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Beyond molecular mastery: reimagining chemistry education for sustainability through knower-aware pedagogy

Margaret A. L. Blackie *[a] and Lausanne Olvitt [b]

This paper argues that chemistry education for sustainability requires explicit attention to the person of the chemist and the contexts in which chemical knowledge is produced and applied. We term this a 'knower-aware pedagogy'. We begin by introducing UNESCO's sustainability competences and highlight the centrality of the education of the particular person in a particular context. We then show the ways in which chemistry education has tended to focus on knowledge and has a tendency towards 'knower blindness'. We proceed to illustrate one way in which a knower-aware pedagogy can be developed. Using the metaphor of the suspension bridge, we demonstrate that transformative chemistry education requires not only robust disciplinary knowledge and understanding of the nature of chemistry, but also development of evaluative judgment and explicit recognition of the learner as the agent. We conclude with a comprehensive self-assessment tool enabling instructors to evaluate whether their courses develop the sustainability competences essential for preparing ethical, socially responsible chemistry practitioners capable of contributing to global sustainability transitions.

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Sustainability spotlight

Global sustainability transitions demand chemists who are not only technically proficient but also ethically aware and socially responsible. Yet chemistry education has historically prioritised knowledge transmission over the development of the whole person, leaving graduates ill-equipped to navigate the complex human and contextual dimensions of sustainable practice. This paper advances chemistry education for sustainability by introducing 'knower-aware pedagogy'—an approach that explicitly foregrounds the identity, values, and agency of the learner alongside disciplinary knowledge. A practical self-assessment tool supports educators in implementing this approach. This work aligns primarily with SDG 4 (quality education) and SDG 12 (responsible consumption and production), while contributing broadly to the educational foundations underpinning all seventeen SDGs.

Introduction

In this paper, we seek to bring together tertiary chemistry education and education for sustainable development culminating in a set of questions which an instructor could use to reflect upon their current courses. The purpose of the paper is to bring into view the point that sustainable development requires a chemist in a particular situation to make specific choices. Indeed, any kind of strategic thinking is governed by the 'rules of the game' of the context. Thus, we begin by introducing the core competences of education for sustainable development. We then discuss key developments in chemistry education over the last several decades thereby making visible the knower blindness in chemistry education. This is followed by illustrating one way to develop a knower-aware pedagogy in chemistry. We then link back to the competences of education for sustainability providing some guidance as to the way programs and courses can be shaped by the position developed herein. To make visible the recognition of the personal and contextual, we begin with a cameo of two hypothetical students.

[a]*Center for Advancing Undergraduate Science Education, North End Center, Virginia Tech, Blacksburg, VA 20460, USA. E-mail: magsblackie@vt.edu*
[b]*Environmental Learning Research Centre, Rhodes University, Lucas Avenue, Makhanda 6139, South Africa*

A cameo to frame the paper

Two postgraduate students are attempting similar projects involving small molecule design and synthesis. They both work in laboratories where results are routinely published in the *Journal of Medicinal Chemistry*, *ChemMedChem* and similar well-respected publications. Sipho is working in a laboratory in South Africa. Some of the context specific issues – the municipal water supply is unreliable; the country is subject to 'load shedding' – electricity supply may be switched off for periods of 2–4 hours at a time between one and three times a day; the freight time of highly reactive reagents may be up to six months; research grants sponsored by the National Research Foundation are in the range of US$20 000–US$50 000 over three years;

buildings are typically not climate controlled and the interior temperature of a lab can vary as much as twenty degrees celsius between summer and winter. Andrew is working at a tier I institution in the United States. In this context, there is near continual supply of water and electricity and labs are temperature controlled; highly reactive reagents arrive in a matter of days; research grants are likely to be US$200 000–US$500 000 over three years. The difference in the environments will shape the choices that are made in terms of synthetic route. However, when the two students write up their synthetic procedures, the driving factors around many of the choices will not be discussed at all. The series of reactions will simply be presented as a logical way to get to the desired product.

The choice to absent the local particularities in the presentation of the synthetic route is the preferred method of presentation of chemical synthesis unless an accepted orientation to synthesis, such as green chemistry, is being employed. In this paper, we wish to explore the implications of this position and to argue that chemistry education for sustainability needs to take cognizance of the particularity of the person of the chemist and the context within which the chemist is working.

Sustainability competences

A focus on competences in sustainability transitions emerged when education research highlighted that addressing complex sustainability challenges requires more than just knowledge; it demands skills, attitudes, and values that enable individuals and societies to navigate transformative change. Informed by research by de Haan,[1] Rieckmann[2] and Wiek *et al.*,[3] the United Nations Educational, Scientific and Cultural Organization[4] presents eight cross-cutting sustainability competences needed for achieving the Sustainable Development Goals (SDGs). In this context, competences are defined as: "the specific attributes individuals need for action and self-organization in various complex contexts and situations. They include cognitive, affective, volitional and motivational elements; hence they are an interplay of knowledge, capacities and skills, motives and affective dispositions" (p. 10).[4] The proposed sustainability competences are: systems thinking; anticipatory competence; normative competence; strategic competence; collaboration; critical thinking; self-awareness and integrated problem-solving.

