions were generally performed as independent duplicates. In order to ensure the clarity of the figures, error bars were not included in the graphs. Instead, the corresponding performance data and their variances are included in the Supporting information (Table S1 1–3). Unless stated otherwise, the presented selectivity and CE data are mean values calculated from duplicates and given with respective mean deviations or variances.

For the electrochemical experiments, two Ismatec Reglo Digital MS-4/12 peristaltic pumps (Cole-Parmer GmbH, USA), equipped with 2.06 mm ID Viton® 3-stop tubes and tubing of same ID (Cole-Parmer GmbH, USA) were used. Pump one was used to pump the electrolyte solution through the flow reactor at a constant flow rate, determining the residence time in the electrochemical cell. Flow rate calibration was achieved volumetrically at the reactor exit before experiments and readjusted if necessary. When the reactor was operated in fully continuous mode with electrolyte recirculation and product separation, Pump 2 was used to dose educt into the feeding solution. For this purpose, pump control, and continuous pH measurement (VOLTCRAFT PHP-410 pH electrode, Conrad Electronics, Germany), were achieved computer controlled, via a custom-made amplifier. A passively working, custom-made vertical gravity separator (Scheme 2B) was designed for product separation.

Three different reactor configurations were utilized for batch and continuous operation (Scheme 2). Their operation is explained in the respective section.

### Analysis

Qualitative and quantitative analysis of aqueous solutions was done by high performance liquid chromatography, HPLC. The employed system is 1260 Infinity II LC (Agilent Technologies, USA) with a refractive index detector (RI), and an additional 1200 series diode array-detector (DAD). The equipped column was an Aminex HPX 87-H (9  $\mu\text{m}$ , 7.8 mm×300 mm) (Bio-Rad Laboratories GmbH, Germany) with Carbo-H protection cartridges (4×3.0 mm) (Phenomenex Ltd., USA). The injected volume was 20  $\mu\text{L}$  at 8 °C autosampler temperature. 2.5 mM H<sub>2</sub>SO<sub>4</sub> served as the eluent at a flow rate of 0.35 mL min<sup>−1</sup>. The column was operated at a temperature of 10 °C with a resulting pressure of 69 bar. Calibration was done by external standards in ranges from 0.1 – 200 mM. OpenLAB Data Analysis software (Agilent Technologies, USA) was used for processing. Samples exceeding calibrated range were neutralized and diluted using 0.1 M H<sub>2</sub>SO<sub>4</sub> in ratio 1:10, 1:4 or 1:2 prior to analysis.

Qualitative and quantitative analysis of non-polar solutions was performed using gas chromatography coupled mass spectrometry, GC/MS, using a series 6890 GC System coupled to a 5975 C inert MSD triple axial mass spectrometer (Agilent Technologies, USA). The column was a DB5 MS UI (30 m×0.25 mm ID×0.25  $\mu\text{m}$  film) column (Agilent JW Scientific, USA), operated at 1 mL min<sup>−1</sup> helium flow. Temperature is 40 °C for 15 min followed by 20 °C min<sup>−1</sup> heating up to 300 °C. External calibration is done by mixed standards from 20–500  $\mu\text{M}$ . Samples are diluted in *n*-hexane in two steps to summed up ration of 1:20000. Injected volume is 1  $\mu\text{L}$ , and evaporated split less at 250 °C. The transfer line temperature is set to 295 °C.

In order to quantify to which extent substrate depletion and pH changes take place during a single pass through the electrochemical flow cell, the respective values were sampled at the inlet and the outlet of the electrochemical cell, and the data are shown in Figures 2–4 as “pH-value in/out” and “*c*<sub>VA</sub> in/out”.

### Acknowledgements

The authors want to acknowledge the funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2163-1 – Sustainable and Energy Efficient Aviation – Project ID 390881007. Open Access funding enabled and organized by Projekt DEAL.

