

# Perspectives in Flow Electrochemistry

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Electrosynthesis is an old method currently moving again in the focus of organic synthesis. Some limitations of conventional electrosynthesis can be overcome by the use of electrochemical flow devices. This perspective indicates where the pitfalls, where the advantages and where the challenges are in implementing flow electrosynthesis as an alternative tool for the synthetic chemist.

**Keywords:** Electrochemistry, flow chemistry, perspective

Organic electrochemistry has its origin in 1830 with Michael Faraday [1], but electrochemistry in general was discovered in 1800 when Alessandro Volta discovered the voltaic pile, the first electrochemical cell (Figure 1) [2].

Since that time, mainly specialists have driven the development of electrochemical reactions. Notable reactions have been discovered, and processes such as the Kolbe electrolysis [3] or the Hall-Héroult process for aluminium production [4] are described in many textbooks. Due to these developments, organic electrosynthesis is nowadays a versatile method with a large number of applications on the laboratory scale [5] and also several processes in industry [6]. However, only very few synthetic laboratories and research institutions are routinely considering electrochemical processes as a tool in synthesis planning or in preparing new compounds or intermediates. Much more advanced, however, is the analytic use of electrochemistry where sensing of molecules [7] or voltammetric measurements [8] are regularly performed.

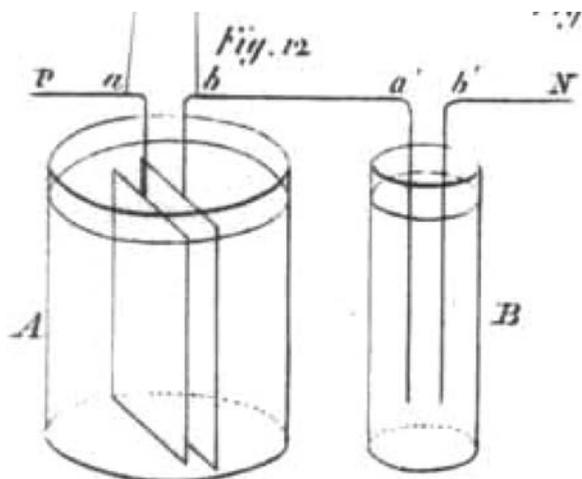
Nevertheless, organic electrosynthesis is recognized as one of the methodologies of the future to perform oxidations and reductions of compounds in environmentally friendly processes, as toxic and/or dangerous oxidants and reducing agents are replaced by electricity [9]. Unstable and hazardous reagents can be produced in situ and directly consumed [10]. This methodology has several advantages over traditional reactions, such as reaction selectivity, which can be controlled by the nature of the electrode, the potential applied at the working electrode, or the composition of the electrolyte used. The degree of transformation of a molecule can also be controlled, as in classical organic chemistry, by regulating the charge consumption. In general, the reaction

conditions for an electrochemical transformation are quite mild, since they are usually performed at atmospheric pressure and ambient temperature. On the other hand, electrosynthesis also has some drawbacks. It is well known that the nature of the electrode material and the overpotential accessible with certain electrodes influence the electrochemical processes. Fine-tuning of electrodes can be very important in order to optimize reactions [11]. For a consistent performance, one also has to ensure that the electrodes do not degrade or change their surface properties during operation, a task which is not always easy to achieve. The potential at the working electrode can also be used for conducting selective reactions [12]. As the reaction only proceeds at the electrode surface, the area for electron transfer is limited. A supporting electrolyte is typically needed to transport the charge through the solution, making such processes less cost-efficient and more time-consuming, as the supporting electrolyte will have to be removed from the product. Not surprisingly, also the nature of the supporting electrolyte influences the reactions.

Some of these limitations of conventional electrosynthesis can be overcome by the use of electrochemical flow cells [5a, 13], which usually have only a small gap between the electrodes. One of the simplest arrangements is shown in Figure 2. Two electrodes are arranged facing each other, and the reaction solution is passed through the gap between the electrodes. Other electrode configurations in such devices have been reported as well such as interdigitated [14] or segmented electrodes [15]. Even paired electrolysis is possible where the cathodic and anodic reactions are both used in the overall process [16]. A number of microfluidic electrochemical cells have been developed, and their performance has been studied and compared [17].

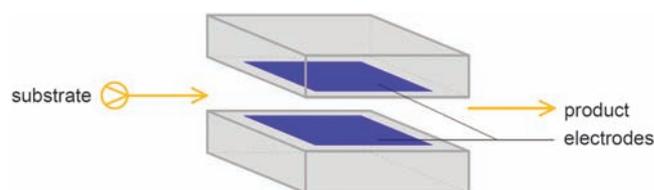
Lower concentrations of supporting electrolytes are possible in flow electrochemical reactors, or reactions can be performed even without any added supporting electrolyte while the solvent and/or substrates and reagents show sufficient conductivity [18]. Due to the smaller volumes handled in the flow devices, transfer and removal of heat are more facile.

The advantages of flow electrochemical microreactors shown in Figure 3 have been exploited in many different reactions. One of the earliest electrochemical reactions in an electrochemical microreactor was reported in 1989, where the product selectivity



**Figure 1.** Apparatus for electrochemical reactions used by M. Faraday [1]

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**Figure 2.** Schematic representation of a plate to plate electrochemical microreactor

**Advantages of flow electrochemical reactors**

- Short distances between electrodes
- No or low concentrations of added supporting electrolyte necessary
- Easy removal of heat
- Large ratio of electrode area to reactor volume

**Figure 3.** Advantages of flow electrochemistry over batch electrochemistry

in the reduction of benzaldehyde to dihydrobenzoin and benzyl alcohol has been controlled by the mass-transfer rate [19]. Since that time, developments in the engineering of electrochemical reactors and the availability of commercial devices have enhanced research in flow electrochemistry. Facile generation of radicals and their controlled reaction [20], the synthesis of highly unstable cationic intermediates [21] and their use in target synthesis, and the adaption of flow electrochemical methods towards large-scale processes have been reported [22]. An industrial relevant example is the “new Monsanto” process, which hydrodimerizes acrylonitrile to adiponitrile (>300.000 t/a), a precursor to hexamethylenediamine for the production of nylon 6-6. It consists of a process employing a two-phase reaction mixture in an undivided flow cell with bipolar electrodes, which was found to give higher current efficiency than the divided cell [23].

Despite these efforts, for a broad adaption of electrochemistry, the research laboratories are still in need of an affordable, practical – and operationally simple – device. Current commercial devices are still expensive and consist of multiple units. An extensive wish list of its features has been published recently, which also includes analytical capabilities and the ability of online updates, in line with 2017 consumer product standards [24]. Most important, however, seems to be the standardization so that an easy reproducibility of experiments is ensured.

With such a tool in hand, the spectacular recent developments in batch electrochemistry [25] can surely be adapted and extended to flow protocols taking advantage of the abovementioned advances. The prospects of flow electrochemistry lie in its capability to generate and use short-lived intermediates, which is impossible in batch protocols. The combination of flow electrochemistry with photochemistry, sonochemistry, or with unusual reaction conditions (high temperatures/pressures) can be achieved much easier in bespoke flow devices, and interesting developments are expected in these areas. In addition, flow electrochemical steps can be combined with other flow reactions, allowing an integration of electrochemical and chemical reactions in a single flow process.

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