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Greening the chemistry curriculum as a contribution to education for sustainable development: When and how to start?

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Abstract
Chemistry's response to the demand for more sustainability in research and its related industries is laid down in the concepts of green and sustainable chemistry (GSC). GSC started to change the way chemistry is and should be operated in the 21st century. It is suggested that GSC implies that also change is needed to come regarding how chemistry is taught. This article reflects the right time to make learners familiar with the ideas of GSC, discusses selected strategies how ideas from GSC can be integrated with school science and chemistry curricula, and provides an illustrative insight into how teaching green chemistry principles can explicitly be implemented in the upper secondary schooling level.

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Introduction

In the Agenda 2030, the United Nations agreed upon 17 Sustainable Development Goals. Goal 4 "Quality Education" suggests Education for Sustainable Development (ESD) for all learners in target 4.7: "*By 2030 ensure all learners acquire knowledge and skills needed to promote sustainable development, including among others through ESD and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship, and appreciation of cultural diversity and of culture's contribution to sustainable development*" [1]. This raises the question: If all learners should be acquainted with the corresponding skills, where are the right places to learn about them?

One of the answers chemistry is suggesting for sustainable development is laid down in the concepts of green and sustainable chemistry (GSC), as recently described in the Global Chemicals Outlook II (GCO II) issued by the United Nations Environment Programme (UNEP) [2]. Although green chemistry and sustainable chemistry are different concepts with different origins and traditions, there is a large overlap. This is why in this article we use the term GSC to address the whole field of green chemistry and sustainable chemistry [3]. Chapter 4.1 in the GCO II explains how important the concepts of GSC are for a sustainable future [2]. If GSC is so important for chemistry, it should also become important in chemistry education [3,4].

In Chapter 4.2 of the GCO II, it is stated that "*Today some elements of green chemistry education have been solidly established in many universities and are being promoted by companies, governments and NGOs worldwide*" [2]. A detailed analysis of the literature, however, shows that today most initiatives address mainly the tertiary educational sector in general, and tertiary students of chemistry and related disciplines in particular, much less is published for the secondary school level [3,4]. Examples for secondary school learners are more rare and mostly restricted to single topics and initiatives, as some are presented in the books by Zuin and Mammino, Benvenuto and Kolopajla, or Obare et al. [5–7]. This point also becomes clear when analyzing recent special issues on green chemistry education, for example, from 2018 in Current Opinion on Green and Sustainable Chemistry [8] or in 2019 in the Journal of Chemical Education [9]. If searching the literature and the Internet, reports are often about extracurricular activities and out-of-school learning, for example, the study by Ballard and Reid Mooring[10]. A systematic integration in the school chemistry curriculum is suggested [11], but hardly reported.

A reflection on all learners needs to take also those into account who do not have the chance to attend academic tertiary education in chemistry, those who leave school after the compulsory schooling time and opt for professional trainings in areas not connected to chemistry. Another set of questions arises: Do also those students have to learn about sustainability issues related to chemistry? And, if yes: How, where, and when?

How to start with green and sustainability education?

In 2012, Burmeister, Rauch and Eilks analyzed the chemistry education literature concerning the potential of chemistry classes to contribute to Education for Sustainable Development (ESD) with a view on secondary chemistry teaching and learning [12]. In this review, many cases were analyzed and it was reflected, how they tie chemistry education with ESD. Based on the analysis, four basic models were identified:

- Model 1: Integrating practices from GSC into school chemistry practical work
- Model 2: Including GSC practices as content in the chemistry curriculum
- Model 3: Using socio-scientific issues that are related to sustainability issues and chemistry as starting points for learning chemistry and about the relevance of GSC for sustainable development
- Model 4: Making sustainability a driver for school reform and changing school life accordingly including aspects that are related to chemistry and its applications

The potential of the different models were also discussed [12]. Model 1 should be a self-evident goal, since every chemistry teacher should deal with chemicals in a responsible and safe way to protect the students and the environment. This seems to be a recognized trend, although Ferk Savec and Mlinarec in their review of the literature found an existing literature gap in this area [13]. They conclude “The results indicate that from 2011 onwards, there was a significant wave of publication of scientific articles about the implementation of green chemistry in laboratory experimental work, especially in the form of experience reports, which point to many examples of good teaching practices.” But, they also found: “Regarding the use of green chemistry in laboratory experimental work in science education at different education levels, our study revealed that it is used much more frequently in tertiary education compared with secondary and primary education.”

