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Faculty perspectives regarding the integration of systems thinking into chemistry education†

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Research suggests that systems thinking is beneficial to education and it has been proposed that training students using systems thinking techniques may enhance their abilities to understand and solve some of the global grand challenges that society currently faces as outlined by the United Nations Sustainable Development Goals. However, before systems thinking can be incorporated into chemistry education, the perceptions of the instructors who would adopt this framework must be investigated. Therefore, semi-structured interviews were conducted with 14 instructors from the Department of Chemistry at the University of York. Responses were analysed using both qualitative (framework method) and quantitative (Likert-style) techniques. The instructors expressed positive opinions of systems thinking as all participants stated that systems thinking techniques should be implemented into the undergraduate chemistry curriculum to some extent. Examples of anticipated advantages to integrating systems thinking into curricula include benefits to student learning, the facilitation of interdisciplinary teaching/learning, enhanced student employability prospects, and societal benefits. Research has suggested that curriculum reform is only successful with support from instructors and so these positive opinions of systems thinking from participants with expertise from a variety of areas within chemistry show great promise for future implementation.

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Introduction

Poverty, access to clean water/sanitation, gender equality, and climate change are just some of the many grand challenges facing today's society. In 2015, the United Nations generated the Sustainable Development Goals with the aim of addressing such challenges. There are 17 goals consisting of 169 more specific targets regarding issues such as hunger, health and well-being, quality education, affordable and clean energy, and sustainable cities and communities. The intention is that these goals will be achieved by 2030 (United Nations, 2015).

Despite the apparent diversity in each of the goals, they are all interrelated and, as such, cannot be considered as distinct, separate issues (Anastas and Zimmerman, 2018). Therefore, to achieve these goals, holistic and interdisciplinary thinking and action must take place, internationally, with contributors from their respective fields working together and considering a wider range of factors from multiple perspectives. The next generation of scientists, engineers, and policymakers should therefore be trained in such a way to best equip them to address these and any new challenges that may arise. A systems thinking

theoretical framework within education sectors could be used as an instructional model to facilitate this (Anastas and Zimmerman, 2018; Reynolds *et al.*, 2018; Mahaffy *et al.*, 2019a; 2019b; 2019c; Zuin and Kümmerer, 2021).

Systems thinking

Systems thinking does not have one, specific definition as different applications allow for slight modifications of how the framework is implemented. Here, systems thinking was taken to be “a holistic approach for examining complex, real-world systems, in which the focus is not on the individual components of the system but on the dynamic interrelationships between the components and on the patterns and behaviours that emerge from those interrelationships” (York *et al.*, 2019).

Systems thinking has been utilised in a variety of fields including biology, maths, engineering, business, and behavioural sciences (Hammond, 2002). In biology, for example, systems thinking has been implemented in research into plant development, growth, and production, allowing for great advancements to be made in this area (Hammer *et al.*, 2004). Benefits can also be observed in business. When developing a new product, companies who adopt systems thinking approaches whilst considering their consumers, competition, market *etc.* tend to perform much better in terms of sales and profits (Monat *et al.*, 2020).

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Systems thinking in education

Recently, systems thinking approaches have also been applied in educational settings with research suggesting potential benefits of using systems thinking for teaching and learning. Examples of such benefits include enhanced understanding of course content and the development of interdisciplinary skills. This has been demonstrated in a study investigating the outcomes of systems thinking implementation into land economics education in which students achieved enhanced exam scores and were able to produce diagrams to display the systems being studied, including factors from multiple disciplines (Mathews and Jones, 2008).

Systems thinking in education is a student-centred approach to teaching that allows students to appreciate the importance of constituent subsystems and how they connect to form the entire system (Kordova *et al.*, 2018). The framework can be used in assisting students to understand and work through real-world problems (Richmond, 1993; Jacobson, 2001). When comparing students with systems thinking experience to those without, enhanced problem-solving skills were exhibited by students with experience in systems thinking as they were able to consider a wider range of factors and organise their responses more effectively (Jacobson, 2001). It has also been suggested that this approach has benefits for instructors as it equips them with a structure and various techniques to assist the incorporation of interdisciplinary content and additional considerations into their course (Sabelli, 2006; Mathews and Jones, 2008).

Research suggests that humans are not innate systems thinkers (Hmelo *et al.*, 2000; Jacobson, 2001; Jordan *et al.*, 2013). However, systems thinking skills can be acquired if students are explicitly taught how to do so (Wylie *et al.*, 1998; Hmelo *et al.*, 2000; Goldstone and Wilensky, 2008). Methods for teaching systems thinking skills include design activities (Hmelo *et al.*, 2000), computer simulations (Riess and Mischo, 2010), and systems modelling (Hung, 2008). For example, within biology education, students have been asked to design and build part-working models of lungs. Within this activity, students were encouraged to consider factors regarding how the model fits together, the consequences of changes to parts of the model, and its function upon completion (Hmelo *et al.*, 2000).

