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# Development of Systems Thinking in a Large First-Year Chemistry Course Using a Group Activity on Detergents

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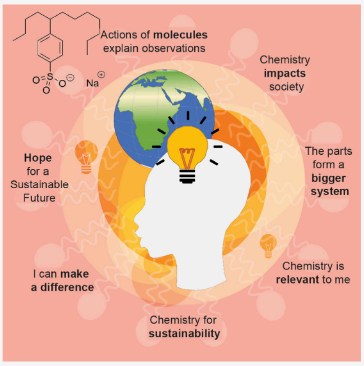

**ABSTRACT:** Systems Thinking is needed to address global sustainability challenges, yet opportunities to develop this skill set are not routinely included in chemistry curricula. Recurriculation is often a lengthy process, with many barriers slowing efforts to introduce Systems Thinking into chemistry education. Little is known concerning what systems thinking skills can be developed in a stand-alone intervention in a large-scale first-year chemistry course or if such an exercise would be valuable. We investigated student artifacts produced during a group activity on the chemistry and impacts of a surfactant commonly used in laundry detergent for evidence of engagement with Systems Thinking skills and a sustainable-action perspective. An adaptation of a virtual activity described elsewhere was introduced in a second-semester, first-year general chemistry course, coinciding with the introduction to organic chemistry. We used the characteristics of Systems Thinking from the ChEMIST table to explore students' Systems-Oriented Concept Maps (SOCMEs) and reflections. Students displayed analytical, bridging, and holistic systems thinking skills, especially identifying the parts of a system and viewing it as a whole, organizing the relationships among these parts, identifying relevant system boundaries, and considering the role of humans. However, there was little evidence of engagement with the dynamic nature of systems. Students valued learning the molecular-level chemistry of surfactants, as the context-based approach highlighted the relevance of chemistry in their lives. They endorsed the role of chemistry in sustainability and were motivated to make a difference. The activity conformed to Talanquer's chemical systems thinking framework and met the primary goal of introducing Systems Thinking in Chemistry Education, to orient Chemistry for sustainability.

**KEYWORDS:** *First-Year Undergraduate, Organic Chemistry, Sustainability, Chemistry Education Research*

Systems Thinking (ST) is a cognitive approach to analyzing and interpreting complex systems.[1−3] This approach is needed to describe and understand the system to the point that it becomes possible to predict its future behavior and influence the system for a desired change. It is therefore not surprising that Systems Thinking has been identified as a key competency to be intentionally developed in Education for Sustainable Development.[4,5] The discipline of Chemistry is essential to address sustainability challenges as it provides the molecular basis for sustainability.[6] Yet, the development of Systems Thinking skills has not generally been incorporated into the tertiary chemistry curriculum. This gap inspired thought leaders in the discipline to initiate the Systems Thinking in Chemistry Education (STICE) projects.[7,8] The broader goals of the STICE agenda, as expressed by the second STICE project, were to

1. Orient Chemistry for sustainability: In particular, the aim was to foreground the role of chemistry in various sustainability issues, thereby reaching chemistry and nonchemistry majors who represent future professionals who may use chemistry directly or might partner with chemists to work toward sustainability.
2. Develop Systems Thinking capacity through Chemistry Education: This would equip chemists to think beyond the immediate applications and, by considering long-term implications, to design more sustainable products and processes to serve the same purpose.

Several challenges to introducing STICE have been identified,[9−11] which include the lack of time for implementation on top of an already packed curriculum and the time and effort needed for total curriculum reform. In addition, little is known of the extent to which Systems Thinking can be cultivated through a single intervention of limited scope in a large enrollment general chemistry class. To circumvent the curriculum barrier, we dedicated 4 h of laboratory time to a Systems Thinking group assignment on laundry detergents without changing the curriculum associated with the theory course. This intervention was implemented virtually during the pandemic. As described in a prior publication, this contribution focused on designing an assessment rubric for grading student

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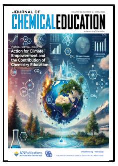

