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Highlight

Student-Focussed Approaches that can Enhance Understanding and Appreciation of Research in the Chemical Sciences

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The alignment of intended learning outcomes for chemistry graduates and the actualised outcomes has been called into question recently. Opportunities to address this lie in the integration of undergraduate learning experiences in which students develop real-world skills and engage with problems that they may encounter as graduates in contemporary workplaces or modern society more broadly. This Highlight article provides an overview of three such approaches, including offering students authentic research experiences within (or outside of) normal degree programs, engaging students in citizen science projects, and considering curriculum reforms to better align with a systems thinking framework. Where possible, we provide explicit examples grounded in the Australian context, accompanied by some thoughts on the challenges that may be encountered when implementing these approaches in practice.

Keywords: systems thinking, curriculum design, undergraduate research, undergraduate chemistry, chemistry education, citizen science, chemistry in society, threshold learning outcomes.

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Introduction

In recent years the specific role of chemistry education at both secondary and tertiary levels has been the subject of discussion,[1] not least because it plays a pivotal role in developing future chemists, but also because it contributes to equipping students with skills that translate beyond the discipline's specific vocations. In addition to developing students' disciplinary knowledge, enhancing students' engagement with research can foster learning outcomes that extend outside of science-specific skills such as understanding the place of science in society, critical thinking, problem solving, and communication.[2] These attributes are essential according to the Australian Science Threshold Learning Outcomes (TLOs) that were defined by the Australian Council of Deans of Science (ACDS) that guide accreditation of chemistry majors by the Royal Australian Chemical Institute (RACI).[3] The aligned Australian TLOs for undergraduate university-level chemistry are shown in Table 1.[4]

The majority of undergraduates arguably complete their studies without developing an accurate understanding of what research in the chemical sciences involves not only from a practical perspective, but also more broadly. The same is true for high school graduates. This can be problematic with respect to missed opportunities to include and engage a wider, more diverse cross-section of Australians in such endeavours. Beyond this, it leads to graduates that are less likely to appreciate and advocate for the need to support research and development in our society. Reviews conducted for the Australia Institute and Australian Government call for pathways that develop not only students' factual and procedural knowledge and problem-solving skills, but skills and frameworks for engaging with global issues, societal challenges, and management of the self in a changing world.[5–7] This is further reflected in the Alice Springs (Mparntwe) Education Declaration which outlines Education Ministers' vision of Australian educational outcomes.[8]

With the above-mentioned issues in mind, this Highlight article strives to draw attention to three student-focussed approaches that can contribute to advancing understanding and appreciation of research in the chemical sciences, and placing chemistry in a broader context. This includes involving students in citizen science activities as part of their studies; the emerging push to design curricula from a systems thinking perspective; and the established practice of offering undergraduates authentic research experiences. Where possible, the focus of this discussion has been grounded in the Australian context. We have related the key features of these approaches to the chemistry TLOs for this reason.

Involving Students in Research Projects through Citizen Science Initiatives

One approach that has been demonstrated to effectively engage students with real-world research methodologies/projects is the

Table 1. The Australian Council of Deans Teaching and Learning Centre National Chemistry's TLOs for undergraduate university-level chemistry in Australia[4]

Understanding the culture of chemistry	**1. Understand ways of scientific thinking by:** 1.1. recognising the creative endeavour involved in acquiring knowledge, and the testable and contestable nature of the principles of chemistry 1.2. recognising that chemistry plays an essential role in society and underpins many industrial, technological and medical advances 1.3. understanding and being able to articulate aspects of the place and importance of chemistry in the local and global community
Scientific knowledge	**2. Exhibit depth and breadth of chemistry knowledge by:** 2.1. demonstrating a knowledge of, and applying the principles and concepts of chemistry 2.2. recognising that chemistry is a broad discipline that impacts on, and is influenced by, other scientific fields
Inquiry, problem solving & critical thinking	**3. Investigate and solve qualitative and quantitative problems in the chemical sciences by:** 3.1. synthesising and evaluating information from a range of sources, including traditional and emerging information technologies and methods 3.2. formulating hypotheses, proposals and predictions and designing and undertaking experiments 3.3. applying recognised methods and appropriate practical techniques and tools, and being able to adapt these techniques when necessary 3.4. collecting, recording and interpreting data and incorporating qualitative and quantitative evidence into scientifically defensible arguments 3.5 demonstrating the cooperativity and effectiveness of working in a team environment
Communication	**4. Communicate chemical knowledge by:** 4.1. presenting information, articulating arguments and conclusions, in a variety of modes, to diverse audiences, and for a range of purposes 4.2. appropriately documenting the essential details of procedures undertaken, key observations, results and conclusions
Personal & social responsibility	**5. Take personal, professional and social responsibility by:** 5.1. demonstrating a capacity for self-directed learning 5.2. demonstrating a capacity for working responsibly and safely 5.3. recognising the relevant and required ethical conduct and behaviour within which chemistry is practised

field of citizen science.[9] Wiggins and Wilbanks define citizen science as '*a range of participatory models for involving non-professionals as collaborators in scientific research*'.[10] Given the breadth of this range, one typology of these participatory models offers a convenient categorisation into five distinct groupings: Action, Conservation, Investigation, Virtual, and Education.[11] Citizen science projects are not a new invention, with some, such as those run by the Cornell Laboratory of Ornithology, having run successfully for decades,[12] while more recent projects have garnered rapid interest for their immediate relevance to global issues.[13]