Various visual/graphical tools have also been constructed to aid the implementation of systems thinking techniques into teaching. Systems oriented concept map extensions (SOCMEs), causal loop diagrams, and stock and flow diagrams are some examples of such tools, each with their own strengths and applications to which they are best suited (Aubrecht *et al.*, 2019). SOCMEs have similar features to concept maps, however, in a SOCME, the subsystems and all connections between them are clearly identified. This allows for consideration of any consequences arising from changes to any subsystem as the user can see which subsystems are linked (Matlin, 2020); an example of a SOCME displaying the production of polystyrene is shown in Fig. 1. Causal loop diagrams are less detailed in that they may not show every feature of all subsystems, however, they do show

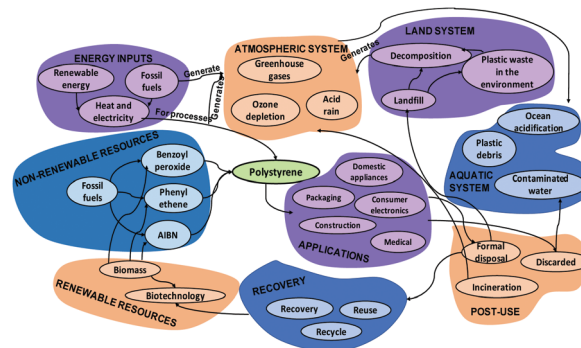


Fig. 1 Systems oriented concept map extension for the production of polystyrene displaying various possible subsystems.

the directionality and polarity of the connections shown, as well as the existence of any feedback loops (Schaffernicht, 2010). This can be seen in Fig. 2, which depicts the feedback loops associated with the disposal of polystyrene. Finally, stock and flow diagrams present different types of variables and their connections distinctly. Such variables are displayed as stocks, flows and auxiliaries. A variable is classed as a stock variable if it involves an accumulation or storage in the system, a flow is how stock moves between subsystems, and an auxiliary provides additional information about said flow and how subsystems are interrelated (Aubrecht *et al.*, 2019). Fig. 3 is an example of a stock and flow diagram displaying different disposal methods of polystyrene.

The application of these, and other, systems thinking tools have only recently been applied in science, technology, engineering and mathematics (STEM) fields, with research into systems thinking in STEM education gaining momentum in the last decade or so (York *et al.*, 2019). By 2018, the US National Science Foundation had provided grant funding for 27 projects focusing on systems thinking within STEM education, amounting

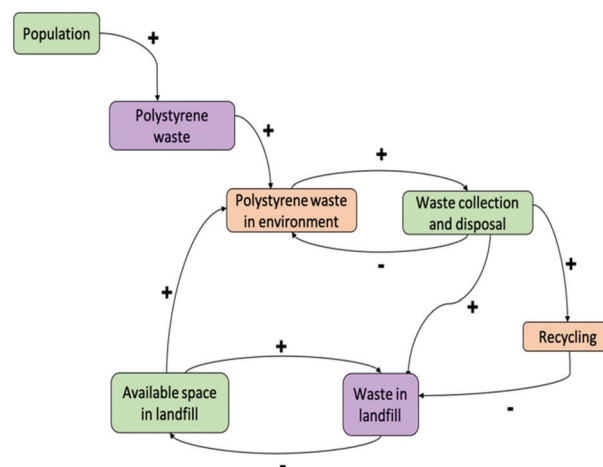


Fig. 2 Causal loop diagram displaying feedback loops associated with polystyrene disposal, where (+) illustrates that a change in one variable causes the connected variable to have a change in the same direction, while (–) illustrates that a change in one variable causes the connected variable to have a change in the opposite direction (Aubrecht *et al.*, 2019).



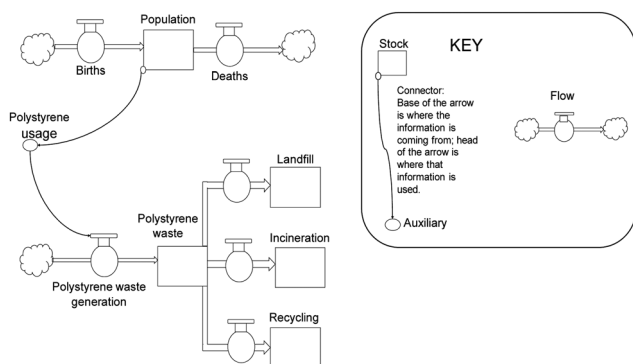


Fig. 3 Stock and flow diagram displaying the connection between population and possible polystyrene disposal methods.

to approximately \$25.8 million (Nsf.gov, 2019). The attention of such projects tended to be concentrated on the ability of students to acquire systems thinking skills and the methods best suited to achieve this, with little or no consideration of training the instructors on how to utilise systems thinking approaches in their teaching. Additionally, most of the funded projects were centred in engineering or environmental sciences with no funding towards mathematics or any of the physical sciences including disciplines that feature molecular, atomic, or sub-atomic behaviour. Examples of projects include the assessment of systems thinking skills of engineering students, an assessment of the viability of concept maps to aid systems thinking in engineering students, and an investigation into whether an interactive simulation game can aid in enhancing systems thinking skills in geoscience students (Nsf.gov, 2019).