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SOCME submissions based on the Structure of Observed Learning Outcomes (SOLO) taxonomy.[12,13] The findings highlighted the challenges faced by teaching assistants in consistent grading when their Systems Thinking skills were underdeveloped.[13]

In this study, we implemented a face-to-face activity in a large general chemistry II course ($N = 1039$). We explored the extent to which the intervention met the requirements for Systems Thinking in chemistry as proposed by Talanquer[2] and elicited Systems Thinking skills deemed essential for STICE.[14]

## ■ LITERATURE REVIEW

In their review, Rodrigues et al. identified four broad categories of frameworks used to situate and guide Chemistry Education Research: constructivist, hermeneutic, critical theory, and organizational.[15] They categorized Systems Thinking among the frameworks that organize chemistry knowledge alongside chemical thinking, mechanistic reasoning, the chemistry triplet, and three-dimensional learning. In conceptualizing what Systems Thinking could look like in chemistry education, Talanquer proposed that it involves the "integration of a mechanistic-reasoning approach, a context-based focus, and a sustainable-action perspective in the development and application of chemical knowledge, practices, and ways of thinking".[2] An earth system, with environmental and human subsystems, influenced by a chemical or chemical process that contributes to global sustainability challenges, would form a suitable study to develop systems thinking in Chemistry. York and Orgill reviewed the conceptualization of Systems Thinking in multiple disciplines to provide an operational definition for the Chemistry education context. They proposed the "Characteristics Essential for Designing or Modifying Instruction for a Systems Thinking" approach, presented in the ChEMIST table, to guide the design of teaching interventions for developing students' Systems Thinking skills.[14] In this table (abbreviated in Table 1), they distilled five characteristics for Systems Thinking in Chemistry. They described how each could be manifested when looking analytically at parts of the system and holistically when considering the system as a whole.

Table 1. Characteristics of Systems Thinking from the ChEMIST Table[a]

| A Systems Thinker in Chemistry Education Should: |
|---|
| **I.** Recognize a system as a whole, not just as a collection of parts (Ch1) |
| **II.** Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviors (Ch2) |
| **III.** Identify variables that cause system behaviors, including unique system-level emergent behaviors (Ch3) |
| **IV.** Examine how system behaviors change over time (Ch4) |
| **V.** Identify interactions between a system and its environment, including the human components of the environment (Ch5) |

[a] Each characteristic is represented by skills ranging from analytical/elaborative to holistic.

Introducing STICE in multiple settings provides an opportunity for students to develop, use and transfer their systems thinking knowledge and skills to everyday situations.[16] Students, particularly nonchemistry majors, are more motivated to learn a discipline when they recognize its relevance to modern society.[9,17−19] In addition, since the discipline of chemistry is composed of systems at many levels, it would be better understood via a systems approach rather than via a linear-causal or additive approach.[20−22] It is also valuable for inviting interdisciplinary student interest to foster collaboration and perspective sharing necessary to solve complex problems.[19,23] With an increased awareness of the need for Systems Thinking, several interventions have been reported since the Journal of Chemical Education special issue on Systems Thinking, Sustainability, and Green Chemistry.[24] These interventions have integrated Systems Thinking in Chemistry courses for Science majors, Chemical Engineering[25,26] and nonscience majors.[27,28] A variety of Systems Thinking activities have been implemented that utilize problem- and project-based learning,[29] outreach programs,[30,31] card games,[32] scratch computer programs,[33] green chemistry complementary quantitative tools,[34] systemic synthesis questions[35] and drawing connection circles.[36] Furthermore, mapping tools such as systemigrams, concept maps, and System Oriented Concept Mapping Extensions (SOCMEs) have received growing attention as they engage students in Systems Thinking.[13,37,38] Recently implemented ST activities, presented in Table 2 highlight that system mapping can be used to teach chemistry meaningfully. Student engagement with system maps allows them to recognize chemistry's relevance while appreciating learning about its connection to socio-scientific issues and sustainability.

