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ARTICLE

Innovating Undergraduate General Chemistry by Integrating Sustainability-related Socio-Scientific Issues

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Many general chemistry courses in U.S. undergraduate education focus on decontextualized content learning, driven by a structure-of-the-discipline approach. Due to this approach, many students perceive general chemistry to be of low relevance to their educations, their lives, and society as a whole. This paper reflects a process of innovation for the integration of sustainability-related socio-scientific issues into U.S. undergraduate general chemistry courses to make chemistry learning more meaningful and relevant to the learners. The innovation originated from teaching and learning materials developed in Germany. Digital learning environments were created on hydraulic fracturing and phosphate recovery, two hot socio-scientific issues, which were then transferred, adapted, and implemented in the USA. This paper reflects selected students' feedback and how this process initiated ongoing curriculum innovation.

Keywords: Action Research, Undergraduate Education, Chemistry Education, Socio-Scientific Issues

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Introduction

Chemistry and chemistry knowledge play an important role for responsibly living in the modern world and for developing a sustainable future (Matlin, Mehta, Hopf & Krief, 2015). Hence, chemists and chemistry educators have the responsibility of helping to shape the future, both in developing sustainable technologies as well as educating the young generation for responsible citizenship (Eilks, Sjöström & Zuin, 2018). Chemistry learning is, however, often perceived as irrelevant by students and thus becomes unpopular. There is a lack of efforts to make the connection between chemistry and its role in everyday life and society clear to learners (Jenkins & Nelson, 2005; Osborne & Dillon, 2008). A solution to overcome the perceived irrelevance of chemistry learning is suggested through the integration of more societal questions and controversial socio-scientific issues (SSIs) into the science curriculum (Stuckey, Hofstein, Mamlok-Naaman & Eilks, 2013). Such approaches are suggested to have a large potential to reform educational efforts that promote sustainable development (Eilks & Hofstein, 2014). However, these approaches are still missing in many science education practices (Hofstein, Eilks & Bybee, 2011).

The idea of integrating contexts and societal issues into teaching and learning of chemistry in order to prepare young learners for their future is not new (Hodson, 2003; Osborne, 2007). In these scenarios, effective teaching practices are utilized to bring the societal dimension of chemistry into teaching and engage students in the processes of debate and discussion (Marks & Eilks, 2009). However, only a very small portion of general chemistry professors have adapted these methods so far, while most focus on "pure chemistry" only, which is, to some extent, isolated from individual life and society (Cooper, 2010; Cooper & Klymkowsky, 2013).

Teachers who have realized that the methods they have been using are ineffective in showing the power of the chemistry knowledge to their students and are willing to change the scope and pedagogy of their teaching should explore action and design research studies as a way of developing new models and teaching approaches (Hodson, 2003; Nieveen & Plomp, 2013). This paper reports how curriculum innovation based on action research in Germany inspired a chemistry professor in the USA to implement similar designs and to learn about potential effects. The discussion goes along two cases of curriculum innovation in college-level general chemistry at a research university located in northern California and gives insights into students' perceptions and effects of such interventions.

Sustainability-related issues in chemistry education

Education for sustainable development (ESD) aims to promote the notion of learners being responsibly prepared for the future. Thus far, in accordance with the Agenda 21 (UNCED; 1992), the UN-Decade of Education for Sustainable Development and similar reports have been issued, each emphasizing the crucial role of education for sustainable development. In 2015, the United Nations announced: Transforming our world - the 2030 Agenda for Sustainable Development (UN, 2015). One hundred and ninety-three countries agreed to take responsible actions for sustainable development. The UN-document refers to a view on sustainable development with its three dimensions (environmental, societal, economic sustainability) in a balanced way. Although, there are other ideas to create a style of living "*that meets the needs of the present while safeguarding Earth's life-support system, on which the welfare of current and future generations depends*" (Griggs et al., 2013; p. 306).