Systems thinking in chemistry education

Systems thinking is not currently incorporated in chemistry education to any great extent (Ho, 2019), with conventional methods being described as reductionist (Orgill *et al.*, 2019). The chemistry education research community claim that these approaches should be updated and have described university undergraduate chemistry courses as “a disjointed trot through a host of unrelated topics” (Cooper, 2010). To enhance the chemistry curriculum, there has been a recent surge in interest into the outcomes of incorporating systems thinking techniques into chemistry education.

The integration of systems thinking into chemistry education would mean that reactions and processes would no longer be studied in an isolated fashion and, instead, the learner would be encouraged to think critically about factors such as the origins of any starting materials, how they are transformed and used and what happens at their end of life. Learners would be assisted in analysing the benefits and impacts of chemical substances and the role they play in societal and environmental systems (Constable, 2017).

Support for the introduction of systems thinking into chemistry education has come from the International Union of Pure & Applied Chemistry (IUPAC) through the development of the Systems Thinking in Chemistry Education (STICE) project in 2017 (IUPAC, 2017). Outcomes of this project include a

special issue of the Journal of Chemical Education (Mahaffy *et al.*, 2018) and the development of a systems thinking framework in the context of chemistry education (Flynn *et al.*, 2019).

This special issue considered several perspectives for implementing systems thinking into chemistry education. These include: an overall introduction (Orgill *et al.*, 2019), the challenges and opportunities of implementing systems thinking into chemistry education (Constable *et al.*, 2019; Pazicni and Flynn, 2019), how it can be used in green chemistry (Hutchison, 2019; Ginzburg *et al.*, 2019; Perosa *et al.*, 2019), and ideas for future development/research (Flynn *et al.*, 2019).

It has been suggested that an incorporation of systems thinking into the curriculum would not only help chemistry students to better understand chemistry, but it would also aid their ability to see the connections between chemistry and other disciplines and allow for greater integration of green and sustainable chemistry concepts into mainstream chemistry courses (Holme, 2019; Hutchison, 2019; Mahaffy *et al.*, 2019a; 2019b; 2019c).

So far, suggested methods for introducing systems thinking approaches into chemistry education have generally done so through a green chemistry lens. Examples include experiments, workshops, and games (Hurst, 2020). For instance, systems thinking techniques were used to find a replacement for a material with toxicity concerns that has been used in rheology experiments and demonstrations in the UK (Hurst *et al.*, 2015; Garrett *et al.*, 2017). When such an experiment was performed in Brazil, waste orange peel was selected as the substitute feedstock given that its disposal in landfill is an issue of national importance. Therefore, in addition to acting as a learning resource, the experiment aids in reducing the issues surrounding the disposal of this ‘waste’, advocating for a transition from a linear to a circular economy (Mackenzie *et al.*, 2019). This demonstrates that the experiment is accessible and transferable while illustrating how systems thinking can be used to help solve global problems.

Outside of the laboratory, workshops have been developed as another potential gateway to implement systems thinking into green chemistry education. The Green Chemistry Centre of Excellence at the University of York established the Renew-Chem graduate training programme in 2016 in which systems thinking approaches have been used in an annual series of themed workshops concerning sustainable manufacturing for the chemical industry. Each workshop focuses on a different aspect of green chemistry/sustainable manufacturing, using real world case studies and being taught by members of staff from chemical companies and a variety of university departments to gain a deep and holistic understanding of the topics discussed (Summerton *et al.*, 2019).

Games that utilise systems thinking skills have also been used in green chemistry education. One example is the “Safer Chemical Design”, a simulation game in which the player is given the task of developing a safer and more sustainable chemical product, considering various factors including toxicity, biodegradability, biotransformation and overall performance, being able to redesign and improve their product



based on real-time feedback and receiving points based on their decisions (Mellor *et al.*, 2018). Other examples include the mobile application game Green Tycoon (Lees *et al.*, 2020) and the card game, Green Machine (Miller *et al.*, 2019). These, and other techniques, have been utilised internationally in a successful endeavour to incorporate systems thinking into green and sustainable chemistry programmes, courses, and resources (Hurst *et al.*, 2019).

