International Conference NEW PERSPECTIVES in SCIENCE EDUCATION

Design of a Science Camp on Sustainable Electrochemistry

Vivian Keune[1], Lea Smolnik[1], Erhard Irmer[2], Thomas Waitz[1]

University of Göttingen, Institute of Inorganic Chemistry, Department of Chemistry Education, Germany[1]
University of Göttingen, XLAB-Experimental laboratory for young people, Germany[2]

Abstract

In 2015 the United Nations adopted the 2030 Agenda for Sustainable Development to address the big environmental, social and economic challenges of our time, such as preserving oceans and forests, tackling climate change and achieving peace and prosperity for all people. Education for sustainable development is one of the main approaches to promote change in young people's knowledge, skills and values.
In this contribution, we present a one-week student camp on sustainable electrochemistry, which will take place at the XLAB student laboratory in Göttingen in March 2025. The camp aims at deepening and expanding knowledge acquired at high school, at connecting the sustainability goals to curricular core concepts and at enabling students to get in touch with current research and researchers.
In order to design a varied and motivating course, we divided it into three sections, in which established chemical reactions are compared to state-of-the-art electrochemical processes. For example, the first two sections oppose the use of elemental bromine to electrochemical bromination [1] and the Fenton experiment to an electro-Fenton reaction [2]. These experiments demonstrate chemical, energetic and environmental advantages of electrochemical in-situ reactions compared to the conventional reactions. In the third section, further experiments cover current research topics such as the electrochemical reduction of carbon dioxide or nitrate and their conversion into high-value chemical substances [3]. In this part, participants are encouraged to contribute their own ideas and to create new experiments by themselves. This is intended as a means of differentiated instruction and to encourage students to experiment independently.
The participants also learn about modern analytical methods to detect the products of electrochemical reactions that are usually not covered in school, e.g. NMR spectroscopy or cyclic voltammetry.
The goal of the camp is to give students insight into current issues in chemistry research and to illustrate the significance of electrochemistry for a sustainable, efficient and secure chemical industry.

Keywords: *Education for sustainable development, sustainable electrochemistry, science camp, electrochemical bromination, nitrate reduction, carbon dioxide reduction*

1. Introduction

A world without electricity would be unimaginable today. Lighting, communications, mobility and industrial production - almost every aspect of our daily lives depends on electrical energy.
However, it is often underestimated that the basis of many electro-based technologies is deeply rooted in chemistry: since the invention of electrolysis, a large number of chemicals can be produced in high purity (e.g. the chloralkali process), metals are galvanically refined, waste water is electrochemically purified and electrochemical sensors are used in hospitals, criminalistics or industrial production [4].
Hence, electrochemistry combines physical, technical and analytical subfields and is closely linked to the donor-acceptor concept and the energy concept of chemistry teaching. This topic is particularly suitable for bridging the gap between reactions already known from school and current scientific research: Before the discovery of electricity, redox reactions had to rely on strong reducing or oxidising agents, e.g. the carbon in charcoal for metal formation or oxygen for oxidation. Instead of chemical substances, however, electric current can be used and the voltage can be varied almost at will, allowing previously unattainable reduction and oxidation potentials. As a result, many long-known reactions can now be carried out electrochemically with less chemical input, at lower temperatures and with a lower hazard potential. [4] This electrification of chemistry often results in cost savings and increased economic efficiency but also in more sustainable, safer and more environmentally friendly chemical production. With this in mind, Paul Anastas and John Warner developed 12 basic principles of 'green chemistry' in the 1990s, which provide specific recommendations for action in chemical research, but also for industry and science education. [5]

In 2015, the 17 UN Sustainable Development Goals (SDGs) were defined as part of a global ‘Education for Sustainable Development’ campaign. These goals are even broader than those of green chemistry, combining environmental, economic and social factors needed for a liveable and sustainable future. Yet, numerous studies have shown that the concept of green chemistry, the SDGs and sustainability in chemistry are not yet sufficiently integrated into school education. [6][7][8]
To address this issue, an innovative concept has been developed to teach pupils how electrochemistry can contribute to a more sustainable and economical production of chemicals, to the degradation of pollutants, the conversion of chemical waste into valuable chemicals, the degradation of carbon dioxide and thus to a more sustainable green chemistry overall.

2. Sustainability in School Chemistry

The words ‘chemistry and ‘chemical’ are often associated with ‘dangerous’, ‘toxic’ or ‘unnatural’. This public perception can be traced back to the safety issues and environmental pollution of the early days of the chemical industry in the 19th century. [8]
But even today, the chemical industry is still responsible for a large number of pollutants, greenhouse gas emissions and toxic waste. Traces of anthropogenic chemicals such as fertilisers, pesticides, plastics or combustion toxins have been found even in uninhabited regions, in the upper atmosphere and in the human food chain. [9]
In the 1990s, Paul Anastas and John Warner developed the concept of green chemistry to help minimising the amount of chemical waste and the need of chemicals and energy in chemical synthesis. This concept combines suggestions from the US Environmental Protection Agency, the European Union and the Organisation for Economic Co-operation and Development (OECD), among others, into 12 principles:

Table 1. The 12 principles of green chemistry [8].