Chemistry is central when it comes to innovations and developments, as highlighted in the production of new forms of sustainable energy supply or the application of "greener" technologies (Matlin et al., 2015). The connection of sustainable development and chemistry education has long been made (Burmeister, Rauch & Eilks, 2012) and became well justified in theory in recent years (Sjöström, Eilks & Zuin, 2016; Sjöström & Talanquer, 2018). Chemistry

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education, among all other educational domains, is suggested to have a core role in contributing to ESD at all levels including college level education (Andraos & Dicks, 2012). This also requires a different approach to reform efforts in chemistry education and chemistry teacher education (Zuin, 2012). To merge chemistry learning with ESD, the teaching and learning of chemistry should not focus on abstract and narrow content knowledge only. The incorporation of a broader view from many perspectives, such as the environment, economy, and society, is needed. Hodson (2003) names several potential topics like food and agriculture including the politics of starvation, energy resources, politics of the petroleum industry, and the use of water and mineral resources. Many of these topics are directly addressed by the Sustainable Development Goals of the United Nations issued in the Agenda 2030 (UN, 2015).

Science education must have a central position in cultivating the next generation of students in order to create responsible future citizens who are able "*to make informed, responsible choices in an increasingly complex world, and to adapt to the continuous changes that the world undergoes*" (Elmose & Roth, 2005, p. 31; Sadler, 2011). Chemistry learning can be made more meaningful and progressed to contribute to the development of responsible citizenry by teaching the societal dimension of chemistry along socio-scientific issues. This provides students with the opportunity to discuss societal dilemmas and their relatedness to science by involving controversial perspectives and calling for a justification of arguments (Sadler, 2004). The method works better if the students start discussing familiar life situations first and continue questioning the type of knowledge that can benefit future citizens. This approach can be called an external perspective on science. Using such external perspectives in science teaching is suggested for their potential to increase the relevance of science teaching and learning (Hofstein et al., 2011).

According to Stuckey et al. (2013) relevance of science teaching and learning is based in three dimensions (individual, societal and vocational relevance), internal and external components and a time scale from now to future. Relevant science learning takes place if the learning has (positive) consequences for the learners now or in the future. Thereby, SSIs should foster relevant science learning when they are connected to sustainability challenges that the young generation and our society need to tackle and are charged to come up with a solution (Hofstein & Eilks, 2014). Sustainability-related SSIs generally are interdisciplinary, incorporate societal and ethical values, and can lead to activism, making them ideal to revamp science teaching (Simonneaux, 2014).

One approach to teaching SSIs in chemistry education is the socio-critical and problem-oriented approach to science teaching (Marks & Eilks, 2009). This approach suggests starting from authentic problems that attracted media's attention leading to questions to be clarified based on science and technology. Afterward, it focuses on the socio-scientific dimensions by discussing and evaluating different perspectives leading over to a meta-reflection on the use of science in society. The approach is a bottom-up curriculum model developed along a series of many action research cases (e.g., Marks & Eilks, 2010). The model proved to lead students into intense discussions about applications and consequences that chemistry and modern technologies have (e.g., Eilks, 2002). However, this model has been developed and tested mainly in lower and upper secondary science education so far. The cases of adapting the basic ideas of this approach for undergraduate general chemistry remain scarce.

Two new sustainability-related topics for secondary chemistry teaching

In a project of participatory action research as suggested by Eilks and Ralle (2002) and illustrated by Marks and Eilks (2010), two lesson plans for German lower and upper secondary chemistry education were developed with a group of experienced teachers, which exists now for almost twenty years (Eilks, 2018). On monthly meetings, the teachers provided feedback on the original designs in three iterations each. The teachers reviewed and commented on the digital learning environment and in the second case also on the experimental instructions. In each iteration, changes were applied on the material before classroom testing led to final changes based on student feedback. One example focuses on fracking (Zowada & Eilks, 2018), the other on the problem of the 'critical raw material' phosphate and modern technologies for phosphate recovery (Zowada, Siol, Gulacar & Eilks, under review). Both lesson plans were introduced via digital learning environments, which were developed using Prezi software. This system provides the opportunity to build open learning platforms where content can be arranged freely to give students the chance to deepen the areas they want to know more about (Krause & Eilks, 2014). Prezi also has been used for other learning scenarios such as the use of cosmetics and coffee production (Hoeg et al., 2016). The topics of the interventions and the content of both learning environments are described briefly below.