As outlined, green chemistry provides a useful context to integrate systems thinking into chemistry education. Systems thinking has also been adopted in related fields such as pharmacy education (Hurst and Clark, 2020). The link between chemistry and pharmacy can be demonstrated by studying the chemistry and life cycle of drugs using systems thinking methods, for example, *via* production of a SOCME for a drug of pharmaceutical importance, displaying a variety of subsystems such as its chemistry, side effects, production, and end of life (Holme, 2020). However, there is still the issue of widespread adoption throughout the curriculum as other areas of chemistry have not yet been investigated for systems thinking implementation. For this to occur, there needs to be interest and willingness from chemistry instructors.

Implementation

Research suggests that previous attempts at reforming science education have been unsuccessful because they exercised a top-down model of change and were not systemic in nature (Fullan and Miles, 1992; Anderson and Mitchener, 1994; Bybee and DeBoer, 1994). Common themes arising in unsuccessful attempts include politics (Fullan and Miles, 1992), lack of clarity for curriculum changes, lack of support (Handal and Herrington, 2003), lack of funding (Foote *et al.*, 2016), lack of time (Dancy and Henderson, 2010), and discrepancies between STEM instructors' attitudes and current approaches to reform (Erdmann *et al.*, 2020).

Systems thinking techniques involving the collaboration and inclusion of students and faculty members of varying positions in the reforming process have been shown to have some success (Dicks *et al.*, 2019; Hutchison, 2019). Additionally, the presence of experts in, for example, chemistry education, may assist reform attempts as they can provide access to the required information, training, and resources and can drive these changes because of observing benefits in the literature.

It is also suggested that any changes to education will only be successful if the opinions and attitudes of the instructors are considered (Trigwell *et al.*, 1994; Ahmad, 2008; Burmeister *et al.*, 2013; Erdmann *et al.*, 2020). Therefore, before attempting to implement systems thinking into the general chemistry curriculum, it would be beneficial to gain a greater awareness of the perceptions and opinions of chemistry instructors in this regard.

Research investigating the opinions of high school teachers with respect to implementing systems thinking into the curriculum has been carried out, comparing chemistry instructors in the Italian education system to those who taught in the International Baccalaureate (IB) organisation (Celestino and Marchetti, 2020).

Within the IB, systems thinking is already nurtured as students are encouraged to "think critically" and "consider both local and global contexts of their work" (International Baccalaureate[®], 2019), which has had great success. On the other hand, the Italian education system is very split into their disciplines with Italian students obtaining a low score for their scientific knowledge in an international assessment of student abilities (OECD, 2018). The teachers were provided with a questionnaire to determine their opinions of systems thinking, whether they use it, and their perceptions of potential implementation. The answers concerning the ability of participants to describe and explain features of systems thinking and its use in teaching practice were broadly positive from participants in both groups, despite their differences in background (Celestino and Marchetti, 2020). This positive feedback from both sets of instructors shows promise for systems thinking implementation. However, as this research was solely focused on instructors who teach students between the ages of 11–19, it cannot be generalised to staff teaching in higher education.

In this work, the opinions of undergraduate instructors were investigated, with the aim of exploring their attitudes towards the potential implementation of systems thinking into the undergraduate chemistry curriculum.

Methods

Sampling

Participants were sampled with the intention of gaining insights from staff from a variety of areas of chemistry, at various stages in their career, allowing for a broader scope and range of responses (Kuzel, 1992; Åkerlind, 2004). An invitation was sent to all instructors at the Department of Chemistry at the University of York to invite staff to participate in an interview. Interviewees ranged from having 0 to 39 years' teaching experience and represented a variety of areas of expertise and academic positions. The demographic information of the participants is presented in Table 1.

14 members of staff participated in the interview. This research received ethical approval from the institutional review board and informed verbal consent was obtained from each participant before the interview was conducted.

Interviews

A series of short, semi-structured interviews was conducted *via* Zoom (Zoom Video, 2018) to gain insight into the instructors' perceptions of systems thinking and whether they believe that it should be incorporated into teaching chemistry at the undergraduate level. The meetings lasted between 16 and 50 minutes and were recorded and transcribed verbatim using software within Zoom. The interview protocol is provided in the Appendix. Each interview was comprised of three sections. The first section contained questions regarding the personal information of the participants, such as topics taught and how many years of teaching experience they had. The second section then used qualitative questions to acquire a detailed understanding