The authors selected the UNESCO sustainability competences framework for its contemporary societal relevance, disciplinary flexibility, and international credibility. Its broad competences transcend disciplines but are nonetheless pedagogically operationalizable, offering chemistry educators more flexibility to argue for curricular or pedagogical transformation. Other frameworks, such as guiding principles for green chemistry[5] and green engineering,[6] are valuable for their technical specificity but do not address the broader societal and systemic dimensions that sustainability transitions require. The sustainability competences framework invites reflection around the question "what capacities do student chemists need for a sustainable world?" rather than "what sustainability content should chemistry curricula include?".

Drawing on the conceptualization of these competences presented by UNESCO,[4] Wiek *et al.*,[3] Rieckmann,[2] and de Haan,[1] this section considers some implications of these cross-cutting sustainability competences for chemistry education. The competences are described below in some detail, as we expect that readers of this paper may not be familiar with them. We return to these competences, summarise key aspects of each competence, and illustrate their implications for chemistry education once we have discussed chemistry education in some detail. At that point in the paper, we highlight the cognitive, socioemotional and behavioural domains of chemistry education.

Systems thinking competence

Systems thinking competence focuses on the capacity to recognize and understand complex, interconnected relationships within systems. It requires analyzing how social, environmental, and economic domains embed across different scales, from local to global. Systems thinking thus bridges current trends and priorities in chemistry education and international sustainability education commitments. For educators, this means teaching students to map complex chemical life cycles, considering cascading effects, feedback loops, and inertia inherent in these systems. Developing this ability to deal with uncertainty is crucial for comprehending the complexity of social-ecological systems and identifying key leverage points for successful interventions toward sustainability.

Anticipatory competence

Anticipatory competence involves evaluating and crafting rich "pictures" of the future—including possible, probable, and desirable outcomes—related to sustainability issues. It requires developing personal visions for the future and applying the precautionary principle to assess the potential consequences, risks, and changes resulting from present actions. Educators should prepare students to use methods like scenario analysis and forecasting to redirect unsustainable path dependencies towards desirable future states, thereby addressing the imperative of intergenerational equity.

Normative competence

Normative competence is the capacity to understand and critically reflect on the norms and values that underpin one's actions. It involves the ability to collectively map, specify, and negotiate sustainability principles, goals, and targets, especially within conflicts of interest and contradictions. Because sustainability is unavoidably value-laden, this skill is essential for assessing whether current or future social-ecological systems meet ethical criteria for justice, fairness, and socio-ecological integrity.

Strategic competence

Strategic competence centers on the ability to collectively develop and implement innovative actions that advance sustainability locally and further afield. It involves the ability to design and implement effective interventions, transitions, and transformative governance strategies toward sustainability. Students must understand strategic concepts like systemic inertia, barriers, and successful alliances, and assess the viability and effectiveness of interventions. This skill enables graduates to link knowledge to action and "get things done" by solving logistical problems and navigating real-world political complexities.

Collaboration competence

Collaboration competence is fundamental to working effectively within heterogeneous groups to solve problems. It encompasses the ability to understand and respect the needs and diverse perspectives of others, show empathy, manage conflicts, and facilitate collaborative and participatory problem-solving. Since sustainability issues affect multiple actors, success requires strong cooperation among scientists (interdisciplinarity), policymakers, and citizens (transdisciplinarity) to build joint capacity and co-construct knowledge.

Critical thinking competence

Critical thinking competence is the ability to question established norms, practices, and opinions, particularly those prevalent within the sustainability discourse. It requires rigorous reflection on one's own values, perceptions, and actions. For university education, this means empowering learners to challenge the *status quo*, think critically about expert consensus, and evaluate the contradictions inherent in sustainable practices. This competence enables individuals to take informed positions on complex issues.

Self-awareness competence

Self-awareness competence involves reflecting on one's own role within the local community and the global society. This internal capacity allows individuals to continuously evaluate and maintain motivation for their actions concerning sustainability. It is closely tied to dealing with personal feelings and desires, and recognizing one's own biases. This competence is key for driving personal behavioral change and reflecting on the impact of one's lifestyle choices as a consumer or producer.

Integrated problem-solving competence

Integrated problem-solving competence is an overarching competence that involves applying various problem-solving frameworks to highly complex, multifaceted sustainability challenges. It requires the synthesis and effective integration of all the other seven key sustainability competences (from systems analysis and future visioning to strategic action and collaboration) in a meaningful way. The ultimate objective is to develop solution options that are viable, inclusive, and equitable, ensuring they effectively promote sustainable development.