(1) Fracking is a method, which uses a hydraulic medium, so-called fracturing fluid, to extract oil and gas from unconventional deposits, where the resources are very dispersed. The fracturing fluid is pumped into the deposit with high pressure to crack the rock. The hydraulic medium connects small reservoirs to make the drilling profitable. The fracturing fluid contains mostly water and proppants to keep the occurring fractures open. Additionally, other additives in small amounts can be, e.g., methanol. A lot of debate has occurred around this hydraulic fracturing, in short debate is referring to earthquakes, possible contamination of groundwater, or the influence on climate change. Today, there is a factual ban in Germany for fracking. Meanwhile, it is used every day in the USA (Zowada, Gulacar & Eilks, 2018). The adapted digital learning environment for the USA emphasizes four topics: the process, fracturing fluid, situation in media and different opinions on fracking and potential environmental issues including earthquakes, drinking water contamination, the demand for water, and release of radioactivity, climate change.

(2) For the second intervention, a topic around phosphate resources, its uses, and recovery methods were selected. Since 2014 phosphate rock has been identified as a critical raw material according to the European Commission (2014). Critical raw materials have a high economic importance and a certain supply risk. The high economic importance lays on the increasing demand of phosphate as a fertilizer. The supply risk arises from the natural distribution of phosphate rock. About 75% of all phosphate reserves in the world are located in Morocco and Western Sahara. Additionally, the use of phosphate is not equally distributed throughout the world. Four countries use about 70% of the world´s phosphate for fertilizer: China, India, the USA, and Brazil. Meanwhile, the countries in Africa in total, with their fast-growing population, have access to only a few percents. Although running out of phosphate seems unlikely in the near future (Killiches, 2013), recycling phosphate out of sewage sludge and waste waters is suggested to lower supply risks and to better protect the environment. In recent years, several

environmental technologies have been developed for phosphate recovery. However, they are still in the emerging state and society has to decide whether corresponding investments should be made. The adapted digital learning environment emphasizes four questions: What is phosphate, how is phosphate used, why is phosphate a limited resource, and how can phosphate be recycled.

Transferring sustainability-related SSIs into undergraduate general chemistry

Based on the observed need to better connect chemistry learning with life and society and the suggestions from the literature (Hofstein et al., 2010), an approach was adopted to evaluate the effects of incorporating sustainability-related SSIs into undergraduate general chemistry education in the USA. The case studies were run at a public research university in California, USA. The question of this innovation study was: How does the integration of sustainability-related SSIs into undergraduate general chemistry teaching affect students' motivation and perception of chemistry and its role in our life?

For the purpose of the study, the digital learning environment on fracking was translated into English in the winter of 2016 and then revised in the content based on local and regional references through several cycles. It was first used in April 2017. Later the second example on phosphate recovery was translated and adapted in the winter of 2017. Again, several revisions took place, adding relevant information and modifying its structure and organization, to increase its effectiveness and adaptability in the USA before running the intervention in April 2018. Both interventions generally followed the structure of the socio-critical and problem-oriented curriculum approach for science teaching (**Figure 1**). In comparison to the original model, no experiments were included in these first implementation cases due to the large number of students enrolled and the rigid lab schedule followed at the institution.

