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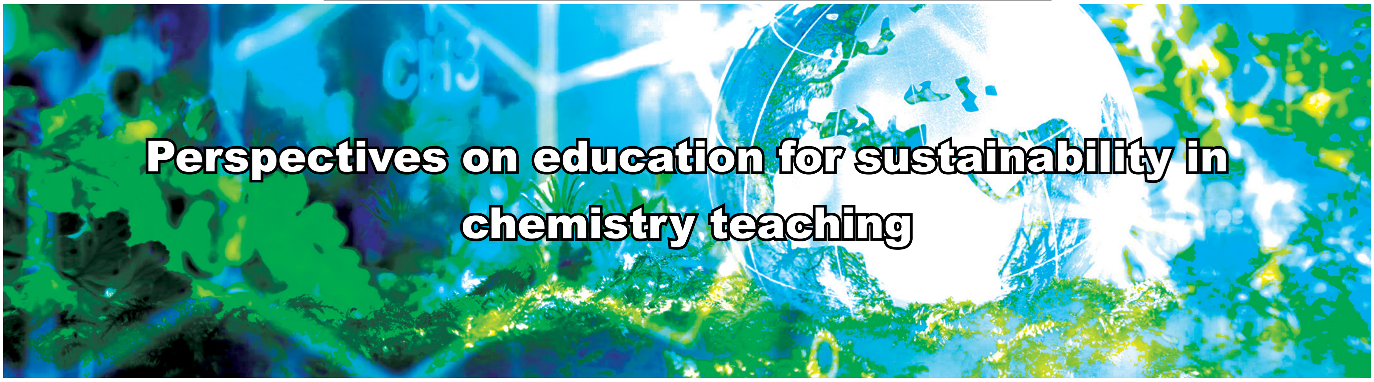

Perspectives on education for sustainability in chemistry teaching

Christian Zowada, Kai Niebert, Ingo Eilks

The media landscape and the public debate are full of reports about the threats caused by unsustainable lifestyles by large parts of the global society today. Climate is changing, water is polluted more and more, natural resources are progressively exploited, inequalities are increasing. It is under constant debate whether and how far humans can continue affecting our planet until these developments lead to irreversible changes in the environment and human life. Regardless of exactly how these changes come to place and what they cause in the end, the political answer is the demand for more sustainability. Sustainable development asks for a way of life that does not permanently damage our planet, so that future generations can still live on earth and meet their needs without being too restricted by both today's contamination of the environment and consumption of resources. It is clearly suggested that this task applies to all school subjects, including chemistry. The aim of this article is to provide an overview of selected concepts in the context of sustainability and refers them to education in general, and chemistry teaching in particular.

▶ Sustainability, Education for Sustainable Development, Chemistry Education ◀

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Sustainability: From the intersection to the cake model

Sustainability is a concept under constant development. Its history has already been described many times (e.g. in Caradonna, 2014). In German-speaking countries, the concept of sustainability originally is traced back to forestry in the early 18th century, where the aim was to avoid timber shortages as a consequence of deforestation. The idea of preservation and stability of natural resources through a consumption of resources that can regenerate themselves at the same time has remained a core concept of sustainability until today, for example in the sense of replacing fossil fuels by renewable energies.

Today, however, sustainability is understood more broadly and has grown into a global regulatory idea that has found its way into politics, business, and education (Rauch, 2018). Sustainability has been refocused because mankind started realizing potential limits to growth that go beyond the mere provision with raw materials. For the first time, this reached a broad public in 1972 through the publication *The Limits to Growth*, which suggested that the carrying capacity of the earth has limits, e.g. in terms of the growing world population (Meadows *et al.*, 1972). Today, the most well-known definition of sustainable development comes from the Brundtland report *Our common future* from 1987 (WCED, 1987). This report calls for a development that meets the needs of today without restricting future generations to meet their needs. Since the 1990s, discussion has generally been shaped by the Agenda 21 by three equally important pillars of sustainability: ecological, economic and social sustainability (UNCED, 1992).