Judgments of students' development of systems thinking in these studies were generally based on students' ability to adopt a more holistic perspective on how chemistry is connected to broader contexts. To address the lack of research on what systems thinking skills students can readily demonstrate and what skills need more explicit scaffolding, Szozda et al. explored the baseline Systems Thinking skills of 18 undergraduate student volunteers as they constructed system maps on a topic related to climate change.[37] Using a detailed rubric derived from the ChEMIST table, they analyzed 11 out of 20 Systems Thinking skills. They excluded 9 skills from their analysis based on the intervention instructions, the terminology used, the overlap between skills, or the challenge of assessing a particular skill. They reported that students demonstrated all 11 skills, but most demonstrated skills associated with Characteristics (Ch) 1 and 2, and more so at the analytical level than at the holistic level. Specific skills that require further development were connecting macroscopic concepts with molecular-level phenomena, depicting causal and circular relationships within systems and describing human impacts on the system. Additionally, skills associated with dynamic behaviors are lacking overall, suggesting that students might not have sufficient prior knowledge to deal with complex dynamic systems in chemistry.[37] Developing a more holistic understanding of these complex dynamic interactions can be encouraged when students expand the boundaries of a SOCME from the core chemistry to relevant subsystems.[41]

There are indications that systems mapping activities can foster the development of ST skills. However, these studies involved small groups of participants (Table 2). There is limited evidence of what can be achieved through a single intervention implemented at scale. To address this gap in research, our study of a single, large-scale activity involving system mapping is guided by the following research questions:

RQ1: Prompted by the assignment, what Systems Thinking skills did students display or reflect on in their artifacts?

RQ2: To what extent does the activity elicit a display of the core Systems Thinking in chemistry education components[2] of mechanistic reasoning, a context-based focus, and a sustainable action perspective?

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Table 2. Recent System Mapping Activities Implemented in Chemistry Education

| Study | Participants and Context | Systems Thinking Activity and Topic | Assessment for grading/analysis | Evaluation for Systems Thinking |
|---|---|---|---|---|
| Ridley et al., 2024[39] | 35 undergraduate students | Design and redesign of a biorefinery after interacting with SOCME diagrams in an online learning platform | Quiz questions as part of the biorefinery interactive experience | Student feedback on their use of ST skills to look beyond the laboratory scale and to consider a system holistically |
| Delaney et al., 2024[40] | 39 secondary school teachers | Fill in a "systems" scaffold guided by prompting questions to create collaborative SOCMEs on lithium for batteries | Frequency of phrases/expressions in system maps | ST capacity based on the ability to make connections, explain impacts across systems, and visualize the broader context of chemical systems |
| Szozda et al., 2023[37] and 2024[19] | Graduate and undergraduate students (18 and 24 participants) | Create an individual system map on climate change, engage with an interactive tool, expand their original map, and then create a new combined map in groups | Modified scoring rubric based on ChEMIST table to assess the structure of system maps | ST skills reflected in system maps and explanations, individual and group experiences and perspectives |
| Reynders et al., 2023[13] | 18 undergraduate students | Concept mapping and its application to an extension of partial SOCMEs on surfactants | Rubric based on SOLO taxonomy to assess ST skills evident in SOCMEs. | ST skills demonstrated on SOCMEs, such as the ability to add and organize concepts and connections within and between subsystems and the ability to make predictions |
| Bruce, 2023[41] | 8 undergraduate 4th year chemistry students | Creation of an individual SOCME of a reaction that includes a periodic table element. | Rubric for SOCME poster and video presentation | Ability to apply systems, life cycle, and circularity thinking, connect chemistry to wider impacts, and communicate science |
| Schultz et al., 2022 Eaton et al., 2019[23] | High school students, 5 science teachers, and 65 out-of-field science teachers | Creation of individual system maps for chemical systems and evaluation of SDG-related impacts of system elements | Summative assessment of an essay and grading of students' system maps for the richness of connections and justified links to SDGs | Ability to view chemical processes as systems, identification of components, relationships, boundaries, and impacts of system elements on sustainability |
| Holme, 2020[43] | 10 undergraduate honors students | Instructor-led building of collaborative SOCMEs on the life cycle of the drug cytarabine | No assessment reported | Ability to visualize the varied and complex connections between key science ideas and society |