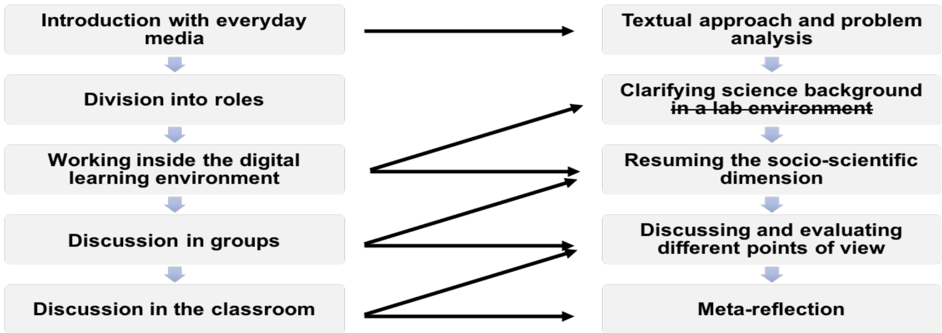

Figure 1. Adaption of the socio-critical and problem-oriented approach

Both interventions started by introducing the students to the digital learning environment and highlighting the connection to the content during the lectures in general chemistry. In each environment, the starting pages contain several newspaper headings which document the societal relevance of the topics like "Thousands of spills at US oil and gas fracking sites" for fracking and "Feeding the world´s insatiable hunger for phosphorus" for the phosphate discussion. Then, the students were assigned different roles for later discussions (**Table 1**). The roles were suggested to prevent the students from getting distracted in the digital learning environment. These tasks allowed students to focus on certain aspects inside the digital learning environment. The students were, however, allowed to read whatever they were interested in. Finally, the students, during the weekly discussion sessions, were split into groups of four, each assuming a specific role. Following the group formations, the students were asked to defend their point of views and present different perspectives on the topic. After the small group discussions, the whole section discussion was encouraged to let them debate on the topic with a broader audience and to reflect the role of chemistry in decisions about the sustainability issues in question.

Table 1. Roleplay roles

Topic	Hydraulic Fracturing	Phosphate Rock
Role 1	Politician	Economist
Role 2	Industrial representative	Industrial representative
Role 3	Environmental activist	Environmental activist
Role 4	Scientist	Farmer

A short overview of students' feedback

Student feedback was collected using a questionnaire with four level Likert scaled items as well as free response questions on the perception of the intervention. In the case of fracking, 888 students enrolled in the course and 842 volunteered to participate in the study (Zowada et al., 2018). 65% mostly or fully agreed that they enjoyed learning about hydraulic fracturing, while about 30% of students partially agreed. After the intervention, 72% of the students agreed and mostly agreed that this activity helped them realize how complex making a decision regarding science and technology in a case like hydraulic fracturing can be. 76.5% fully and mostly agreed that the combination of the learning environment and a guided discussion around the topic provided an effective way to learn how society generally deals with chemical issues. Although it seems that political leaders in the US have already made their mind about fracking, 70% of the students supported that it is still important to discuss different dimensions of hydraulic fracturing. A small group of students, about 30%, agreed or mostly agreed that learning about topics like fracking motivated them to learn chemistry more in depth. 82% of the students supported a view that hydraulic fracturing is relevant to their lives, but only 38% of students agreed or mostly agreed that fracking should be part of the chemistry curriculum. The students took a similar stance when asked about incorporating more SSI topics into the general chemistry curriculum, with 40% fully or mostly agreed with the concept. So, the students see this topic as relevant for themselves, but meanwhile many of them would be reluctant to integrate it into chemistry curriculum. 55% considered fracking interesting and 73% agreed that they became more sensitive to environmental issues. There seemed to be a mismatch in the appreciation of the topic as such and its integration into college chemistry education. In the free response questions, most students mentioned how much they enjoyed learning about fracking and suggested that it was a good way to learn how society deals with chemistry-based topics. One student mentioned that "*The topic of fracking enriches my curriculum by bringing in a real-world topic that we are able to discuss and further learn* *about. […] it is important to be informed on the different aspects of it. Learning about all the different sides of fracking allows me to make a well-rounded opinion about it and I will be able to discuss it with my peers.*" While most students appreciated the personal relevance, some did not think that fracking should be part of the college chemistry curriculum. The students in this group did not see a connection and stated that "*We are learning about buffer solutions, acids, and bases. Fracking has no relationship to these topics in our class, as we are learning them*". This reluctance could be related to the fact that the instructor did not plan to include a question on the topic of fracking or phosphate on the test. It is well known that students in general study for the test, not for meaningful learning to happen (McGuire & McGuire, 2016).