Citizen science projects have the capacity to develop and assess student outcomes that are strongly aligned with the chemistry TLOs and thus offer valuable opportunities to support undergraduate education. In particular, TLOs 1, 3.1, 3.3, 3.4, and 4.1 are prominent when considering the potential learning outcomes offered by citizen science projects. The integration of citizen science projects into both K-12 and higher education have resulted in successful outcomes for students in various cases.[9,14–16]

A chemistry-specific citizen science project of note is the Breaking Good project based out of The University of Sydney. Established in 2012, this project has challenged high school and undergraduate students to serve as active researchers striving to improve human health.[17] This example would fit into the Wiggins and Crowston definition of an Investigation-type citizen science project.[11] Foldit, an online protein folding game developed by the same institution[18] is an example of a Virtual-type citizen science project that has been integrated into undergraduate education and recently published as part of the ACDS Digital Repository project.[19] This tool serves as the centrepiece of a theoretically driven, substitute laboratory experience devised in response to the COVID-19-imposed shift to online learning in which students engage with an authentic research challenge while considering the role of citizen science in society.

A common implementation of citizen science inspired/related chemistry laboratory experiments involves a blend of Conservation- and Investigation-type projects. This includes using environmental pollution as a focal point for research. For example, Rowe and co-workers recently reported a multi-week research project tasking first-year students with investigating the presence of microplastics in soil and sediment.[20] A post-laboratory survey indicated that this experience increased student awareness of scientific research, microplastic pollution, and the potential impact on the environment, thereby aligning with TLO 1. In addition, this endeavour had a positive impact on the chemistry-specific learning outcomes. A similar study has been published as a laboratory experiment focussed on analysing water quality.[21] Through direct observation and student interviews, the authors found similar learning benefits to those described by Rowe and co-workers.[20]

While we have provided some specific examples in the area of chemistry, there are few published examples reported. Furthermore, concerns have been raised over ethical considerations for citizen science.[22] This necessitates careful consideration when designing and pursuing the implementation of citizen science projects in your practice.

Placing Research in the Chemical Sciences in a Greater Context via Systems Thinking

Over the last five years, attention has focussed on adopting systems thinking in an attempt to better prepare chemistry students for not only a career within the discipline, but also for success beyond this as engaged and constructive members of society capable of tackling complex global challenges and interconnected societal issues.[23–26] 'Systems Skills' are ranked higher even than 'Complex Problem Solving Skills' in the estimates of future skills shortages in a report from the Australia Institute (Centre for Future Work) in 2019.[5] Talanquer and co-workers advocate for the utility of systems thinking by employing it as the underpinning form of reasoning in their proposed reimagining of foundational level chemistry education as we emerge from the COVID-19 pandemic.[27] Placed within the context of the chemistry TLOs, a systems thinking approach has the potential to align closely with TLOs 1.2, 1.3, 2.2, and 5.3.

An operational definition of systems thinking in a chemistry context is supplied by Orgill and co-workers:[28]

> *Systems thinking employs a variety of tools and cognitive frameworks to enhance our understanding of complex behaviours and phenomena within and between systems, both natural and artificial, from a holistic perspective. Systems thinking enables one to see higher-level behaviours and phenomena that one may not have predicted to arise out of a mere sum of the component parts of a system.*

In addition to the definition above, Orgill et al.,[28] Constable et al.,[29] and York et al.[26] provide further clarity on the evolution of systems thinking in other disciplines, insights into how it might be applied generally and with examples to chemistry, and how it differs from more traditional 'reductionist' approaches to STEM education. Although current definitions, characteristics, and educational tools relating to systems thinking have been commonplace in disciplines such as sociology, philosophy, organisational theory, biology, and engineering,[26,30] they are not well developed in a chemistry context.

The international call for reorienting chemistry towards a systems thinking framework was highlighted by Matlin et al.[23] and Mahaffy et al.,[24] who led an IUPAC- and IOCD-supported project titled Systems Thinking in Chemistry Education (STICE).[31] This project aimed to accelerate the incorporation of systems thinking into secondary and tertiary chemistry education, and a major outcome was the release of the *Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry Special Issue* in the *Journal of Chemical Education* (2019, Volume 96, Issue 12).