The sustainability competences outlined above are strongly focused on the development of the human person. In the next section, we draw attention to the ways in which chemistry education has been largely 'knower-blind'. That is to say that efforts to improve chemistry education have been focused on ways to improve dissemination of chemical knowledge rather than considering the formation of the chemist.

Positions shaping chemistry education

In the 1980's and 1990's there was a significant emphasis in conceptual understanding in chemistry education. Alex Johnstone introduced the chemistry triplet highlighting the challenge students face in moving between the symbolic, the microscopic and the macroscopic.[7] Keith Taber worked on misconceptions bringing into focus issues such as ionisation of complex ions.[8] Dorothy Gabel and coworkers reported asking chemistry graduates what was in the bubbles that are formed as water comes to the boil. The shattering result was that far too many chemistry graduates failed to give the correct answer of water in the gaseous phase.[9] The students had failed to achieve what Ashwin and coworkers recently report as a 'molecular view of the world'.[10] In the quest of sound, coherent conceptual understanding, an 'atoms first' approach to teaching foundational chemistry was born. As Talanquer and Pollard[11] argue, this approach to the teaching of chemical concepts follows the logic of disciplinary knowledge as viewed by an expert chemist. And with that perspective is a major limitation – a disconnection between the sensorial experience of the world and the molecular reality. Chemistry in this form is taught in a manner that is entirely self-referential and disconnected from one's experience of the world.[12] That is to say that we can teach chemistry in a way that is beautifully coherent to teaching chemistry but has no connection to the life-world of either student or lecturer.

Over the last twenty years, in an attempt to make chemistry more relevant to students, there have been several significant attempts to 'rethink' chemistry education. Some of these approaches are aimed at developing new curricula for introductory courses. The CLUE (Chemistry, Life, the Universe and Everything) curriculum innovates by explicitly articulating how molecular structure, macroscopic properties, and energetics interrelate.[13] Similarly, the Chemistry Unbound curriculum employs 'core ideas' to highlight linkages between structure (emphasized in organic chemistry) and mathematical reasoning (emphasized in physical chemistry).[14] These curricula are both grounded in contemporary chemistry education research and have strong potential to enhance chemistry instruction. However, the proposed modifications do not challenge the fundamental nature of chemistry education and may not address the self-referential critique raised by Johnstone.[12] 'Chemical Thinking' (along with its associated curriculum) extends somewhat beyond these approaches. Sevian and Talanquer[15] characterize chemical thinking 'as the development and application of chemical knowledge and practices with the main intent of analyzing, synthesizing, and transforming matter for practical purposes.' They further clarify that their objective is establishing a foundational mode of thinking that will influence an individual's decision-making whether or not they ultimately pursue a chemistry career, thereby bringing the knower into view.

An alternative and potentially complementary strategy has been to focus on the introduction of new approaches to chemistry largely brought about by the recognition that chemical industries are not renowned for their attention to the environment. Public awareness of the problem of PFAS and microplastics is growing. There is little doubt that substantial changes in lifestyle brought about by new materials and new bioactive agents developed by chemical industries in the 20th century have brought tremendous benefit to human society. But these advances have come at a great cost to the environment. Ideas such as donut economics,[16] planetary boundaries[17] and the United Nations Sustainable Development Goals (SDGs)[18] bring the dual issues of the source and safe disposal of chemical compounds into focus. Bringing green chemistry, sustainable chemistry and systems thinking into undergraduate chemistry courses is an effort to shape the teaching of chemistry in line with the ethical practice of chemistry. Sustainable chemistry is the design, manufacture, and use of environmentally benign chemical products and processes that prevent pollution, reduce or eliminate the use and generation of hazardous waste, and reduce risk to human health and the environment.[19] Green chemistry is 'the invention, design, and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances.'[20] Since the turn of the 21st century, courses have been offered in both green chemistry and sustainable chemistry.[21] These courses tend to be taught as optional modules or graduate level courses. More recently, the projects sponsored by International Union of Pure and Applied Chemistry (IUPAC) have turned to systems thinking. In 2017, IUPAC initiated a project with the goal of developing strategies for the inclusion of systems thinking into undergraduate chemistry courses. The dual aim of this project was to provide a coherent grounding for introductory chemistry courses which can be quite fragmented and to connect chemical knowledge to earth systems and social systems (https://iupac.org/project/2020-014-3-050/).

Systems thinking is understood to emphasize a holistic understanding of the field. Chemistry at an introductory level is notorious for being seen as a 'disjointed trot through a host of unrelated topics'.[22] At more senior levels, chemistry tends to be taught in sub-disciplinary silos. The focus of the degree tends to be on preparing students for further study in chemistry, rather than the development of the molecular level view of the world which can be applied across different contexts.[23]

In the next section, we draw on the work of the first author to show ways in which the transformation of the chemist can be brought into view within the bounds of a rigorous chemistry curriculum, thus achieving a knower-aware pedagogy. We also show that systems thinking approaches make connections to society but can be adopted in a manner which is knower blind.