1) Prevention of waste	7) Use of renewable feedstocks
2) Atom economy	8) Reduce unnecessary derivatisation
3) Less hazardous chemical syntheses	9) Catalysis
4) Designing safer chemicals	10) Design for degradation
5) Safer solvents and auxiliaries	11) Real-time analysis for pollution prevention
6) Design for energy efficiency	12) Inherently safer chemistry for accident prevention

Initially, green chemistry (GC) mainly focused on aspects of chemical synthesis and later expanded, particularly in Europe, into the broader concept of sustainable chemistry, which also includes aspects of energy production, manufacturing and technological progress. [8]
The importance of new sustainable chemical processes has been increasingly recognised by educational research over the last 30 years. With increasing digitalisation and automation, it is becoming increasingly clear that particularly creative thinking skills are needed to meet the challenges of the 21st century. In 2007, Paul Anastas, one of the founders of green chemistry, also noted [10]:

„Finally, the success of Green Chemistry ultimately depends on the practicing chemists who will use the same brilliance and creativity that is the long tradition of chemistry and use it with the new perspective for transformative innovations for sustainability.”

It is therefore essential to integrate GC and sustainable research projects into teaching, e.g. into university education, chemistry courses and school curricula. This can also be a way to improve the negative image of science and make chemical research more attractive.
The UN education campaign ‘Education for sustainable development’ (ESD) marks a particularly important step in this desirable development. As part of this campaign, 17 Sustainable Development Goals (SDGs) have been defined, which are even broader than the GC or SC criteria and are intended to enable a life in peace, prosperity and ecological balance. The SDGs and ESD have already led to changes in curricula and to the introduction of teacher training courses and are increasingly being incorporated into scientific and educational research. [8] For example, numerous outstanding educational institutions in Germany have been certified as ‘extracurricular learning locations for ESD’, including the Experimental Laboratory for Young People (XLAB). This facility, which is affiliated to the University of Göttingen, is one of the largest student laboratories in Germany and offers an extensive range of experiments as well as numerous training courses for teachers on various scientific and socially relevant topics. The science camp presented here will also take place at the XLAB and will

demonstrate ways to achieve sustainable, safe and efficient chemistry based on the 12 principles of GC and the 17 SDGs of ESD.

3. Sustainable Chemistry through Electrochemistry

Electrochemistry, which shows enormous potential for the optimisation and simplification of chemical processes and can realise the principle of sustainability, has been a particular focus of GC and the XLAB's programme for some time. For this reason, the science camp presented here is also dedicated to this topic.
Although the systematic study of electrochemistry only began around 1900, this field has led to major technical and economic advancements since (see the examples in the introduction).
In addition to research into new technologies, electrochemistry has always contributed to the improvement and simplification of existing chemical processes: many thermodynamically stable compounds require a large amount of energy for reduction and have to be combined with strong reducing agents or exothermic reactions. The reaction of carbon dioxide and burning magnesium or the reduction of nitrate with zinc powder are just two examples of such energy-intensive processes.
However, these reductions can also be carried out electrochemically, requiring only electrical energy, ideally generated from renewable sources, and can therefore be considered sustainable. The electrode material, which often acts as an electrocatalyst and thereby influences the reaction mechanism, is also of crucial importance in electrochemical reactions. Depending on the electrode material used, undesired side reactions can be suppressed and the reaction pathways to the desired products can be facilitated. This allows selective control of the products formed and avoids waste.
Not only the electrochemical reduction of environmentally harmful substances can be linked to ESD. In fact, a bridge can be built between ESD and most electrochemical processes from school curricula, as summarized in Table 2:

Table 2. Linking electrochemical school topics to ESD (visual assets from [11]).

Electrochemical school topics	**Connections to the 12 principles of GC and the SDGs**	
Electrochemical production of chemicals, e.g. metals, and fertilisers	**GC principles 1, 2, 3, 5, 6, 9** **SDG 2, 3, 8, 9, 13, 15**	
Electrochemical degradation of pollutants (CO_2, nitrate), utilisation of these pollutants to produce valuable chemicals	**GC principles 1, 3, 7, 9, 12** **SDG 3, 6, 8, 9, 14, 15**	
Rechargeable batteries, fuel cells, energy storage	**GC principles 3, 6, 10** **SDG 7, 9, 11, 13**	
Experiments with electrochemical measurement methods, electrochemical detection of substances	**GC principles 11, 12** **SDG 3, 6, 14, 15**	

4. Design of the Science Camp

4.1 Programme and Goals of the Camp

The camp has a modular structure, and each of the modules compares thermal processes, often already familiar from school, to innovative electrochemical experiments.