### Conflict of Interests

The authors declare no conflict of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords:** Chemostatic processes · Continuous electrosynthesis · Green chemistry · Kolbe reaction · Valeric acid



- [1] A. Wiebe, T. Gieshoff, S. Möhle, E. Rodrigo, M. Zirbes, S. R. Waldvogel, *Angew. Chem. Int. Ed.* **2018**, *57*, 5594–5619.
- [2] M. Faraday, *Philos. Trans. R. Soc. London* **1834**, *124*, 55–76.
- [3] H. Kolbe, *Justus Liebigs Ann. Chem.* **1849**, *69*, 257–294.
- [4] S. Maljuric, W. Jud, C. O. Kappe, D. Cantillo, *J. Flow Chem.* **2020**, DOI 10.1007/s41981-019-00050-z.
- [5] M. Yan, Y. Kawamata, P. S. Baran, *Chem. Rev.* **2017**, *117*, 13230–13319.
- [6] R. Palkovits, I. Delidovich, *Philos. Trans. R. Soc. London* **2018**, *376*, DOI 10.1098/rsta.2017.0064.
- [7] P. Gallezot, *Chem. Soc. Rev.* **2012**, *41*, 1538–1558.
- [8] F. Harnisch, U. Schröder, *ChemElectroChem* **2019**, *6*, 4126–4133.
- [9] D. S. P. Cardoso, B. Šljukić, D. M. F. Santos, C. A. C. Sequeira, *Org. Process Res. Dev.* **2017**, *21*, 1213–1226.
- [10] L. Schulz, S. R. Waldvogel, *Synlett* **2019**, *30*, 275–285.
- [11] S. Cembellín, B. Batanero, *Chem. Rec.* **2021**, *21*, 2453–2471.
- [12] P. Nilges, T. R. Dos Santos, F. Harnisch, U. Schröder, *Energy Environ. Sci.* **2012**, *5*, 5231–5235.
- [13] M. C. Rehbein, M. Guschakowski, W. Sauter, J. Kunz, U. Schröder, S. Scholl, *Front. Energy Res.* **2020**, *8*, 1–7.
- [14] N. Baumgarten, B. J. M. Etzold, J. Magomajew, A. Ziogas, *ChemistryOpen* **2022**, *11*, e202200171.
- [15] F. J. Holzhäuser, J. B. Mensah, R. Palkovits, *Green Chem.* **2020**, *22*, 286–301.
- [16] G. Atherton, M. Fleischmann, F. Goodridge, *Trans. Faraday Soc.* **1967**, *63*, 1468–1477.
- [17] W. M. Haynes, Ed., *CRC Handbook of Chemistry and Physics*, CRC Press LLC, Boca Raton, **2016**.
- [18] S. H. Yalkowsky, *Handbook of Aqueous Solubility Data*, CRC Press, **2003**.
- [19] R. A. Green, R. C. D. Brown, D. Pletcher, *J. Flow Chem.* **2016**, *6*, 191–197.
- [20] S. D. Schaber, D. I. Gerogiorgis, R. Ramachandran, J. M. B. Evans, P. I. Barton, B. L. Trout, *Ind. Eng. Chem. Res.* **2011**, *50*, 10083–10092.
- [21] M. Atobe, H. Tateno, Y. Matsumura, *Chem. Rev.* **2018**, *118*, 4541–4572.
- [22] N. Jongen, M. Donnet, P. Bowen, J. Lemaître, H. Hofmann, R. Schenk, C. Hofmann, M. Aoun-Habbache, S. Guillemet-Fritsch, J. Sarrias, A. Rousset, M. Viviani, M. T. Buscaglia, V. Buscaglia, P. Nanni, A. Testino, R. Herguijuela, *Chem. Eng. Technol.* **2003**, *26*, 304–306.
- [23] B. M. Weckhuysen, *Chem Catal.* **2022**, *2*, 920–922.
- [24] D. Klüh, W. Waldmüller, M. Gaderer, *Clean Technol.* **2021**, *3*, 1–18.
- [25] C. Stang, F. Harnisch, *ChemSusChem* **2016**, *9*, 50–60.
- [26] W. Hayduk, H. Asatani, Y. Miyano, *Can. J. Chem. Eng.* **1988**, *66*, 466–473.
- [27] M. O. Nordkamp, B. Mei, R. Venderbosch, G. Mul, *ChemCatChem* **2022**, *14*, e202200438.
- [28] A. F. Holleman, N. Wiberg, E. Wiberg, *Lehrbuch Der Anorganischen Chemie*, Walter De Gruyter, **2007**.

Manuscript received: July 5, 2023

Revised manuscript received: September 7, 2023

Accepted manuscript online: September 7, 2023

Version of record online: November 3, 2023