Towards a knower-aware pedagogy

In this section, we illustrate that the ways in which we think about chemistry education shape approaches to teaching and assessment. In particular, we bring into view the importance of a knower-aware pedagogy, because as noted above, this seems necessary if one is to develop the sustainability competences. It is important to note that there are several approaches in the current literature which point to a similar end but proceed *via* different routes. To name just two examples thereof, Sjöström uses *Bildung*[24] to reveal the relationship between chemistry and society, and Sjöström and Talanquer argue for the extension of Johnstone's triangle to include the 'human element'.[25] Nonetheless, it seems that the idea of a knower-aware pedagogy still needs to gain traction in tertiary chemistry education. In this paper, we have chosen to use the work of the first author to illustrate one way in which a knower-aware pedagogy can be conceived and implemented.

This section begins with a focus on what is taught. Ensuring that the underlying principles are adequately conveyed is essential. Few chemists would accept a shift in pedagogical approach that is not grounded in the teaching of chemical knowledge. The frame then broadens to the way in which chemists think about chemistry. The manner in which chemists think about chemistry knowledge will impact the way in which they communicate the underlying principles. The main point here is to show the significance of the social dimension of chemistry. Finally, the way in which systems thinking has been used in chemistry education is brought into conversation with Blackie's model of the practice of chemistry.

The inside view and the underlying principles

In a longitudinal study of chemistry students, Ashwin *et al.*[26] argue that students need to achieve an 'inside view' of the discipline if they are to have the transformative experience of undergraduate education that is the value proposition of higher education. This must include a robust grasp of disciplinary knowledge. Yucel and Blackie[27] suggest that this must also include an understanding of how knowledge claims are made in the discipline – the nature of discipline. Students must also develop an interior understanding of the extent of their knowledge – evaluative judgement.[28] The development of evaluative judgement is facilitated by feedback on meaningful assessment tasks. Yucel and Blackie[27] represent this architecture with an image of a suspension bridge, Fig. 1.

One can only claim that robust disciplinary knowledge is being taught if there is evidence in assessment practices. Blackie argues that meaningful assessment requires a good grasp of the knowledge structure of the discipline.[29] After analysing her own assessment practices with Rootman-le Grange,[30]

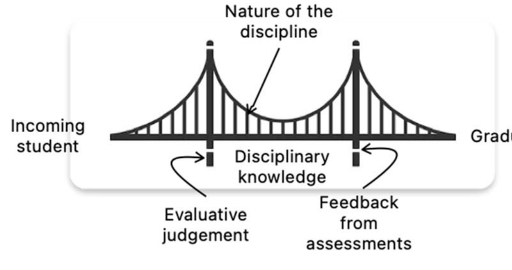

Fig. 1 The suspension bridge illustrates the elements required to achieve mastery in chemistry.

Blackie developed the epistemic assessment framework.[29] The framework distinguishes between different kinds of knowledge required for mastery of organic chemistry. Some things, such as the structure of toluene, just need to be learned (vocabulary). Many familiar questions such as balancing a chemical equation or giving the product of a reaction are classified as procedural knowledge. Some chemical understanding is required to carry out simple and complex procedures, but the capacity to accurately answer these questions does not actually test the student's understanding of the underlying principles or chemical concepts. Thus, finding ways to test that the student has actually grasped the concept is important. For example, in organic chemistry, asking a student to complete a mechanism for a reaction that they know does not mean that they fully understand the underlying principle of the flow of electrons from the nucleophilic center to the electrophilic center and the meaning of the double headed arrow. The combination of finding ways to test the principle and ask students to apply the principle in new situations is required.

Blackie *et al.* have demonstrated that using the epistemic assessment framework can assist in creating more meaningful assessment tasks and can assist students in developing an understanding of disciplinary knowledge.[31] Labelling assessment tasks can also give students access to the kind of feedback they require in order to achieve accurate evaluative judgement. Thus, the epistemic assessment framework can be used to create and evaluate better assessment tasks, and make visible to students where they are struggling and what they need to focus on. Thus, the epistemic assessment framework can be used in a way that forms the foundation for a knower-aware pedagogy as the relationship of the student to the knowledge is revealed.

If we return to the cameo with which the paper began, in order to achieve the design of a molecular synthesis, both students must have a good grasp of mechanistic understanding. Sipho may need to substitute reagents or solvents to work around the local complexities of an intermittent water and electricity supply. Andrew may need to choose reagents and solvents that are already available in the laboratory. To make chemically sound choices, a robust understanding of principles is necessary. Without this understanding, much inefficiency can be introduced in the optimization of the reaction if the student is relying on trial and error to adapt known reaction sequences to the constraints of the context. The use of the epistemic assessment framework increases the probability that Sipho and Andrew will have the required mechanistic understanding for two reasons. The assessment tasks are more likely to meaningfully evaluate mechanistic understanding and both students will be more aware that mechanistic understanding is at the heart of developing the inside view of organic chemistry.