In the course of time there have been repeated suggestions to integrate further dimensions of sustainability, such as cultural or political sustainability, into a multi-dimensional model. However, this has not found broad reception. In the beginning, the three dimensions - ecological, economic, and social sustainability - were often presented as pillars of sustainability or in an intersection model (Figure 1A). The intersections were suggested to show the interdependence of the three dimensions. The aim was to find a balance between the three dimensions. However, it became critically noted that model A in Figure 1 degenerated into a "Mickey Mouse" sustainability in reality (Figure 1B), in which economy determines how society and ecology

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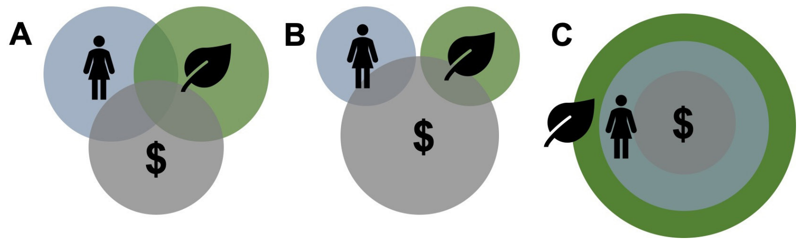

Figure 1. Different views on the interdependence of sustainability dimensions (Niebert, 2018)

develop. Today, it becomes more and more a consensus to understand sustainability operating economy in a way that it must serve the fulfillment of social needs and takes place within a functional and stable natural environment (Griggs *et al.*, 2013, Niebert, 2018). This could be illustrated as in Figure 1C. In concrete terms, it means that a resource-saving approach to the world should be seen as the top priority.

From sustainable development goals to a large social contract

There has already been a set of key moments in politics for more sustainability. In addition to the Brundtland-report of 1987 (WCED, 1987) and the Agenda 21 adopted in Rio de Janeiro in 1992 (UNCED, 1992), such a moment was certainly the resolution of the United Nations, the World Bank and other actors from 2000, in which eight Millennium Development Goals were adopted (UN, 2000). The common intention was expressed to halve hunger and poverty worldwide by 2015. It was also about providing all children with basic education, promoting gender equality and strengthening women's rights, reducing child mortality, improving maternal health, combating HIV/AIDS, malaria and other diseases, to improve the protection of the environment, and to establish a global development partnership. The individual goals were achieved to varying degrees.

In 2015, new goals were issued for a period up to 2030: the United Nations Sustainable Development Goals (SDGs) (UN, 2015). Under the Agenda 2030 - Transforming Our World, 193 countries agreed on a transformation towards sustainability and on the recognition that current problems can only be solved collectively. In doing so, the SDGs focus on sustainability with the three dimensions in balance (Figure 1A). The planet and human dignity are to be protected, prosperity, peace and global partnerships are to be established. The SDGs are set out in 17 goals (Figure 2). Many of the goals are directly or indirectly linked to chemistry. The American Chemical Society (ACS) "has identified seven priority SDGs and five additional SDGs that are foundational to the work of the chemistry community. The chemistry enterprise has a broad reach into technology, the economy, and human health, and there are already many ways chemists are working to support global sustainable development" (ACS, w.y.). The SDGs identified by the ACS are SDGs 2, 3, 6, 7, 9, 12 and 13. It is, however, clear that chemistry has also a big influence on the actual achievement of other SDGs such as 14 – Life below water and 15 – Life on land (see Figure 2).

There were various interpretations for any hierarchy among the SDGs. Such an attempt was made in the so-called wedding cake model by Rockström and Sukhdev (2016). In the model, the SDGs are linked to the three traditional dimensions of sustainability (Figure 3). The base is the biosphere, which can be understood as the ecological base for any sustainability. This base is formed by the SDGs 14, 15, 6 and 13. Embedded in this base is the life of people in society, represented by the SDGs 1-5, 7, 11 and 16. Finally, environmental and societal sustainability frame the SDGs 8-10 and 12, which relate to work, livelihood, economy and consumption. Above that there is SDG 17, the goal of

Figure 2. The Sustainable Development Goals (UN, 2015)