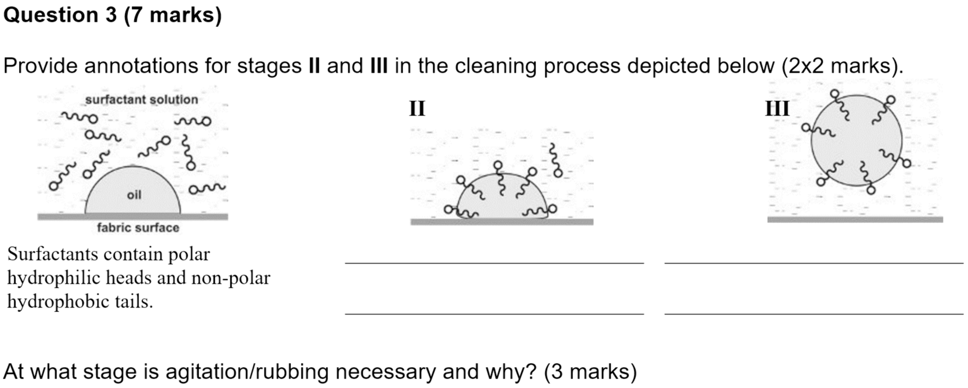
We used the characteristics of Systems Thinking in chemistry education (STICE) proposed by York and Orgill[14] and the core components of STICE as proposed by Talanquer[2] as lenses to answer research questions 1 and 2, respectively.

## ■ THE CONTEXT

This study was conducted at a large research- and teaching-intensive university in South Africa. The intervention was implemented during the introductory organic chemistry component at the end of a second-semester general chemistry course that served science majors, of whom only 5% would major in Chemistry. Two of the six laboratory sessions used to illustrate the theory taught in class were dedicated to this intervention (2 × 2 h). The activity was mediated by teaching assistants new to systems thinking.

The intervention centered on the systems associated with linear alkyl benzenesulfonate (LAS), the chemical commonly found in laundry detergents. This topic was relevant to the students' context because LAS is produced by SASOL, the most significant role player in South Africa's chemical industry. Foaming is an obvious problem in a water system flowing out of an informal settlement in a local municipality. Rural communities depend on river systems for fish, for laundering their clothes, and for supplying water to drink and irrigate their crops. For this study, the previously reported online activity[13] was implemented face-to-face on a much larger scale with 1039 students. Students were required to prepare for the first face-to-face session by watching three interactive videos that introduced concept mapping skills, a molecular-level explanation for why oil and water do not mix, and the chemistry and impacts of detergents on the economy, environment, and society. At the first session, they were divided into home groups, and a structured worksheet (available in the Supporting Information, SI) guided their engagement with the chemistry of LAS as a surfactant. Figure 1 shows a question prompting students to consider the molecular-level action of LAS in removing oil from fabric. After that, using a jigsaw design,[44] the three students in a home group each chose a different subsystem and were then reallocated to subsystem groups with three or four students who had chosen to explore the same subsystem. In this context, the larger system was defined as the full reach of the impacts of the manufacture and use of LAS. The three subsystems were (i) the economic subsystem, which included the economic impacts associated with the manufacture of LAS; (ii) the environmental subsystem focused on the environmental effects of the use of LAS by the consumer; and (iii) the societal subsystem focused on the impacts of the use of LAS on people. The subsystem groups rewatched a 5 to 8 min video clip extracted from their preparation video with the content directly related to their subsystem. Then, they used a guided inquiry worksheet (SI) to deepen their learning and explore the molecular-level chemistry associated with their subsystem, e.g., chemical synthesis, foaming, or phospholipid bilayer disruption. Prompting questions asked students to identify concepts that might belong to more than one subsystem. The groups then proceeded to capture their learning using concept maps. The activity description and concept mapping question are available in the SI.

Two weeks later, the groups returned for their second face-to-face session, reconvening in their original home groups. Each student came prepared with a concept map of the subsystems they represented. The group completed a fill-in question that served to revise the content of the short video clips while



**Question 3 (7 marks)**

Provide annotations for stages **II** and **III** in the cleaning process depicted below (2x2 marks).