Making the social aspects more visible

It is also important for student chemists to understand the nature of the discipline. Chemical knowledge is not a universal truth that dropped from the sky. Synthetic chemistry, in particular, relies on what Bernstein calls a 'fuzzy logic'. Chemistry is a science of general rules and exceptions to those rules.[32] The 'rules' of synthesis are based on patterns derived from empirical observation. Thus, the development of the skill of a chemist is the development of the way of thinking like a chemist.

Blackie has proposed that the study of chemistry is the interplay of three domains.[33]

(1) Physical realm (molecular interaction level) – chemistry does not examine the entire physical universe but concentrates on molecular interactions specifically. The boundaries start where targeted interaction emerges (molecules can engage in directed interactions, whereas point charges cannot) and concluding at the viral level, where one distinct molecular configuration encases another and the complete structure possesses an explicit self-replication mechanism.

(2) Conceptual realm (chemical concept level) – while individual chemists may draw upon knowledge from fields like mathematics, physics, and biology, the community collectively shares an overlapping foundation of chemical concepts. The established body of chemical knowledge has been accepted by the chemistry community through history, and this foundational knowledge shapes how chemists interpret empirical evidence.

(3) Social realm (chemistry community level) – within this domain, it is equally important to define boundaries for the societal segment under examination. The chemistry community is defined as the group of individuals who investigate, construct, and disseminate chemical knowledge.

There are several points that are made visible in this model with its roots in critical realism. Firstly, that there is an ontological reality which causes the collision of molecules to result in the breaking and making of new bonds and the formation of new chemical entities (physical realm). Individuals (social realm), driven by curiosity, who have taken careful observation of these reactions, have resulted in the development of the field of synthetic organic chemistry and its underlying principles (conceptual realm). Over time, these concepts have been refined and developed. The recognition of the social dimension of chemistry is important for a knower-aware pedagogy.

The combination of careful observation (level 1) and the development of concepts (level 2) constitute the practice of chemistry as science (Fig. 2). Nowadays, organic chemistry comprises a rich and extensive body of chemical reactions. These established reactions can be taken and applied to form new chemical entities. This is the practice of chemistry as technology (level 1). To practice as a chemist at this level may require little more than procedural knowledge. Provided the required reagents, glassware and other stipulated requirements are available, both Sipho and Andrew should be able to carry out a synthetic procedure described in the literature. However, if innovation is required, the process will be significantly more efficient if the students have been trained in a manner which makes visible the underlying principles. To engage chemical intuition and chemical creativity one needs to have developed 'chemical thinking' which requires a robust grasp of the underlying principles. Recognizing the different ways in which chemistry knowledge can be used, shows the particular use in

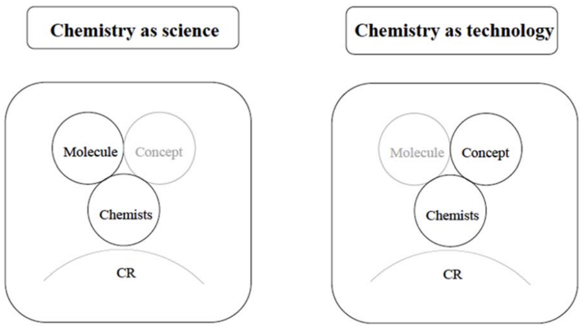

Fig. 2 Upon the foundation of critical realism, chemistry can be seen as the interplay of three realms – the physical, the conceptual and the social. Chemistry can be conceived of as science or technology depending whether the focus is the development of new concepts (science) or the application of existing concepts to new problems (technology).

a particular context. This awareness contributes to a knower-aware pedagogy.

Thus far, we have covered the different aspects of the suspension bridge model of the curriculum. However, there is one crucial remaining element which has not been addressed – the student. The successful graduating student is the one who has been transformed by developing an 'inside view of knowledge'.[26] Thus we come to the heart of a knower-aware pedagogy. No two students come into the undergraduate degree with the same motivations, the same life experience, the same study practices, *etc.* Whilst it is clear that Sipho and Andrew will have had different life experiences, their respective labmates, Sizwe and Angela will also differ in their approaches to problems. If Sipho has cycling as a hobby and Sizwe likes to bake, Sipho may first turn to ensuring that the glassware is accurately assembled and inert gas flow is adequate, while Sizwe may first check whether the reagent is still fully active. Thus, it becomes clear that it is not simply a matter of a difference in context, it is also important to recognize that different students will engage with the knowledge in different ways.