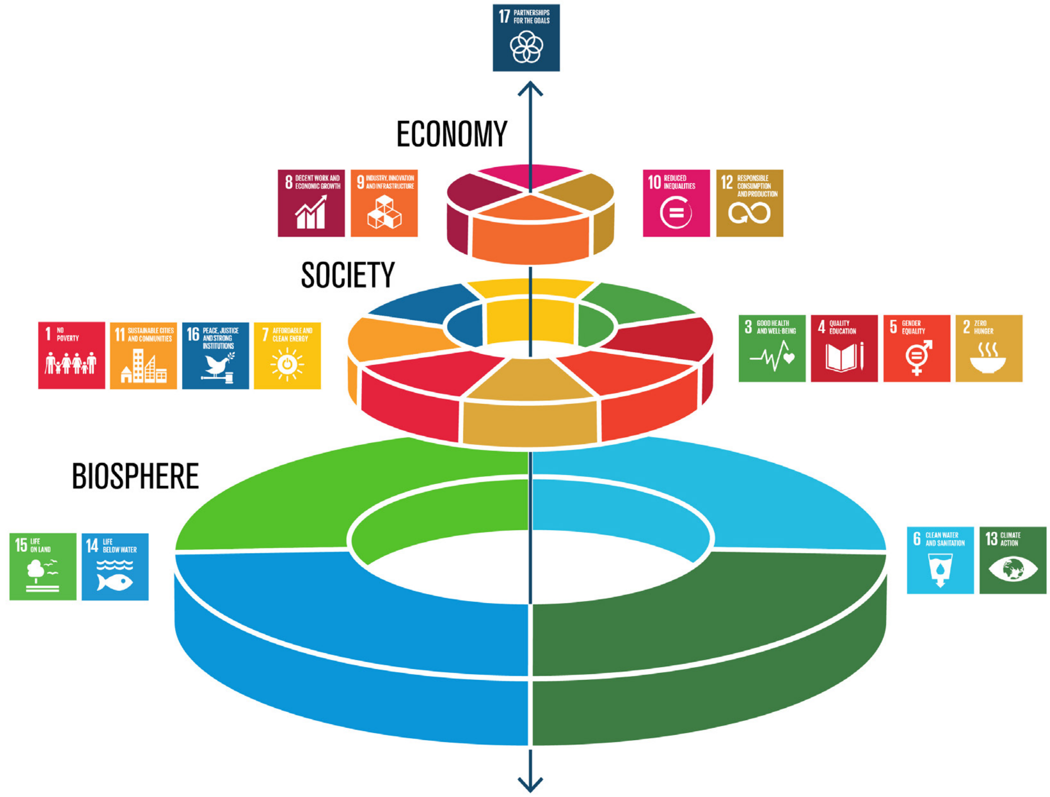

Figure 3: The SDGs operated in different layers (Rockström and Sukhdev, 2016)

global partnerships to achieve all other goals. The wedding cake model supports the idea of sustainability to be operated within ecological limits as given in Figure 1C.

These ecological limits can be more precisely understood by the concept of the planetary boundaries (Steffen *et al.*, 2015). This concept tries to define the safe operating space for human activity in which it can move without irreversibly damaging the planet. Nine planetary boundaries have been defined (Figure 4), such as global warming or ozone depletion. The planetary boundary is crossed at the end of the green area in Figure 4. This represents the "safe" area. When the limit (yellow) is exceeded, risk and uncertainty for irreversible damage to the earth system increase. Moving into the red area, there is a high risk of irreversible damage. Control variables are defined for the exposure limits, such as the carbon dioxide content of the atmosphere. Question marks stand for the (currently) missing key variables to measure the exposure limits.

If one compares calculations for 1990 and 2015 (Figure 4), there is a negative trend, i.e. a worsening of all planetary exposure limits with one exception: ozone depletion. Ozone depletion was partially reversed due to the prohibition of fluorochlorinated hydrocarbons in the Montreal Protocol of 1987 (UNEP, w.y.). The example shows that a strong political will as well as ongoing innovations in chemistry and technology might help to keep the world within its limits. The planetary boundaries represent an example of an ecologically dominated sustainability model. However,