Surfactants contain polar hydrophilic heads and non-polar hydrophobic tails.

At what stage is agitation/rubbing necessary and why? (3 marks)

**Figure 1.** Question requiring engagement with the molecular level basis for detergent action in cleaning.

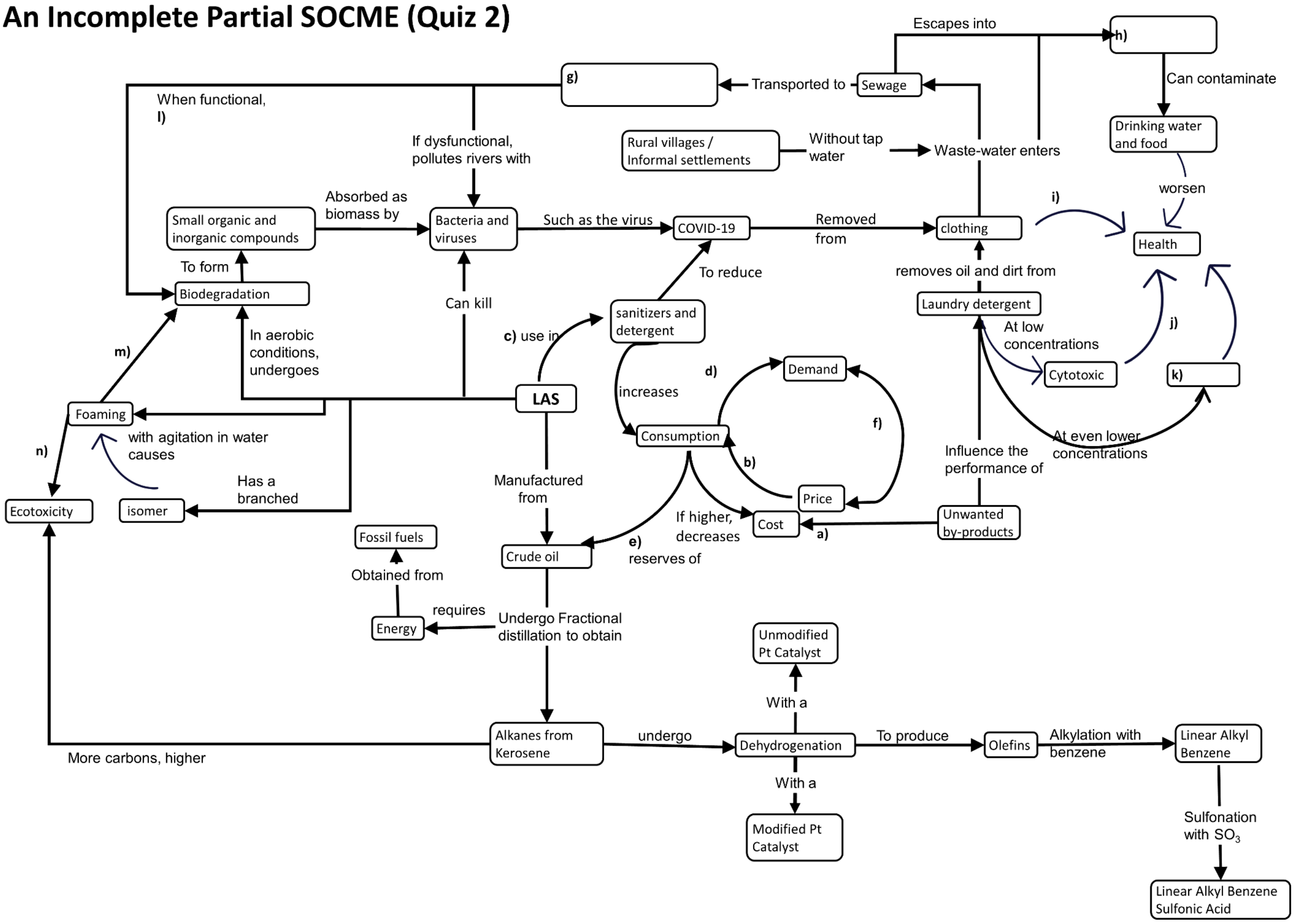


**Figure 2.** Partial SOCME provided to all Home groups for completion during session 2. This partial SOCME could serve as a starting point for constructing the groups' own SOCME.