Table 1 Demographic information of participants

Gender	Male	10
	Female	4
Area of expertise	Physical	3
	Organic	1
	Inorganic	1
	Biochemistry	5
	Green chemistry	4
	Management	2
	Computational	1
	Analytical	1
	Materials	1
	Education	1
Number of years of teaching experience	0–5	4
	6–10	4
	16–20	1
	21–25	2
	25+	3
Professional title	Associate lecturer	4
	Research fellow	1
	Lecturer	3
	Senior lecturer	2
	Reader	1
	Professor	3

of the interviewees' opinions/perceptions of systems thinking. At the start of this section the participants were asked if they were able to provide a definition of systems thinking and, regardless of their answer, were then provided with a standard definition and shown a SOCME to illustrate the production of polystyrene (shown in the electronic ESI†). This allowed for greater validity of further answers as the participants were all answering with at least a basic understanding of what systems thinking is and an example of how it may be applied to chemistry education. Finally, the third section contained quantitative questions in which the participants were asked to rate a series of statements from one to five (strongly disagree to strongly agree) (Boone and Boone, 2012; Nemoto and Beglar, 2014; Joshi *et al.*, 2015) and explain the reasoning for their response.

Once transcribed, the responses were summarised in a table to allow for initial impressions to be formed through familiarisation with the content. More detailed qualitative analysis of the responses was then conducted by the first author using the framework method; one approach of thematic analysis commonly used for qualitative data analysis (Furber, 2010; Gale *et al.*, 2013; Bennett *et al.*, 2018). Once initial impressions were formed, the transcripts were coded using NVivo (QSR International Pty Ltd, 2012). Open coding was used to ensure that no information was missed, and all content was coded as effectively and as accurately as possible (Wilson, 2017; Williams and Moser, 2019).

The first transcript was coded and the codes were then collated into a table along with a brief description of each code to form the initial analytical framework. At this point, an "other" code was also displayed in the table and was not defined or separated until all transcripts were coded. Further transcripts were then coded using this initial framework, taking

care to note any new codes or impressions that did not fit with the initial set. Whilst working through coding each of the transcripts, the codes were refined with the procedure of applying, refining and grouping codes being iterated multiple times throughout the coding process until no new codes were generated. The completed set of codes were then grouped together into categories and reviewed to ensure that they were used as fully and effectively as possible. Upon completion of this analytical framework, the categories were displayed as a matrix comprised of one row per participant and one column per code with each category in a separate sheet. Once the matrix was populated with data from the transcripts and verbatim quotes, the matrix was studied to generate themes and make connections within and between participants and categories.

Quantitative analysis was also carried out where possible. For example, observing the number of participants able to give a correct definition of "systems thinking", how often a particular area of chemistry was noted as lending itself particularly well to systems thinking and the Likert-style questions from the third section of the interview. The results were then analysed by subgroup to see if there were any correlations between the demographic information of the participant and the responses that they gave. For example, the Likert-style questions were analysed as a whole and then by area of expertise and number of years' experience teaching.

Results and discussion

Half of the instructors were able to offer a coherent definition including the main themes/characteristics of systems thinking, whilst the other half were not aware of what systems thinking was, despite two of them having heard the term previously. Once the participants had been provided with a standard definition of systems thinking and shown an example of how it could be applied within the chemistry curriculum, their views on the matter were investigated. Overall, the instructors displayed broadly positive opinions of systems thinking, with all participants believing that incorporating systems thinking into the undergraduate chemistry curriculum (at least to some extent) would be beneficial. Participant responses were coded, which gave rise to the formation of six categories.

Student learning

Participants claimed that the implementation of systems thinking into the chemistry curriculum would have advantages in terms of student learning. These include supporting revision, an increase in student understanding, increase in interest/engagement, and perspective and forethought.

These benefits were generally considered to be because of the formation of links between course content, relation to real-world applications, and the facilitation of incorporating additional considerations into planning processes in the laboratory. These proposed benefits have been demonstrated in other fields (Richmond, 1993; Jacobson, 2001; Mathews and Jones, 2008)



and so this serves as a positive indication that such advantages are transferrable within chemistry education.

Interdisciplinary nature

Instructors also commented on the facilitation of interdisciplinary teaching and learning due to systems thinking implementation. This was mentioned regarding allowing students to see the relevance of the material that they are learning in terms of other areas of the programme, 'real-world applications', and other subjects. Eleven out of the fourteen participants commented on this interdisciplinarity as a feature of systems thinking and claimed that this was one of the major advantages of using such techniques in education. Instructors argued that this is a useful way for students to be thinking and that this can contribute to the development of further skills that may not be fostered when thinking purely from the perspective of one discipline. Communication skills and the ability to work with individuals and teams from different fields were emphasised by participants as important advantages resulting from this interdisciplinary nature of systems thinking and it was suggested that this will allow for greater and more effective progress to be made on interdisciplinary projects such those required to address the UN SDGs.

The impacts of systems thinking implementation on interdisciplinary learning and teaching have been investigated. Research suggests that systems thinking methods do in fact aid students' ability to see the connection between chemistry and other disciplines (Flynn *et al.*, 2019). Such methods are also believed to assist instructors in teaching in a more interdisciplinary fashion (Sabelli, 2006; Mathews and Jones, 2008).