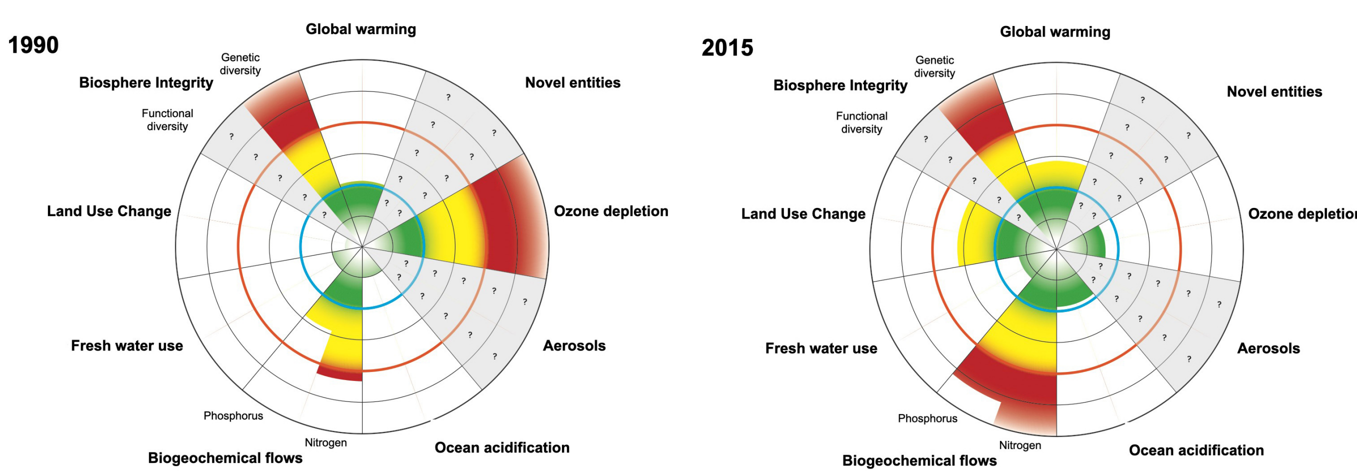

Figure 4: Planetary boundaries 1990 und 2015 (Müller e Niebert, 2017, adapted from Steffen et al., 2015)

there are also approaches that try to expand these ecological boundaries to include social boundaries and here, too, show limits for a tolerable life. This is known as the doughnut model and includes topics such as education, food, water, or energy supply (Raworth, 2017). Furthermore, this idea tries to particularly emphasize social needs in connection to ecological boundaries.

The idea of the planetary boundaries is closely connected to the acknowledgment of mankind taking on the role of the leading protagonist of the earth system. With steadily growing and globalizing economic activities since the beginning of industrialization, it has brought so many new materials into circulation in such a short time; the earth has not experienced in a billion years. Due to the worldwide exchange of goods, various species cross geographical barriers in airplanes or on ships and thus change the course of evolution. Socio-economic factors have also changed in the last few decades, such as the rapid increase in energy consumption and the growth of the urban population (Steffen, Broadgate, Deutsch, Gaffney e Ludwig, 2015). Under these circumstances the Nobel laureates Paul Crutzen and Eugene Stoermer in 2000 proposed a new earth epoch: the Anthropocene – the manmade age. Today, geologists started agreeing that mankind became the greatest geological force on our planet, e.g. acknowledged by the Congress of the International Geographical Society in 2016 (Carrington, 2016). The central question today is no longer whether we live in the Anthropocene, but when this epoch began (Lewis e Maslin, 2015). One proposal is the middle of the 20th century, which would be characterized by the first human-made entry of radioactive substances into sediments as a result of the first nuclear tests.

An idea to tackle this change to a sustainable world and to reduce human impact on the Earth system was suggested in 2011 by the German Advisory Council on Global Change (WBGU, 2011). So far, there have been two great transformations in human history with the Neolithic Revolution (the transition to agriculture and growing livestock) and the Industrial Revolution. In the eye of the WBGU another transformation has to take place. In order to achieve this transformation, the WGBU proposes a global social contract that is designed for a climate-friendly future in a sustainable world economic order: *"It is based on the central concept that individuals and civil societies, states and the global community of states, as well as the economy and science, carry the joint responsibility for the avoidance of dangerous climate change, and the aversion of other threats to humankind as part of the Earth system. […] One key element of such a social contract is the 'proactive state', a state that actively sets priorities for the transformation, at the same time increasing the number of ways in which its citizens can participate, and offering the economy choices when it comes to acting with sustainability in mind. […] The WBGU has developed the concept of a new social contract for the transformation towards sustainability – not so much on paper, but rather in people's consciousness – as an analogy to the emergence of the industrialised societies during the course of the 19th century*" (WBGU, 2011, p. 2).