integrating their subsystem knowledge. They were then presented with dilemmas where they had to consider the benefits and drawbacks of using LAS. These led to the main objective of the second session: the construction of Systems Oriented Concept Map Extension (SOCME) diagrams. They could extend from the worksheet (Figure 2) or build a SOCME diagram from a blank sheet of paper. To conclude the second session, an instructional video highlighted the contribution that chemistry is making to developing more sustainable surfactants and suggested actions individuals could take to reduce potential negative impacts from their use of detergents.

The submitted SOCME diagrams were graded using a simplified rubric compared with that initially reported to facilitate assessment for the large class (SI). A more recent iteration of the intervention, adapted for a more general audience, i.e., less contextualized for South Africa, can be accessed on the Sustainability and Systems Thinking in Chemistry Education (SASTICE) Web site created to make teaching materials for Systems Thinking readily available.[45]

Table 3. Summary of the Criteria Used to Analyze the Extent of Systems Thinking (ST) Displayed from the Analysis of 13 Group SOCMEs and the Associated Reflections of the Group Members

| Extent of ST | Analytical | Bridging | Holistic |
|---|---|---|---|
| Ch1 | · Mentioned 2 or more concepts on a subsystem level or reported "breaking down" or "analysing" the parts in a system. | · 2 or more granularity groups are evident in the reflections and/or on the SOCME. | · Evidence of understanding both the whole (bigger picture) and the contribution of the parts (small parts or concepts in the system) to the whole. |
| | · Added 15 or more new concepts to the SOCME. | | |
| Ch2 | · Relationships that influence subsystems are mentioned in reflections. | · Cause and effect relationships evident in reflections. | · Chain of reasoning expressed multiple relationships that could explain a cyclic behavior. |
| | · Added both linear and more complex propositions on SOCME. | · Cause and effect propositions or cyclic connections on SOCME. | · Multiple concepts linked that could describe cyclic behavior on SOCME. |
| Ch3 | · At least 3 variables per emergent behavior in reflections and/or SOCME. | · Describes how 3 or more of these variables influence behaviors in reflections and/or SOCME. | · Not assessed |
| Ch4 | · Reflected on 2 or more concepts with explicit reference to time dependence. | · Report explicitly *how* 2 or more concepts change over time. | · Prediction impacting 2 or more subsystems evident in reflections and/or SOCME. |
| Ch5 | · Named 2 or more subsystems in reflections. | · Connected 2 subsystems more than once in reflections. | · Human influence on 2 or more subsystems reported in reflections. |
| | · Boundaries drawn for 2 or more subsystems on SOCME. | · Added 2 or more relationships to link different subsystems in SOCME. | · Added human influence within 2 or more subsystems on SOCMEs |

## ■ METHODOLOGY

Two systems thinking frameworks proposed for Chemistry Education were used to analyze and interpret the data. To address RQ1, a codebook based on the Systems Thinking characteristics outlined in York and Orgill's ChEMIST table[14] was used, whereas to explore RQ2, we coded for the three components in Talanquer's outline of Chemical Systems Thinking.[2] Since thinking is covert, we used students' reflections and SOCME diagrams, submitted as part of the intervention activities, as indirect evidence to explore their demonstrated Systems Thinking and experiences.

## ■ METHODS

The study received ethical approval (NAS222/2021) from the institutional ethics committee.

### Data Collection

The intervention was integrated into a course activity for all students enrolled in the course. Groups submitted SOCME diagrams as part of their activity, and all students completed the postactivity reflection to consolidate their learning and to provide feedback. Responses to two questions were used:

1. What did you learn from practicals 5 and 6? You can mention specific knowledge, understanding, or skills and was it interesting or useful?
2. What aspects did you like or enjoy about the practicals?