The *Special Issue* brought forward many examples of how systems thinking has already been implemented around the world, particularly in the sustainability and environmental chemistry subdisciplines.[32–41] One Australian example we wish to highlight is a study completed by Schultz and co-workers, in which secondary chemistry students created system maps to represent industrial chemical processes and evaluate the broader impact of the processes in relation to the United Nations Global Goals for Development.[41] Through teacher reflections in an action research framework, the study evaluated whether system mapping 'allowed the teacher to situate the learning of sustainability within the learning of chemistry content.' These reflections revealed several positive outcomes for students, including comparable content knowledge development to previous cohorts (TLO 2), high levels of enthusiasm when engaging with higher order evaluation tasks (TLO 3), and the successful linking of chemistry and sustainable development concepts, both situated within a global context (TLO 1).

Thoughtful, evidence-based incorporation of systems thinking approaches in mainstream undergraduate curricula will require significant investment and face a variety of challenges.[24,37,42] However, the leaders of the STICE project and authors of the closing article of the *Special Issue* outline three key areas of future development:[43] resource development, chemistry education research to improve systems thinking approaches, and applying approaches to broader educational contexts.

Involving Undergraduates in Authentic Research Experiences: Course-Based Approaches

Exposing undergraduates to research during their candidature represents one mechanism that can better equip them with a clearer picture of what research in chemistry entails. The Council for Undergraduate Research defines undergraduate research (UR) as; '*An inquiry or investigation conducted by an undergraduate student that makes an original intellectual or creative contribution to the discipline*'.[44] When considered within this framework, the overarching goal of an UR project is to extend the experiences of students beyond solely repeating previously reported work to developing original research findings and communicating these discoveries in traditional scholarly forums.[45] The key features of excellent and rigorous UR experiences have been discussed in detail.[46] It is clear that incorporating inquiry and discovery in the undergraduate curriculum is beneficial,[47,48] and Wenzel notes that, *'It is doubtful that any other activity in the undergraduate curriculum matches the intensity of problem solving, decision making, critical thought, independence, and responsibility that occurs in research'*.[45] The objectives of UR align with all five of the chemistry TLOs. Specifically, the following TLOs are prominent when considering potential learning opportunities offered by UR: TLO 1.1, 2.1 3.1–3.5, 4.1, 4.2, and 5.1–5.3.

Various Australian universities offer some form of summer research experience to undergraduates or select project units, while longer-term classical undergraduate 'research internships' that operate throughout main semester periods are often less well developed and are typically facilitated by individual research group leaders on more of an *ad hoc* basis.[49–51] However, course-based undergraduate research experiences (CUREs) have been growing in prominence for some years.[50] While the structure and format of CUREs can vary significantly, these experiences should incorporate key themes, such as training students in scientific best practice, exposing students to contemporary/topical areas of discovery-based research, emphasising the role of teamwork/collaboration, and highlighting how/why iteration is required to progress science.[49] These aspects of CUREs have been discussed in detail.[49,52]

CUREs offer the capacity to broaden participation in research at undergraduate levels beyond small numbers of select students by integrating research-focussed experiences (or whole units) within degree programs that count towards course credit.[52] With the increasingly decentralised approach to university education in Australia and shrinking undergraduate laboratory programs that effectively limit in-person teacher–student interactions, CUREs may offer several important benefits. This includes, but is not limited to, allowing undergraduates to more easily form connections, become part of a team, better integrate themselves into departments and widen networks across year levels and degree programs, and broaden participation of traditionally underrepresented groups.[49] Beyond this, CUREs may offer valuable opportunities for finding mentors and these mechanisms often serve as clarifying experiences that allow undergraduates to identify the topic(s) they are most passionate about and may pursue further in their prospective careers.[53]

Conclusion

In conclusion, we hope that this Highlight serves as a useful entry point to strategies that could be adopted in practice while also prompting members of the community who have developed rigorous, successful student-focussed approaches to share and disseminate their findings. We suggest that there is substantial potential to further embed and expand research opportunities in undergraduate degree programs. The small subset of examples detailed here have been provided to prompt a reflection on our current practice and consider how we can continue working towards our desired graduate standards. This is not to say that the path towards implementation will always be smooth. There are several potential foreseen challenges that could detract from the intended purpose or even be detrimental to a students' learning. One such example was highlighted by Pazicni and Flynn when attempting to reconcile systems thinking with current learning frameworks, articulating the risk to learners' needs that is posed by introducing systems thinking before adequate evaluation of this framework is complete.[42] This risk is one that is easily translated across the examples provided here. Another significant limitation to many of these models is the lack of evidence-based studies to both validate these approaches and offer well defined guidelines for implementation in a degree program. Finally, we suggest that chemical practitioners in Australian universities cannot appropriately advance this situation without the assistance of senior leaders within their institutions. Questionable management ideology and burdensome administrative processes that have pervaded higher education in this country pose inherent threats to continuing outstanding practice while also representing barriers to developing innovative curricula that align with excellence in learning and teaching, perhaps now more than ever.

Data Availability Statement

All data used for this article is available through the referenced literature.

Conflicts of Interest

The authors declare no conflicts of interest.

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