As part of the interview, the participants were asked if they thought that systems thinking should be incorporated into teaching other subjects at the degree level and, if so, to provide examples. A wide range of subjects were mentioned including archaeology, English, medicine, music, and sciences. Eight out of the fourteen participants said that systems thinking should be incorporated into all physical/natural sciences and five participants believed that systems thinking should be incorporated into all subjects at the degree level. If this was to occur, this could further aid in interdisciplinary learning for all students and allow for interdisciplinary projects to occur more readily and effectively.

Benefits outside of the degree

The proposed advantages of teaching using systems thinking techniques were not limited to the degree programme. Participants also mentioned that learning through systems thinking methods may increase the employability of the students and further enable them to be a benefit to society. As students will be encouraged to consider a variety of factors in any planning process and will be learning about what reactions and processes are more viable due to features such as economics or safety concerns, instructors mentioned that this may aid in their employability skills. Also, as systems thinking incorporates information from other disciplines, one instructor suggested that this may expose students to less mainstream, but

equally viable, career paths that they may not have previously considered such as policy making or business and so may enhance employability prospects in these areas too.

Additionally, when students are encouraged to think about the consequences of the course material they are learning, this may result in their behaviour being more responsible and conscientious. It was suggested that if students are taught about the negative impacts of certain processes, this may inspire them to improve their behaviour as well as working to find further enhancements and so benefit society as a whole. These changes to student mindset and behaviour are necessary for challenges such as the UN SDGs to be accomplished. This has also been suggested in previous research into the impacts of systems thinking in chemistry education (Holme, 2019; Hutchison, 2019; Mahaffy *et al.*, 2019a; 2019b; 2019c).

Suitability

Despite the aforementioned benefits, there was disagreement about the level of suitability of systems thinking within chemistry education. When asked if instructors believed that systems thinking should be incorporated into teaching chemistry at the undergraduate level, all participants agreed to some extent. However, half of the participants stated that it may not be appropriate in all areas of chemistry, with some areas being more suited than others. The main reason for staff resistance to systems thinking implementation was their claim that what they currently teach is "too fragmented", though, these staff did say that if they were teaching what they believe to be a more suitable topic, they would be willing to implement some systems thinking techniques in their teaching.

Within the second section of the interview, all participants were asked "are there any parts of the chemistry curriculum you think would lend themselves particularly well to systems thinking?". A variety of answers were provided here, however, the most common responses were green chemistry, biochemistry, and "most". Green chemistry and biochemistry also had the highest number of participants able to give a definition of systems thinking and a very high percentage of participants (80% of biochemistry participants and all green chemistry participants) claimed that they currently incorporate systems thinking in their teaching to some degree. This is noteworthy as, currently, most research into the incorporation of systems thinking into chemistry education has focused on green chemistry applications with little mention of implications for other areas of chemistry (Hurst, 2020).

Whilst some participants believed that systems thinking is inappropriate for some areas of chemistry, three participants argued that systems thinking is actually "inherent in science" and that you cannot teach science properly without it. They reasoned that chemistry is all interlinked and so to be able to teach it effectively, systems thinking techniques must be used, even if this is not explicitly expressed to students.

Student workload

There was also disagreement with regards to the effects of systems thinking on student workload. Five participants stated



that, as systems thinking involves the inclusion of additional considerations and a reduction in the distinction between separate topics, this may lead some students to become overwhelmed/confused. Additionally, the participants explained that students already become concerned about what is examinable content within the course, and this may add to such worries.

On the other hand, five participants argued that systems thinking would decrease the workload of the students. If the course content is interlinked and concepts and ideas are continually revisited throughout the course, the instructors argued that this would alleviate some of the workload as students are not learning new information, rather, they are relating existing knowledge to new contexts and developing their skills. Furthermore, these participants also mentioned that excess work in the laboratory may be reduced as less time will be wasted on reactions and processes that are not viable as students will be considering broader aspects at earlier stages in a development process.

Implementation

Finally, challenges regarding the process of implementing systems thinking were raised. The main limitation of implementing systems thinking was claimed to be the time/space available in the curriculum. The instructors explained that there is no space to add any more information or learning into the curriculum without removing something else and that a cost-benefit analysis must take place before doing so. In addition, participants suggested that they would not have the time to plan the necessary changes to allow for the implementation. Despite these challenges, 79% of participants claimed that they already incorporate at least some aspects of systems thinking in their teaching, Fig. 4 shows the subgroup analysis of this statistic in terms of area of expertise while Fig. 5 shows subgroup analysis by number of years of teaching experience.