Questions inviting constructive criticism revealed that students were largely satisfied with the activity. Still, some students suggested that more time could have been allocated for the activity, that they should have been given the freedom to choose their groups, and that they would have liked a laboratory experience to support their learning of the chemistry of surfactants. A few experienced negative group dynamics, and some requested increased numbers of teaching assistants. As these responses did not assist in answering our research questions, they were not used in the analysis. However, they were used to improve the subsequent rollout of the activity.

The research aims were explained to the students before the start of the intervention, and students were invited to participate by allowing us to use their individual and group submissions for analysis. They confirmed their consent at the end of the intervention.

### Sampling

Of the 990 students who completed both contact sessions of the intervention, 97% consented to using their data. Thus, we used a systematic random sampling strategy to reduce the number of data for analysis. Every sixth SOCME was selected from a random pile of SOCMEs collected after grading by tutors provided that (i) the group members had given their consent and (ii) at least two group members had completed the reflection questionnaire. If these conditions were not met, the seventh, eighth, or ninth SOCME was chosen until these conditions were satisfied while the original sequence was kept for the subsequent selection. The 34 chosen SOCMEs represented 105 students, of whom 84 completed and consented to using their self-reflections. These students were a representative sample of the population in terms of their study programs and their SOCME grades. Student data was anonymized in the selected sample, and SOCMEs with their associated reflections were given a group number for cross-comparison. These groups were used as the units of analysis.

### Analysis

Data collected from SOCMEs and reflections were analyzed with well-established qualitative research methods, drawing on Cresswell and Poth's data analysis spiral.[46] Coding software (Atlas.ti) was used for coding and organizing the codes into meaningful units and central themes.[47] The codebook, developed from a pilot study[48] evolved during the inductive coding of the 84 reflections. The resulting codes were refined and categorized into systems thinking characteristics and skills according to the ChEMIST table[14] and it is application reported by Szozda et al.[37] To answer RQ1, these codes for analyzing the reflections were adjusted for the analysis of the SOCMEs, allowing the extent to which systems thinking was displayed by a group to be classified as partial or clear. Criteria for clear evidence are summarized in Table 3, and criteria for partial display of the skills are given in the SI.

Two authors used the codebook and the above criteria to analyze three groups' reflections and SOCMEs until agreement was reached. The first author used the refined codebook (SI) to code the remainder of the 34 groups' reflections. Detailed analysis of the SOCMEs was demanding, and thus, a subset of 13 SOCMEs was systematically chosen by selecting every third SOCME from the sample. The mapped-out findings for the reflections of this subset compared well with the findings of the complete set of 84 coded reflections and were found to be representative (SI). Therefore, we were satisfied that the 13 SOCMEs would also adequately represent the findings of the sample.

To explore our second research question, we also coded the reflections for mechanistic reasoning, references to contextualized chemistry, and a sustainable action perspective. The categorization of these codes is detailed in the SI. We drew on inductively derived codes indicating that the students had (i) engaged in mechanistic reasoning during the activity, (ii) appreciated the relevance of chemistry, (iii) acknowledged that chemicals may have both benefits and disadvantages that must be considered together, (iv) appreciated the importance of sustainability, and (v) indicated a willingness to act more sustainably.

In reporting the findings, the student responses and data excerpts represented on the SOCMEs were kept as expressed by the students unless indicated otherwise. However, with respect to the participants who did not use routine spelling or grammar checks when crafting their responses, obvious typographical errors have been corrected, and repeating words were removed.

## ■ FINDINGS

### RQ1: Prompted by the Assignment, What Systems Thinking Skills Did Students Display/Reflect?

This section describes the analysis of the SOCME diagrams and students' reflections in the search for evidence of engagement with the skills associated with each of the five characteristics of Systems Thinking outlined in the ChEMIST table.[14] The codebook (Table 3) was used to identify demonstrations of analytical, bridging, and holistic thinking skills for each characteristic. The findings from this analysis are then summarized to present a holistic view of the extent to which the intervention elicited demonstrations of Systems Thinking skills. In answering our first research question, we considered evidence from the 13 groups for whom both SOCMEs and reflections had been coded.