Anyhow replacement of toxic and hazardous chemicals by safer alternatives or reducing the consumption is not only in the original interest of every chemist or chemistry teacher; in many countries it became even a legal rule, for example, as given in the REACH (***R**egistration, **E**valuation, **A**uthorisation and Restriction of **Ch**emicals*) programme enacted by the European Union. It is, however, that just applying green chemistry practices in the school laboratory does not also mean to learn about it. For learning about GSC, it must be accompanied by also educating the learner about the reasons for changed approaches and that there were more hazardous practices in the past [14].

Models 2 and 3 have more potential to learn about GSC if examples are presented where chemistry started to make a change. There are many examples in the literature, for example, to learn about bio-fuels, plastics, and other materials from renewable sources, or new battery systems for e-mobility applications [15]. The difference between models 2 and 3 is that in model 2 only the application and the chemistry behind it are taught. Model 3 aims at broader skills via the learning of chemistry that include the reflection whether a new development should be promoted and thus aims at skills for decision making and societal participation. Learning for a holistic understanding of GSC needs teaching approaches based on systems thinking and incorporating the societal, cultural and ethical dimensions behind them. Systems thinking approaches will show the learner that chemistry or its sub-disciplines are not isolated fields within science but all chemistry fields and their associated applications are interacting with broader systems such ecology, economy, society, etc. [12,16]. Such an approach will also allow high school learners deeper insights in and reflections on their learning of chemistry and its relevance [17].

Model 4 might have the biggest potential to contribute physically and chemically to sustainability. Schools who change school life and infrastructure in a way that less waste is produced, energy is saved, or that a school even becomes climate neutral can contribute to sustainability. A corresponding scenario from the viewpoint of chemistry education is presented in the study by Ause [11]. Model 4, however, needs a practical and interdisciplinary endeavor, which is often difficult to integrate and might only match with very few points with the current chemistry curricula and syllabi.

For another discussion about potential models or fields of goals and their connection, Jegstad and Sinnes in 2015 suggested five categories: chemical content knowledge, chemistry in context, the distinctiveness and methodological character of chemistry, ESD competences and lived ESD [18]. Their model is illustrated through five ellipses, visualizing the hierarchy of the categories. They suggest that all five ESD categories need to be considered, where lived ESD is much in line with model 4 described by Burmeister et al. [12].

Many examples exist for merging school chemistry education with ESD concerning the four different models described above or the categories from Jegstad and Sinnes, from elementary to upper secondary education. It is, however, that most of the examples focus on single developments or applications of chemistry with relation to sustainability in a more or less fragmented way and more tied to units and content of school curricula, than intended to form a holistic picture. Furthermore, there hardly are any suggestions for explicitly dealing in school curricula with the philosophical base and technical guidelines of GSC, as, for example, the twelve principles outlined by Anastas and Warner [19] or the OECD framework [20].

Where and when to start with green and sustainability education?

In most countries of the world, aspects from science and technology on the elementary level are taught in a practical and integrated way. Although even elementary students are educated to take care of the environment, to produce less waste, or to be responsible in energy consumption, e.g. by turning off the light, regularly an understanding of what chemistry is as a discipline would hardly come into focus. In some countries, science is taught in an integrated way even on the lower secondary level, but not in all countries. There seems to be an agreement that on the upper secondary level the sciences are mostly taught in differentiated subjects, such as chemistry. Unfortunately, not in all countries chemistry is compulsory on the upper secondary level, or it is only compulsory for one year or in certain strands. An overview about chemistry education in many different countries in the world was collected in 2010 by Risch [21]. Although this analysis is more than 10 years old, it shows the diversity in educational approaches and curricula that still exists.

Starting from this situation and taking the age ranges of the learners into account, it might be suggested that elementary education should focus on making the youngest students sensitive for general issues of sustainability in their personal life. This might be issues of responsible consumption in their daily life, reducing and recollecting waste for recycling, or respecting the cleanliness of nature. On the lower secondary level, students might be taught via contexts and socio-scientific issues from the sustainability debate and how they as individuals, or as society at large, have to react to them. Issues are, for example, climate change, the plastics problem in the environment, or needed developments in raw materials supply. This can be connected to chemistry learning, but also needs to take broader views about chemistry and systems thinking into account. An example of such kind of approach is described in the study by Ause [11]. It is suggested that an explicit contention with the philosophy and principles of GSC can successfully start at the upper secondary schooling level, as e.g. described in the study by Linkwitz and Eilks [22] (see below). It can be operated by all models 1 to 3 identified by Burmeister et al. [12], but should also include making the students familiar with the justification of GSC, its historical roots, objectives and selected practices and examples.