Table 3. Programme of the science camp.

<table>
<tr><th>Date</th><th>3rd of March</th><th>4th of March</th><th>5th of March</th><th>6th of March</th><th>7th of March</th></tr>
<tr><td rowspan="2">Morning programme</td><td rowspan="2">Arrival</td><td rowspan="2">Electrochemical bromination</td><td rowspan="4">Focus modules:

reduction of nitrogen oxides
or
reduction of carbon dioxide</td><td rowspan="2">Visits to research facilities in Göttingen</td><td rowspan="2">Science symposium</td></tr>
<tr></tr>
<tr><td rowspan="2">Afternoon programme</td><td>Fundamentals of electrochemistry</td><td rowspan="2">Electro-Fenton reaction</td><td rowspan="2">Preparation of presentations</td><td rowspan="2">Departure</td></tr>
<tr><td>Green chemistry</td></tr>
</table>

The first module, f**undamentals of electrochemistry**, repeats fundamental concepts of redox chemistry and electrochemistry and provides practice in calculating with standard potentials. The next module provides an introduction to the concept and principles of **green chemistry**, which will be the main theme of the subsequent modules.
On the next day of the camp, a module on **electrochemical bromination** follows: in this unit, the students analyse important reaction mechanisms such as electrophilic addition and the electrophilic and radical substitution of bromine and compare them with electrochemical bromination in terms of their reaction conditions. [1] This unit focuses on the principles 3, 5 and 12 of GC and the hazards of bromine compared to bromide. A selection of the experiments used in this module is given below.
Electrochemical processes are also playing an increasingly important role in the degradation of organic waste products: for example, the **electro-Fenton reaction** can be used to remove persistent pharmaceutical residues from wastewater. [2] This process is presented in the following module and compared to the classical Fenton reaction for wastewater treatment. In this module, the principles of GC are further explored, in particular by identifying the risks associated with the use of hydrogen peroxide. This unit also covers the SDGs 3 and 14.
On the third and fourth day of the camp, the participants are divided into groups in order to broaden, deepen and specialise their knowledge in one of two focus modules. These modules are linked to current research projects and innovative experiments from our laboratories.
In these focus modules, the participants will explore the **reduction of nitrogen oxides** to nitrogen and ammonia, and the **reduction of carbon dioxide** [12] to formic acid, and will learn that toxic or climate-damaging industrial waste can not only be rendered harmless electrochemically, but can also be further processed into economically interesting products. By using different electrode materials and reaction conditions, the electrochemical processes can be precisely controlled and the formation of undesired by-products can be minimised. Using modern measurement techniques such as cyclic voltammetry and FTIR spectroscopy, the participants will be able to directly detect the main and intermediate products formed and to investigate the reaction mechanisms. These focus modules address the SDGs 3, 6, 8, 9, 14 and 15 in particular.

In the end of the camp, the participants evaluate their experiences and findings. For this, we have chosen the form of a '**science symposium'**, in which the participants summarise their main 'research findings' in the form of short presentations. This sequence of familiarisation with a topic, experiments, in-depth study and final presentation replicates the processes of scientific research and gives an insight into scientific working methods, equipment and procedures.
These consecutive modules allow the participants to familiarise themselves with the topic of sustainability through practical experiments. These experiments are linked to important school topics (e.g. redox reactions, electrolysis, classes of organic matter, carbon dioxide and climate change, nitrogen cycle) and provide a bridge to current research topics. This is particularly important, since the subject of electrochemistry is usually limited to current-generating electrochemical systems and electrolysis in school chemistry classes and is not transferred to other areas (e.g. organic chemistry or synthetic chemistry).

In order to intensify this link between school chemistry and research, the participants will visit various **research institutions in Göttingen** on the fourth day of the camp, e.g. a working group of the **Collaborative Research Centre 1633**. Through direct contact with researchers, the participants will learn how important perseverance and enthusiasm for the research subject are for the success of scientific research activities. The participants will also have the opportunity to interact with university students and doctoral candidates supervising the camp, who will share information about their studies and their own research. In this way, the camp also provides guidance for a future career in science.

4.2 Selected Experiments

As this course aims to show how electrochemical methods can be used to avoid pollutants and degrade pollutants from a sustainability perspective, these new methods need to be contrasted with ‘dirty’ conventional methods. For example, the ‘electrochemical bromination’ module starts with two experiments on the traditional generation of bromine water and its use in the bromination of alkenes. The subsequent experiment 3 then shows that bromine can also be obtained by the electrolysis of a much less dangerous bromide solution. The following experiment 4 demonstrates that the bromine formed in situ can be used to synthesise eosin Y from fluorescein.