Before complete and widespread implementation can take place, five participants expressed that they would appreciate further training. They requested additional guidance on exactly

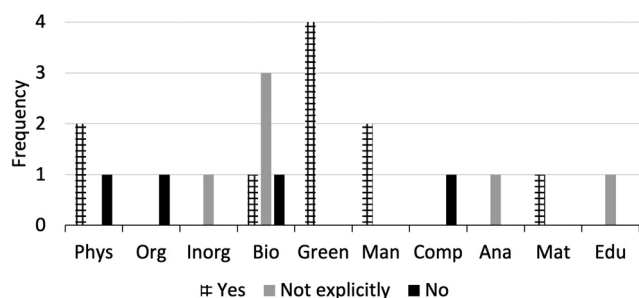


Fig. 4 Column chart displaying the frequency of participants who claim to incorporate systems thinking in their teaching, separated into their area of expertise. Phys = physical chemistry; Org = organic chemistry; Inorg = inorganic chemistry; Bio = biochemistry; Green = green chemistry; Man = management; Comp = computational; Ana = analytical; Mat = materials; Edu = educational. Those under the category 'not explicitly' do incorporate some aspects of systems thinking in their teaching but not to the full extent or without making it clear what they are doing to their students.

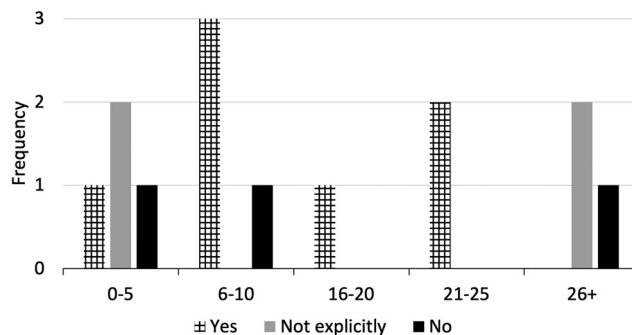


Fig. 5 Column chart displaying the frequency of participants who claim to incorporate systems thinking in their teaching, divided into groups dependent on the number of years of teaching experience they have obtained. Those under the category 'not explicitly' do incorporate some aspects of systems thinking in their teaching but not to the full extent or without making it clear what they are doing to their students.

what systems thinking entails and specific training on how to best incorporate it into their teaching. All but two participants said they would be interested in learning how to implement systems thinking in their teaching.

Quantitative analysis

The third, and final, section of the interview consisted of Likert-style questions regarding the use of systems thinking in chemistry education. These are displayed in Table 2. The participants were asked to rate their responses between 1–5 (strongly disagree to strongly agree) and provide reasons for their answers. Fig. 6 displays the responses collected.

Statement 1

No participants strongly agreed to this statement and 36% of participants either disagreed or strongly disagreed with this statement, suggesting that faculty participants believe that it is accessible for systems thinking to be incorporated into chemistry education.

Generally, it was found that instructors who had less experience of teaching were more prone to suggest that it may not be challenging to incorporate systems thinking into chemistry education.

Of those who agreed with this statement, a variety of justifications were provided. Participants explained that, although implementing systems thinking could be challenging, it would be no more challenging than any other change to the curriculum as any new implementation requires time, effort, and acceptance from other staff members. Other issues raised in response to this statement included lack of space in the curriculum, "fight back" from other instructors and that systems thinking may not be appropriate for all areas of chemistry. Similar answers were also provided by those who responded neutrally to this statement. Instructors who disagreed with this statement also understood that any change to the curriculum would have challenges, however, they held the opinion that systems thinking may be less difficult to incorporate into a curriculum as it provides a framework and guiding principles



Table 2 Likert-style questions provided to the participants

Statement 1	It could be challenging to incorporate systems thinking into chemistry education.
Statement 2	Incorporating systems thinking into chemistry education may help develop a wider range of skills for students.
Statement 3	Students' understanding of chemistry could be enhanced if interconnections were made between topics and systems thinking was implemented.
Statement 4	Systems thinking could allow students to learn in a more interdisciplinary fashion both within chemistry itself and between chemistry and other subjects.
Statement 5	I would be comfortable implementing systems thinking approaches into my teaching.

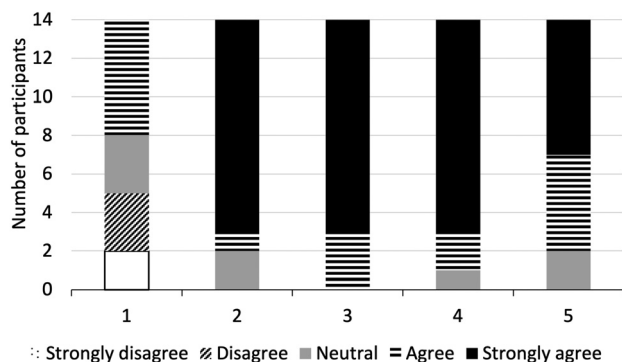


Fig. 6 Stacked column chart displaying participant responses to the Likert-style questions. The numbers on the x-axis represent statement 1, statement 2 etc.

for the staff to work with. Those who strongly disagreed stated that “any of the academics on the degree shouldn’t have difficulty connecting together different areas and teaching students [like] that” and that chemistry is very well suited to systems thinking principles and so it should not be challenging to implement such techniques into the chemistry curriculum.