Sustainability and education in general, and in chemistry in particular

The role of education for sustainable development was already pronounced in the Agenda 21 in 1992 (Chapter 36) (UNCED, 1992). Education for Sustainable Development (ESD) was described and considered necessary to convey concepts, show ways, and stimulate action for more sustainability without falling into indoctrination. In contrast to Education for Sustainability (EfS) the idea of ESD always refers to the framework of the United Nations. In the following years, a whole decade, the UN World Decade of Education for Sustainable Development (2005-2014) was proclaimed with the aim of sharpening the definition and anchoring a sustainable way of thinking in education. This has been reflected in many projects and initiatives, such as the educational projects 21 and Transfer-21 in Germany. However, according to Michelsen (2013), despite the global decade, ESD has still not become "mainstream" in education in Germany, as in many other countries (see e.g. Goes *et al.*, 2018). Further progress has been made by the UNESCO Global Action Program for ESD (GAP; 2015-2019) but is still criticized as being not coherent and not fast enough with respect to different educational domains (Holst *et al.*, 2020).

The GAP was launched as a follow-up to the UN World Decade. The GAP once again aimed to anchor ESD more firmly in education and training. The program's roadmap (UNESCO, 2014) suggests four dimensions: the learning content, which integrates topics of the sustainability debate such as climate change or consumption and production patterns into the curriculum; the pedagogy and the learning environment, which is interactive and focused on research-based, action-oriented and transformative learning; learning outcomes that relate to critical thinking and systems thinking and recognize collaboration as important; and ultimately a social transformation in which the individual is enabled to transform himself and society.

Also, the SDGs include learning about sustainable development (UN, 2015). In SDG 4- Quality education, it is intended to ensure by 2030 that "*all learners acquire knowledge and skills needed to promote sustainable development*" (UN, 2015). For this purpose, the UNESCO describes learning goals (UNESCO, 2017), which should be aimed at for each SDG on three levels (cognitive, socio-emotional, and action-oriented). As a result of these learning objectives, teachers are also seen as important "change agents" who are supposed to actively initiate and guide change.

Table 1 gives a short insight into two examples. SDG 2 - Zero hunger is closely related with chemistry's sustainable provision of fertilizers or pesticides. SDG 13 - Climate action is closely related to our use of fossil energy or energy consumption in the production of metals, concrete or other raw materials by the chemical industry. With respect to chemistry education, this demands to deal with climate change and to address possibilities for climate action, or to deal with questions of world nutrition, for example in connection with fertilizer provision and recovery. In the means of ESD this needs to include knowledge about the chemistry and technology behind, but also about societal and economic implications (e.g. Feierabend e Eilks, 2010; Zowada *et al.*, 2019)

Regardless of whether it is about recycling, wastewater treatment, achieving higher efficiencies and yields in technical processes, or better protection and higher harvests for agricultural production, science and especially chemistry have a great responsibility for a sustainable future and the achievement of the SDGs (Matlin *et al.*, 2015). To make the role of chemistry visible, it is important to integrate these topics into the classroom while considering different perspectives, including the ideas of green and sustainable chemistry (Zuin *et al.*, 2021). When searching for relevant topics for sustainability issues in chemistry education, the planetary boundary model (fig. 4) can act as a helpful guideline to set priorities. Niebert (2019) has shown that the concepts covered by the planetary boundary framework and the scientific core ideas and crosscutting concepts that are demanded in different school science curricula – at least in Western countries – provide a perfect match.

For the case of chemistry, Burmeister *et al.* (2012) identified, based in a review of the chemistry education literature, four models to combine education for sustainability with chemistry teaching:

- Model 1: Use of the principles of green chemistry in the school science laboratory
- Model 2: Use of topics related to sustainable chemistry as contexts for learning chemistry content and concepts
- Model 3: Consideration of relevant topics including chemistry from the sustainability debate as socio-scientific issues for chemistry education
- Model 4: Application of sustainability strategies as an element of school development

These models show different capacities to contribute to sustainability or to learning about sustainable development (Table 2). Laboratory work based on green chemistry, on the one hand, creates opportunities to directly serve for a more sustainable future by reducing or replacing environmentally hazardous chemicals, but does not necessarily address learning about the change. Other ideas, such as the third model, on the other hand, have no direct physical contribution to sustainability, but by addressing socio-scientific issues (SSIs) it becomes possible to learn about sustainable development and to recognize the role of chemistry in it. SSI-approaches take up authentic, relevant, and debatable topics from society and discuss them in the science classroom. SSIs start learning from the societal problem (current examples would be climate change, microplastics, pesticides use, or fracking). Chemistry lessons become interdisciplinary in order to integrate different perspectives and systems thinking (Marks e Eilks, 2009).