An explicit approach to green and sustainable chemistry on the secondary schooling level

In 2020, Linkwitz and Eilks presented a curriculum development project based on action research about how to introduce GSC explicitly into an already existing high school chemistry curriculum [22]. The target group were students in the first year of upper secondary chemistry education at a school in North Rhine-Westphalia, one of the German federal states. From the syllabus, this is a year typically dedicated to extend understanding of organic chemistry beyond the basics already learned in lower secondary chemistry. The aim was to operate a half-year long course on organic chemistry by integrating the three models 1 to 3 of ESD in chemistry education as described above.

The course "from sugar beet to bioplastics" includes several important innovations. It circles around the socio-scientific issue of how to replace conventional plastics by plastics based in renewable raw materials. It addresses in each part to the twelve principles of green chemistry set up by Anastas and Warner. In the end, all twelve principles are introduced. The whole lesson plan even starts with the question what green chemistry is and where it has its roots. The experiments are updated so that experiments now include microwave assisted syntheses and reactions induced by ultrasound. Several syntheses are integrated using immobilized lipase as examples for reactions catalyzed by enzymes. Finally, students are introduced to different green evaluation metrics to compare changed practices in chemistry in terms of sustainability and how to present them in forms like spider web diagrams inspired by the Green Star [23]. Especially involving green metrics is suggested to foster reflection on the justification of GSC and leads students to new insights already on the secondary schooling level [24].

The course received very positive feedback from the students in each cycle of development in the time span of four consecutive schooling years. Two student quotes from the last year of testing might illustrate the students' perception:

> *"Yes, the topic should definitely be included more often in chemistry lessons, because the topic of sustainability is particularly important for our generation as well as for all those who come after us. Students should be taught that chemistry is not just about making things explode. Chemistry can contribute to a sustainable and environmentally friendly world. Green chemistry offers many opportunities to our generation, which we should definitely learn about in class."*

> *"Sustainability is an important topic in general, especially at the moment. That alone would greatly expand and positively improve chemistry teaching. Green chemistry is certainly an interesting topic, although for many it might not be as interesting as something as broad as sustainability. But, if you combine these two topics well, you can certainly learn a lot from them and it will be a positive enrichment for everyone. So, yes, I think these things should be integrated more (although we already do a lot with them)."*

Also empirical research studies show that inclusion of green chemistry into the secondary school curriculum can have significant effects on student content learning, argumentation skills and motivation, for example, in formal [25,26] and non-formal education [10].

Conclusion

GSC are important developments in the field of chemistry and its associated industries. This has implications for the teaching and learning of chemistry, both in its practical operation in the laboratory and in the content of the chemistry curricula [3]. Chemistry curricula need to address GSC to provide learners an adequate picture of modern chemistry. It is anyhow also important for life since chemicals are not only handled by chemists and chemistry students. Every citizen in society has to learn it even for two practical reasons: (1) to deal responsibly with chemicals in order to avoid health or environmental problems on the one side [27], and (2) to be prohibited to develop chemophobic attitudes that may have negative implications for one's life on the other side [28].

If we want to reach the target that all learners have sufficient knowledge and skills to contribute to sustainable development, they should at least know about what chemistry has to do and to contribute. This is needed to make own decisions as consumers and to be able to participate in societal decisions about applications of chemistry and its associated impact on life and the environment. Since GSC should be addressed to all learners, it has to take place during the time where we can reach all learners, and thus has to start during the compulsory schooling time everyone has to attend. Examples are there, as presented, for example, in different articles, books or special issues [3,5–9]. Models on how to integrate ESD in chemistry education are also available, for example, in the artciles by Burmeister et al., Eaton et al., or Juntunen and Aksela[12,17,29].

Nevertheless, further curriculum development is needed and educational reform initiatives need to be intensified to provide schools and teachers with sufficient information and ideas. A good example is Beyond Benign in the USA, a charity that develops and disseminates green chemistry and sustainable science educational resources [30]. In the USA, there is recently the $250 k funding from the Argosy foundation that Beyond Benign and the ACS-GCI are using in the Green Chemistry Teaching and Learning Community for developing teaching and learning from kindergarten to age 18 education [31]. Another initiative in the UK is the draft for a Sustainability and Climate Change Strategy suggested in April 2022. It looks at sustainability education within early years, schools, further and higher education [32].

Further investment in teacher education is also needed, since many chemistry teachers still lack in a theory based understanding of GSC, for example, the studies by Burmeister et al. or Husssein and dried Ahmed. [33.34]. This is a challenge for curriculum developers and teachers. It might also be a chance to promote a more balanced view on chemistry between its mostly negative image in the past [35] and chemistry's current endeavor to become a sustainable science. Finally, reform is needed in educational standards and national curricula with the associated culture of exams to incorporate aspects of the philosophy and practice of GSC to provide learners with a contemporary picture of modern chemistry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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