Experiment 1: Generation of Bromine Water

Pure bromine is not allowed to be used by pupils in German schools due to its hazardous nature; indeed, it is the cause of most accidents in German schools. [13] For this reason, bromine water can be used as a slightly safer alternative. To avoid the need for elemental bromine for preparing this chemical, bromine water is often produced by the reaction of bromide and bromate.
This is done by dissolving about 0.5 g of potassium bromide and 0.05 g of sodium bromate in 40 ml of demineralised water in a beaker. This solution is then carefully mixed with a few drops of concentrated hydrochloric acid. The appearance of a yellow to orange colour indicates the formation of bromine water. However, it is now known that both potassium bromate and sodium bromate are carcinogenic, which is why they are no longer allowed in school experiment. [13] Due to the strict safety precautions at the science camp presented here, this experiment can nevertheless be carried out as an introductory experiment to illustrate the dangers of handling bromine. However, it is essential that the experiment is conducted under supervision inside a fume hood and that participants wear protective gloves at all times. The bromine water produced can then be used for experiment 2.

Experiment 2: Addition of Bromine to Cyclohexene

Add about 2 ml of cyclohexane to one test tube and 2 ml of cyclohexene to a second test tube. A few drops of bromine water are then added to both test tubes. This experiment must be carried out with protective gloves and under a fume hood.
After adding the bromine water, only the solution in the test tube containing cyclohexene loses its colour. This is because the halogen molecules are added to the double bond of the alkene, according to the mechanism of electrophilic addition. This results in 1,2-dibromocyclohexane as the product of this experiment. Finally, an aqueous solution of sodium thiosulphate is added to the solutions to neutralise any remaining bromine.
The high toxicity of bromine and bromine water and the necessary safety precautions in these first experiments clearly show that a different method of bromination would be beneficial for creating a more sustainable chemistry.

Experiment 3: Electrochemical Generation of Bromine

Dissolve about 10 g of sodium bicarbonate and 5 g of potassium bromide in 100 ml of water. Keep 50 ml of this solution for the next experiment 4.
The remaining 50 ml of the solutions are electrolysed for about 2 minutes at 3 V DC under constant stirring, using the graphite electrode as the anode and the iron electrode as the cathode. A few millilitres of this solution are added to a few drops of cyclohexene in a test tube and mixed thoroughly by shaking. Similar to the second experiment, the solution decolourises. This shows that the electrolysis has caused the oxidation of bromide to bromine, which then reacts with cyclohexene to form 1,2-dibromocyclohexane. If a few drops of cyclohexene are added to the non-electrolysed sample, no discolouration is observed.

Experiment 4: Electrochemical Bromination of Fluorescein

A spatula tip of fluorescein is added to the unelectrolysed solution from experiment 3. The solution is then divided into two beakers. One of the solutions is set aside as a reference sample. The second solution is electrolysed for 2 minutes at 3 V DC under constant stirring. A graphite electrode is used as the anode and an iron electrode as the cathode. A clear colour change from yellowish-green to red can be observed during the reaction. The samples are then analysed under UV light. The fluorescence of the solution also decreases significantly (cf. fig. 1).
As in experiment 3, bromine was first formed electrochemically and then immediately reacted with fluorescein to form eosin Y.

Fig.1. Left: fluorescein solution under UV illumination; Right: fluorescence of eosin Y as the product of electrochemical bromination of fluorescein.

As an in-depth experiment, thin-layer chromatography (TLC) can be used to detect the resulting product: A butanone-ammonia-ethanol mixture in a ratio of 12:1:5 is used as the eluent, and a non-fluorescent silica TLC plate is used as the stationary phase. The TLC plate is then viewed under UV light and the fluorescent spots are compared with each other. In this way, the formation of eosin Y can be clearly demonstrated.

These selected experiments illustrate the overall concept of the science camp, which is continued in the other experimental modules. The first experiments are classic reactions often involving hazardous substances, high chemical consumption or the formation of waste products. These experiments usually have to be carried out in a fume hood and with protective gloves, which is why they are usually only discussed and not actually carried out at school. This science camp eventually gives the participants the opportunity to carry out the experiments themselves.
These classic methods are usually followed by short discussion questions that encourage the participants to evaluate the experiments from a sustainability perspective. Electrochemical processes are then presented as a contrast and provide an insight into current research projects. In order to detect the electrochemically formed products, different analytical methods are used, e.g. methods familiar from school such as thin-layer chromatography, but also FTIR and cyclic voltammetry.

In this way, this science camp bridges the gap between inorganic, organic, physical and analytical areas of chemistry, combines school knowledge with state-of-the-art research and shows that chemistry does not only have to be dangerous and harmful to the environment, but can also offer fascinating solutions for a more sustainable future.

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