The findings on the phosphate issue were very similar with 709 students, who completed the perception questionnaire. According to the survey on phosphate recovery, about 91% of the students agreed or mostly agreed, that they learned a lot on phosphate according to their own perception. About 73% partially agreed that they will be more sensitive in future towards the issue. Most students stated that they liked (79% agreed or mostly agreed) the activity and had fun (62% agreed or mostly agreed) learning about this issue. Also, the topic was unknown to most students, so that 68% agreed that they learned a lot of information they did not know before. 63% of the students agreed or mostly agreed that the topic motivated them to deal more in depth with chemistry in their daily life. This finding was different from that obtained the fracking study. The phosphate intervention motivated them more to learn chemistry in depth. In the free response questions, again, some saw the importance but did not consider the topic relevant for a college chemistry curriculum: "*Learning about phosphates is very important however it has nothing to do with my chosen field of study*". Another student also did not see the value in learning about phosphate: "*I don't think learning about phosphates is beneficial in improving my skills in my major*".

Reflections from the transfer implementation process

These cases are based in two lesson plans designed for secondary chemistry education in Germany. Due to the need for innovation in undergraduate general chemistry teaching in the USA, the underlying curriculum model and both examples were transferred and adapted to local conditions in the USA. While one can adapt a totally new approach, like Chemical Thinking (Talanquer & Pollard, 2017) or CLUE (Cooper & Klymkowskiy, 2013), and revamp the whole general chemistry curriculum including lectures and labs, it is clear that it requires a lot of resources, time, and effort on the side of the instructor. Even if the whole curriculum was reformed by adapting one of these innovative approaches, the instructor still needs to do a lot to find out if all the components of the new approach are successful and deal with several implementation challenges like convincing students that this new method is more effective. Therefore, starting to change small portions of the curriculum at a time seems more practical. This way, the instructor can test their effectiveness more easily and monitor students' reaction closely to determine the best set of actions for the future implementation plans. This was the case here. Having felt a missing connection between curriculum content and the real world, the idea raised to include further small SSIs into the course.

In the first case (fracking), the adaptation of the learning environment and the associated lesson plan was mostly driven by the external partners from Germany to bring the digital learning environment into teaching. The digital learning environment was introduced via a video conference and roughly translated afterwards. The translation was reviewed by the local partners and the content was adapted to the debate in the USA. In a second video conference, the digital learning environment was reviewed together, and critical points were clarified. After a second revision round including a third video conference, the digital learning was tested. So, the typical iterative process of action research was applied here as in its original development. Since the student feedback was generally positive (Zowada et al. 2018), the idea emerged to include more sustainability-related SSI into U.S. undergraduate chemistry teaching. While incorporating the second case (phosphate recovery), views began to change and the influence of the local partners in the USA increased as they modified the digital learning environment more thoroughly on their own and took more control on the whole implementation plan. The student feedback documented after the implementation of the first case changed the views and beliefs of the local partners and encouraged them to assume more responsibility, which resulted in increasing their ownership of the innovation process, as described in long-term cooperation of teachers for curriculum innovation by participatory action research (Eilks & Markic, 2011; Eilks, 2018). Furthermore, the process led to new plans to design their own learning environments on new topics such as nanotechnology and alternative energies with the involvement of students.

The role of the external partners changed from providing learning environments to guide lining processes and discussing the issues. The local partner became engaged in thinking of new ways of teaching and developing techniques for incorporating sustainability-related SSIs (**Figure 2**). Action research and innovation started engaging and empowering the local partners to design own interventions to solve problems and fight deficits in their own teaching. This procedure is comparable to a case recently described by Laudonia and Eilks (2018) related to innovating vocational education through international cooperation and use of action research.