The reproducibility of a chemical experiment is dependent on the consistent reaction of chemical entities (ontological reality) and on the accurate description of the reaction conditions (social realm). However, the prevalent habit of synthetic chemists to simply report how the reaction was successfully achieved, rather than discussing the design choices means that the particularity of the environment which gave rise to specific contextual constraints or affordances are ignored and the person of the chemist is inadvertently erased from the process. This unconscious move to erase the particularity of the learner has been described by Blackie as 'knower blindness'.[34] And in terms of educating with societal and planetary sustainability in mind, the context and the particular motivations of the chemist are vitally important.

Knower blindness and systems thinking in chemistry education

Knower blindness is evident in some of the systems thinking literature. For example, York and Orgill[35] note the following five

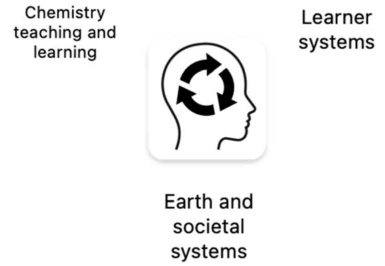

Fig. 3 The learner at the center of the development of systems thinking.

essential characteristics. 'A systems thinker in chemistry education should:

- Recognize a system as a whole, not just as a collection of parts.
- Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviors.
- Identify variables that cause system behaviors, including unique system-level emergent behaviors.
- Examine how system behaviors change over time.
- Identify interactions between a system and its environment, including the human components of the environment.'

The 'systems thinker' is presented as a passive, neutral source of information whose primary goals are to 'recognize, identify and examine'. In an age of generative AI, one must ask the value of the human person in such a system.[36] In the framework for analysis of systems thinking in chemistry education given by Mahaffy *et al.*,[23] the learner is central (Fig. 3). If we consider Sipho and Andrew making decisions around the design of a synthetic strategy, it is immediately clear that the particularity of the person and the context in which they are working are vital if we are to create chemistry education for sustainability. In the next section, we make practical links between the sustainability competences discussed at the start of the paper and chemistry curricula in order to make the implementation of a knower-aware pedagogy possible in any tertiary education context.

Towards reviewing and reorienting chemistry education curricula

At the start of the paper, we introduced UNESCO's sustainability competences. We then posed an argument for the importance of a knower-aware pedagogy. In this section, we seek to show the connections and give some guidance as to how tertiary level chemistry education may respond.

Agenda 2030 is a broad United Nations framework for global peace and prosperity containing 17 Sustainable Development Goals (SDGs) that are the specific, actionable targets to be achieved by 2030.[37] The framework includes a call for universities to embed sustainable development principles across all disciplines, and to educate students about the social, economic, and environmental implications of their future careers. This requires much more than compliance-driven approaches for revising policy frameworks or isolated course curricula. Orr

Table 1 UNESCO's sustainability competences and some implications for chemistry education

Sustainability competence	Key characteristics	Implications for chemistry education
Systems thinking competence	Recognize and understand relationships within complex systems Analyze how systems are embedded across different domains and scales Deal with uncertainty	There are many examples of ways in which to introduce systems thinking to introductory chemistry courses. Systems thinking could also be introduced to capstone courses. This is currently being presented in a primarily cognitive manner, but could introduce socioemotional and behavioural aspects
Anticipatory competence	Understand and evaluate multiple future scenarios (possible, probable, and desirable) Create personal visions for the future Apply precautionary principle and assess consequences of actions Deal with risks and changes	This requires engagement with chemical challenges that will have an impact in the future. Beginning with historical cases of well intentioned projects which ended with unanticipated negative consequences could aid in laying the foundation for the importance of developing this competence. Can be taught from a cognitive angle, but using examples that are relevant to the class have the potential to invoke socioemotional or behavioral aspects
Normative competence	Understand and reflect on norms and values underlying actions negotiate sustainability values, principles, goals, and targets Navigate conflicts of interest, trade-offs, and uncertain knowledge	This requires developing the understanding of the social realm of chemistry. There is always a chemist making choices, on what basis are those choices made. Sipho and Andrew will have different considerations in the choices that they make. This is primarily behavioral and socioemotional. Asking why a norm is accepted will help move beyond the presumed rationale
Strategic competence	Collectively develop and implement innovative actions Further sustainability at local and broader levels	Strategy is always in a context. Using principles of green chemistry or sustainable chemistry to redesign established procedures could provide the foundation for developing this competence. This is primarily behavioral. Enacting a strategy requires compliance
Collaboration competence	Learn from others and practice empathy Understand and respect diverse needs, perspectives, and actions Dealing with group conflicts facilitates collaborative and participatory problem-solving	Establishing group work with meaningful peer review of participation over several tasks can assist in developing this competence. This is a combination of socioemotional and behavioral. Enabling students to reflect on giving and receiving feedback on personal performance is essential. Students need to be trained to give useful feedback to their peers
Critical thinking competence	Question norms, practices, and opinions Reflect on personal values, perceptions, and actions take positions in sustainability discourse	In chemistry, critical thinking is normally taken to mean the capacity to 'think outside the box' or to integrate different ideas to solve a problem. In chemistry, it is thus conceived cognitively. Here it is positioned as socioemotional. Developing a knower awareness approach to chemistry education reveals the importance of personal values and the potential limitations of current understanding
Self-awareness competence	Reflect on personal role in local and global society Continually evaluate and motivate actions Deal with feelings and desires	The development of evaluative judgement is one aspect of this. Bringing into view that one's lifeworld will shape choices made in the chemistry laboratory begins to open this aspect. It is vital here to recognise that human choices are often steered by emotion. Rational arguments to support the choice are developed post-decision. This is a confluence of cognitive, socioemotional and behavioral
Integrated problem-solving competence	Apply diverse problem-solving frameworks to complex sustainability problems Develop viable, inclusive, and equitable solutions Integrate all above competences to promote sustainable development	This competence requires engagement with people and material beyond chemistry. This could be achieved engaging with a local community to solve a problem which has a chemical component. This requires active engagement of cognitive, socioemotional and behavioral