Statement 2

No participants disagreed to any extent that incorporating systems thinking into chemistry education may develop a wider range of skills for students, with 79% of participants answering, “strongly agree”.

When participants were asked to provide specific examples of such skills a range of responses were given, including those mentioned in previous sections. However, independent learning, literature skills, multitasking, and advocacy were also mentioned by the instructors as proficiencies that students could gain/develop as a result of implementing systems thinking into the chemistry curriculum. One participant who answered neutrally to this statement reasoned that the incorporation of systems thinking into chemistry education has the potential to improve such skills, but it depends on the way in which it is implemented. In contrast, another instructor argued that this implementation would not develop more skills, rather, the benefit would purely be the integration of the students’ knowledge.

Statement 3

All participants either agreed or strongly agreed that students’ understanding of chemistry could be enhanced if interconnections were made between topics and systems thinking was

implemented. Instructors’ perceptions of the impact of systems thinking on student understanding have been discussed above.

Statement 4

No participants disagreed to any extent that systems thinking could allow students to learn in a more interdisciplinary fashion both within and between chemistry and other subjects. The responses provided by those who agreed or strongly disagreed with this statement were included in the coded information in the previous section.

Statement 5

No participants disagreed to any extent that they would be comfortable implementing systems thinking in their teaching. The instructors showed enthusiasm towards the prospect of teaching using systems thinking methods, with multiple participants claiming that they have used similar techniques previously with success, or that they would be willing to adapt their teaching to incorporate systems thinking to a greater extent. The only caveats mentioned were that they must be teaching what they believe to be an appropriate topic and that further training would be required as some participants deemed their current level of understanding insufficient to implement systems thinking effectively.

Conclusions

The results of the interviews, undertaken by participants from a variety of areas of chemistry, demonstrated broadly positive perceptions of the integration of systems thinking into the undergraduate chemistry curriculum. This is in keeping with the prior work conducted into the opinions of instructors of younger students who also expressed positive opinions of systems thinking at their level of education. Participants noted a wide range of benefits that this implementation may demonstrate both within and beyond the course, with the majority of the instructors being enthusiastic about the prospect. One of the major benefits proposed by many of the participants was the ability of systems thinking to facilitate interdisciplinary working and thinking. Further examples of anticipated benefits include contextualisation of information, increased employability prospects and enhanced understanding of course content. This enthusiasm and recognition of interdisciplinarity shows great promise for the prospect of widespread implementation within chemistry and for it to be used in the process of training students in such a way that they are equipped to address global challenges such as the UN SDGs. However, for systems thinking to reach its full potential, we believe that



engagement will also be required from students and so research into the opinions of students may be beneficial, together with collaboratively working with students as partners for the co-creation of curricula.

Conflicts of interest

There are no conflicts to declare.

Appendix

Personal

- In which department are you a member of staff?

Which lecture courses have you taught at the undergraduate level?

- Experience teaching (years)

How many years have you been teaching at the undergraduate level?

- Title

What is your professional title?

Systems Thinking

- (1) Can you describe/give a definition of systems thinking?

Read literature definition of systems thinking and display polystyrene SOCME.

- (2) What is your opinion of systems thinking?

(3) Do you think systems thinking approaches should be incorporated into teaching chemistry at the undergraduate degree level?

• *Are there any parts of the chemistry curriculum you think lend themselves particularly well to systems thinking?*

- *What do you think students could gain from this?*

• *(if more appropriate) What are your reasons for having the opinion that systems thinking should not be incorporated into chemistry education?*

- (4) Do you incorporate systems thinking in your teaching?

- *How have you done this?*

- *How do you think this affects your students' learning?*

(5) Do you think systems thinking approaches should be incorporated into teaching other subjects at the degree level? If so, what subjects?

(6) Would you be interested in learning how to implement systems thinking in your teaching?

Please rate the following statements from 1–5 (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree) and explain your reasoning.

(1) It could be challenging to incorporate systems thinking into chemistry education.

(2) Incorporating systems thinking into chemistry education may help develop a wider range of skills for students.

(3) Students' understanding of chemistry could be enhanced if interconnections were made between topics and systems thinking was implemented.

(4) Systems thinking could allow students to learn in a more interdisciplinary fashion both within chemistry itself and between chemistry and other subjects.

(5) I would be comfortable implementing systems thinking approaches into my teaching.

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