Table 1: Exemplary learning objectives for the SDGs in the case of SDGs 2 and 13 (UNESCO, 2017)

Level	SDG	Content
Cognitive	Zero Hunger	The learner knows about hunger and malnutrition and their main physical and psychological effects on human life, and about specific vulnerable groups.
	Climate Action	The learner understands the greenhouse effect as a natural phenomenon caused by an insulating layer of greenhouse gases.
Socio-emotional	Zero Hunger	The learner is able to communicate on the issues and connections between combating hunger and promoting sustainable agriculture and improved nutrition.
	Climate Action	The learner is able to explain ecosystem dynamics and the environmental, social, economic and ethical impact of climate change.
Action-oriented	Zero Hunger	The learner is able to evaluate and implement actions personally and locally to combat hunger and to promote sustainable agriculture.
	Climate Action	The learner is able to evaluate whether their private and job activities are climate friendly and – where not – to revise them.

Table 2: The potential of the four basic models by Burmeister et al. (2012) in terms of their potential to learn about sustainable development, to learn for sustainable development, or directly contribute to sustainable development by imminently changing social, ecological or economical practices.

Potential for …	Model 1	Model 2	Model 3	Model 4
… learning about sustainable development.	o	++	++	+
… learning for sustainable development.	-	-	++	++
… direct contributing to sustainable development.	o	-	-	+

Reflection of the potential of the four basic models of dealing with ESD in chemistry education (- = low; o = medium; + = high; ++ = very high)

Final considerations

The Global Chemicals Outlook II (GCO II) recently adopted by the United Nations not only discusses how the world has dealt with chemicals so far and how it should do so in the future, Chapter 4 of the GCO II also gives a clear position on education. Green and sustainable chemistry education is suggested as important for all levels of education, from school to university (UNEP, 2019). Many points of contact for chemistry and science classes can be found on the topic of sustainable development (Zuin *et al*., 2021). This becomes clear, for example, in the concept of the planetary boundaries (Steffen *et al.,* 2015). The planetary boundaries and the SDGs suggest issues that can be implemented in chemistry education easily. All the content in our curricula needs to be reflected to provide the young generation with knowledge and the skills to understand the needed changes for transforming the world. SSI-based teaching approaches are needed to allow students understanding the debate about transformation processes and participating in them on a well-founded base. This is also a question of the pedagogy. Pedagogies are needed that prepare for societal participation and action – also in chemistry teaching (Eilks, Sjöström e Mahaffy, 2019). In this light, teaching a structure-to-the--discipline approach might no longer be a proper way of teaching chemistry. Instead, chemistry teaching needs to have a stronger connection to societal debates as well as current sustainability challenges as suggested in the models 3 or 4 from Table 2. Recent examples for this way of teaching chemistry with respect to model 3 may concern, e.g., fracking (Zowada *et al.*, 2018), phosphate recovery (Zowada *et al*., 2019), or alternative pesticides (Zowada *et al.*, 2020). Concerning model 4, a prominent example is the eco schools movement (e.g., Ecoschools, w.y.). And finally, this is also a question of teacher education. Chemistry teacher education has to include learning about sustainable development issues and green and sustainable chemistry (Zuin *et al*., 2021).

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Abstract: *Perspectives on education for sustainability in chemistry teaching.* In recent years, increasing global challenges and the term sustainability (or sustainable development) directed our way to think about our common future. It is suggested that learners should encounter this way of thinking as early as possible and the integration of education for sustainability into the classroom is currently demanded more than ever. The aim of this article is to provide an overview about current concepts of sustainability and education for sustainability in general, and for chemistry education in particular. It is suggested that sustainability issues can and should play a central role in chemistry classes.

Keywords: Sustainability, Education for Sustainable Development, Chemistry Education

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