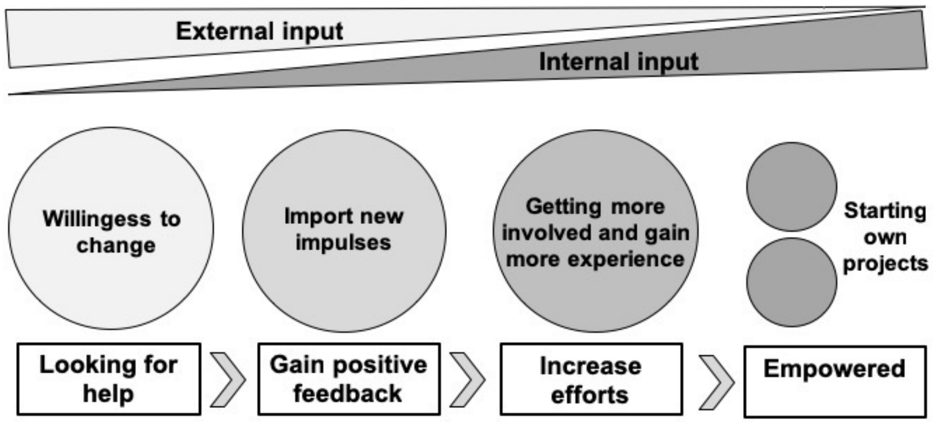

Figure 2. *Visualization of emancipation process out the perspective of the local partner*

Conclusion

Teaching about current developments of sustainability is challenging, but promising (Zuin & Mammino, 2016). Some topics might cool down, while others heat up. Topics such as those discussed in this paper may go out of fashion in some years – but the cases described here show that they should be included into teaching chemistry, both at the secondary and undergraduate level. Critical views on whether the topics are relevant for the curriculum, exam, or future profession must be dealt with. It is, however, maybe a question of how to integrate them, to reform assessment accordingly, and to teach the students to have a more holistic view about chemistry and its applications. Educational theory has enough justification that students should learn about them, both as being a science minor or major (Sjöström et al., 2016).

Along with a discussion around sustainability-related SSIs, young learners can learn, how society deals with chemical issues and how decisions are made. A more comprehensive view is provided with the opportunity of thinking across disciplines. Additionally, there is opportunity to better connect science learning to issues relevant to daily life and society. Bringing such "hot" topics into teaching through action research and innovation studies have high potential for both, curriculum innovation and teacher professional development. Furthermore, Hodson (2003) sees action research as *"probably the only coherent and viable way of addressing the issues of curriculum evaluation, curriculum development and professional development/teacher education that are central to the implementation of this radically new form of science education"* (p. 665). Action research aims for change and involves the learners as subjects and as part of the development process; their feedback is useful to improve learning environments but also to allow the teachers to better understand their students' perception and constraints.

Interrelated problems in teaching chemistry as summarized by Gilbert (2006) (e.g. an overload of curricula or the learning of isolated facts) should lead to think about changes in teaching. This was also recently suggested for undergraduate general chemistry courses (Cooper, 2010; Cooper & Klymkowsky, 2013). Thereby, including human activities into teaching of general chemistry is important because an "*overemphasis is often placed on providing all of the foundational pieces for the few students who major in chemistry, rather than for the majority of students who will pursue careers in health professions, engineering, or other areas*" (Mahaffy, 2015, p. 7). An example of this integration was done on climate change with postsecondary general chemistry students, which aims for surpassing "inert" ideas (Mahaffy et al., 2017). This can be interpreted as a radical change towards a more societal oriented approach. Current topics and issues, like nanotechnology, food security and alternative energy supply, are, however, of upmost importance for the sustainable development of every modern society. Also, the discourse on the Anthropocene and the planetary boundaries can lead to fruitful discussion in chemistry teaching (Mahaffy, 2014). Action research and cooperation for innovation in the two cases described here proved to provide a potential way of action. However, assessment also has to change in order to allow students not only to be motivated by the content and pedagogy, but also by a clear view on the benefit of this kind of learning for their future.

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