presents the broad challenge for educators and educational institutions to "nurture a profound yet practical awareness of our interrelatedness in the evolving enterprise of life" (p. 2).[38] More specifically, this requires that people everywhere – including chemists – "need to learn how to cross disciplinary boundaries, expand epistemological horizons, transgress stubborn research and education routines and hegemonic powers, and transcend mono-cultural practices in order to create new forms of human activity and new social systems that are more sustainable and socially just" (p. 74).[39]

Against this backdrop, the overall expectation is that science faculties across the world move beyond purely technical education to prepare professionals who understand their role in addressing interconnected global challenges through sustainable, ethical, and socially responsible practice.

In Table 1, we show how these competences can be operationalised in tertiary chemistry education. The implications are based on discussions between the authors, drawing from their teaching experience in chemistry and in sustainability education. The examples given are illustrative. It is important to recognise that developing these competences is not as simple as inserting some content. Rather returning to the argument laid out above about the significance of the way in which we think about chemistry, it is important here to consider the implications of what is included, the way it is included, and the desired ends. This table provides a meaningful connection between the UNESCO sustainability competences and the potential implications for chemistry education enabling chemistry instructors to consider ways in which sustainability can be woven through curricula. This table can also be used to make visible any absences of these competences in curricula.

The implications developed in Table 1 are useful considerations for curricula at the program level. Where in the program are these competences fostered and developed? However, program level interventions are not likely to fulfil their potential impact if they are not supported by incorporating the ways of thinking we have noted earlier in the paper in each course. In the next section, we provide a series of questions which can be used by instructors at the course level.

Course level questions

Based on the position presented in this paper, we offer a series of questions which may help educators see the strengths and weaknesses in their current courses. It is important to note that it is not reasonable to expect all chemistry courses to cover all aspects equally well. Ensuring students emerge with the desired transformational understanding of chemistry and with emergent evidence of the competences is a desired outcome of an undergraduate program. This exercise should be carried out for each course, and there may be reasonable choices made about focusing on a few specific aspects. However, it is important to consider these questions over a degree program too.

Answer each question honestly with yes, partially or no. Look over your responses and see the patterns. Pick one aspect where there is room for improvement and design an achievable action plan to shift your teaching practice. Revisit these questions at least annually.

Category 1: disciplinary knowledge. (1) Do your assessment tasks explicitly test different types of knowledge (vocabulary, simple procedures, complex procedures, principles, and application), with transparent feedback that helps students develop evaluative judgment?

(2) Do students develop robust understanding across all three realms of chemistry: the physical realm (molecular interactions), the conceptual realm (underlying principles and chemical thinking), and the social realm (how chemical knowledge is constructed and validated)?

(3) Do students learn that chemical knowledge is built on empirical observation, and understand chemistry as both science (developing new concepts) and technology (applying existing concepts)?

(4) Are students able to apply chemical principles to novel situations and contexts, demonstrating "chemical intuition" beyond memorization and procedural execution?

(5) Are students empowered to question established chemical practices and norms, critically evaluate claims within chemistry and sustainability discourse, and think independently about chemical solutions?

(6) Do students achieve a "molecular view of the world" and develop an "inside view" of chemistry that enables them to think and act as chemists?

(7) Can you identify specific assessment items that test students' understanding of chemical principles rather than just procedural execution, ensuring conceptual competence is not conflated with procedural competence?

(8) Have students been transformed by the end of your course, demonstrating robust disciplinary knowledge, understanding of how knowledge claims are made, and evaluative judgment about the extent of their knowledge?

Category 2: knower awareness. (1) Do your teaching examples and case studies represent diverse contexts (different geographical locations, resource constraints, infrastructure limitations, and climate conditions) that help students recognize how local contexts shape chemical practice?

(2) Do students learn to articulate the contextual factors that influence synthetic route design and experimental choices, discussing the "why" behind chemical choices rather than just presenting procedures as logical inevitabilities?

(3) Do your pedagogical approaches recognize students as active agents whose diverse motivations, life experiences, and approaches to problem-solving are acknowledged and valued?

(4) Do students reflect on their own role as chemists within local communities and global society, examining their own biases, values, motivations, and the impact of their choices as producers and consumers?

(5) Are students encouraged to reflect on how their own backgrounds, experiences, and perspectives influence their approach to chemical problems, recognizing that different chemists may approach the same problem differently?

(6) Do assessment tasks allow for multiple valid approaches that reflect different contexts and decision-making processes,

making visible that the particularity of the chemist is often inadvertently erased in traditional chemical reporting?

(7) Do you help students develop their identity as chemists who can make informed, context-aware decisions?

(8) Are students supported in developing and maintaining motivation for sustainable chemical practice?

Category 3: environmental and social responsibility. (1) Do students critically reflect on the norms and values that underpin their chemical practice, engage with ethical contradictions, and assess whether practices meet criteria for justice, fairness, and socio-ecological integrity?

(2) Are principles of green chemistry and sustainable chemistry integrated throughout the course, with students learning about the source, use, and safe disposal of chemical compounds across their full life cycle?

(3) Do students understand the environmental costs and benefits of chemical innovations, including awareness of contemporary issues like PFAS and microplastics, and can they evaluate practices against planetary boundaries and sustainable development goals?

(4) Do students understand how chemistry is practiced in different global contexts beyond wealthy Western institutions, with case studies drawn from diverse geographical and socio-economic settings?

(5) Do students appreciate constraints and affordances specific to different laboratory contexts, and consider issues of global justice, fairness, and equity in chemical practice and innovation?

(6) Do students understand that chemistry and sustainability decisions are inherently value-laden rather than purely technical, requiring normative judgment?

(7) Are students prepared to be ethical, socially responsible practitioners who understand their role in addressing interconnected global challenges and see themselves as agents of change capable of contributing to sustainability transitions?

(8) Can students collectively map, specify, and negotiate sustainability principles and goals in chemical contexts, understanding how chemical industries and practices differentially affect communities based on geography, wealth, and power?

Category 4: curriculum design. (1) Does your course provide coherent organizing principles that connect different chemical topics, rather than presenting a "disjointed trot through unrelated topics"?

(2) Are students taught to recognize chemistry within broader social, environmental, and economic systems across different scales (local to global), including chemical life cycles with cascading effects and feedback loops?

(3) Are students taught to evaluate possible, probable, and desirable future outcomes of chemical innovations, applying the precautionary principle and considering intergenerational equity?

(4) Do students learn to design and implement interventions that advance sustainability, understanding systemic inertia, barriers to change, and strategies for linking chemical knowledge to concrete action?

(5) Do students work in heterogeneous groups and engage in interdisciplinary and transdisciplinary collaboration, developing conflict management and participatory problem-solving skills?

(6) Do assessment tasks require students to apply multiple sustainability competences simultaneously, developing solution options that are viable, inclusive, and equitable?

(7) Do your learning outcomes explicitly include sustainability competences alongside disciplinary knowledge?

(8) Does the course prepare students for applying chemical thinking across different contexts beyond further chemistry study?

Conclusion

Chemistry education stands at a critical juncture. While the field has made significant strides in developing conceptual coherence through innovations like systems thinking and chemical thinking frameworks, and in addressing environmental concerns through green and sustainable chemistry, these advances remain incomplete without explicit attention to the person of the chemist. The cameo of Sipho and Andrew with which we began this paper reveals a fundamental tension: the very conventions that give chemistry its claim to objectivity—the erasure of context and particularity in the reporting of synthetic procedures—simultaneously obscure the reality that all chemical practice is shaped by the constraints and affordances of specific contexts and enacted by particular individuals with unique perspectives and motivations. Education for sustainability demands that we move beyond knower blindness to a pedagogy that recognizes students as agents capable of making informed, context-aware, ethically grounded decisions. The framework and self-assessment tool presented here provide chemistry educators with a pathway toward this transformation. By integrating robust disciplinary knowledge with explicit development of sustainability competences, by attending to the nature of chemistry as both science and technology, and by valuing rather than erasing the particularity of learners and contexts, we can prepare chemistry graduates who possess not only molecular mastery but also the wisdom, values, and capabilities necessary to navigate the complex sustainability challenges of the twenty-first century. The question is no longer whether chemistry education must change to meet the demands of our planetary moment, but whether we have the courage and commitment to enact that change comprehensively and urgently.

Author contributions

Blackie was responsible for conceptualisation. Both authors contributed to writing. Blackie is a specialist in chemistry education. Olvitt is a specialist in sustainability development.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed.

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