**Ch1: Recognize a System as a Whole, Not Just as a Collection of Parts.** Systems Thinking characteristic 1 is the ability to identify a system's parts, examine and understand their organization, and view the system as a whole. All groups clearly demonstrated analytical skills by adding many new concepts to their SOCMEs in a logical manner (Example shown in Figure 3). In addition, students from three of the 13 groups mentioned "breaking down the parts", "analyzing ideas," or "dissecting topics" in their reflections. For example, a student from Group 18 commented: "I learned that it is important to think logically about a problem because any major problem can be broken down into much simpler, smaller steps."

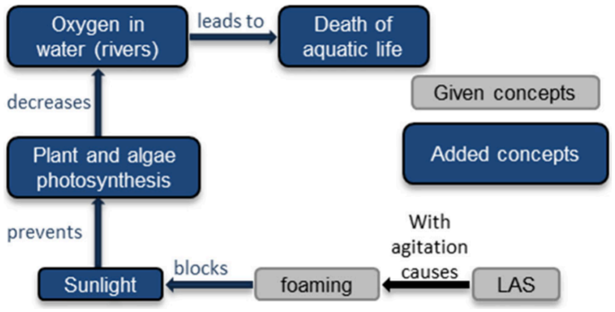


**Figure 3.** Examples of added concepts in propositions from SOCME 2 are shown in blue. Concepts that were included in the partial SOCME provided are shown in gray.

Following the lead by Szozda et al.,[37] the engagement of each group with the bridging skills of Ch1 was analyzed by looking at the different levels of granularity of the added concepts. Levels of granularity were coded from three perspectives: (i) chemistry concepts at the submicroscopic or macroscopic scales, (ii) impacts resulting directly or indirectly from chemicals (labeled primary or secondary), as well as (iii) considerations of sustainability connected to chemistry. Generally, groups demonstrated macroscopic chemistry and primary impacts on the SOCMEs but did not indicate different levels of granularity in their reflections. Instead, they mostly commented on impacts.

It was not possible to determine whether students could see the system as a unified whole from the SOCMEs alone. However, they revealed engaging in this aspect of Ch1 in their reflections, where they mentioned "learning to see the bigger picture" as a benefit of the activity or contemplated the purpose of the Systems Thinking activity as resulting in a better understanding of the risks and benefits of chemistry in moving toward global sustainability. Two groups provided clear evidence of holistic thinking skills, for example: "I really enjoyed the experience of understanding how the subsystems were related and had to be thought of as one system rather than them being isolated." (Group 2) Reflections from students in eight groups were less eloquent and simply mentioned the "bigger picture" or "parts of a *system*" coded as a partial indication of holistic thinking skills.

**Ch2: Examine the Relationships between the Parts of a System and How Those Interconnections Lead to Cyclic System Behaviors.** Whereas Ch1 includes the structural organization of the components to form the whole, Ch2 considers the relationships among the components. We considered this Systems Thinking characteristic to include all relationships and not only those contributing to cyclic behaviors. Deviating from the ChEMIST table similar to Szozda et al.,[37] we considered types of connections when coding for analytical skills and types of reasoning for evaluating bridging and holistic thinking skills. We considered bridging skills to include increasingly complex causal relationships between components and holistic thinking skills to be demonstrated by multicomponent causal reasoning, thus, using a chain of reasoning to explain potential cyclic behaviors in the system. A full discussion is provided in the SI. Out of the 13 groups, three SOCMEs showed only simple propositions indicating a partial engagement, whereas ten groups displayed a clear engagement with systems thinking skills for Ch2 by showing indirect, moderated, and circular connections (Figure 4). While the reflections did not distinguish types of relationships, they provided additional evidence that students were engaging with analytical skills for Ch2. One of the students wrote, "I learnt about the importance of concept maps in summarizing and interlinking different concepts together to form a bigger picture that is easy to understand" (Group 2).

All SOCMEs included many propositions showing relational reasoning with linking phrases such as "influences", "causes" and "effects" with some including a direction, as in "decreases", "prevents" and "blocks". This reasoning represents a bridge to more holistic thinking skills and hence is attributed as evidence of bridging skills. Reflections revealed an appreciation of the relationships without indicating potential causes of cyclic

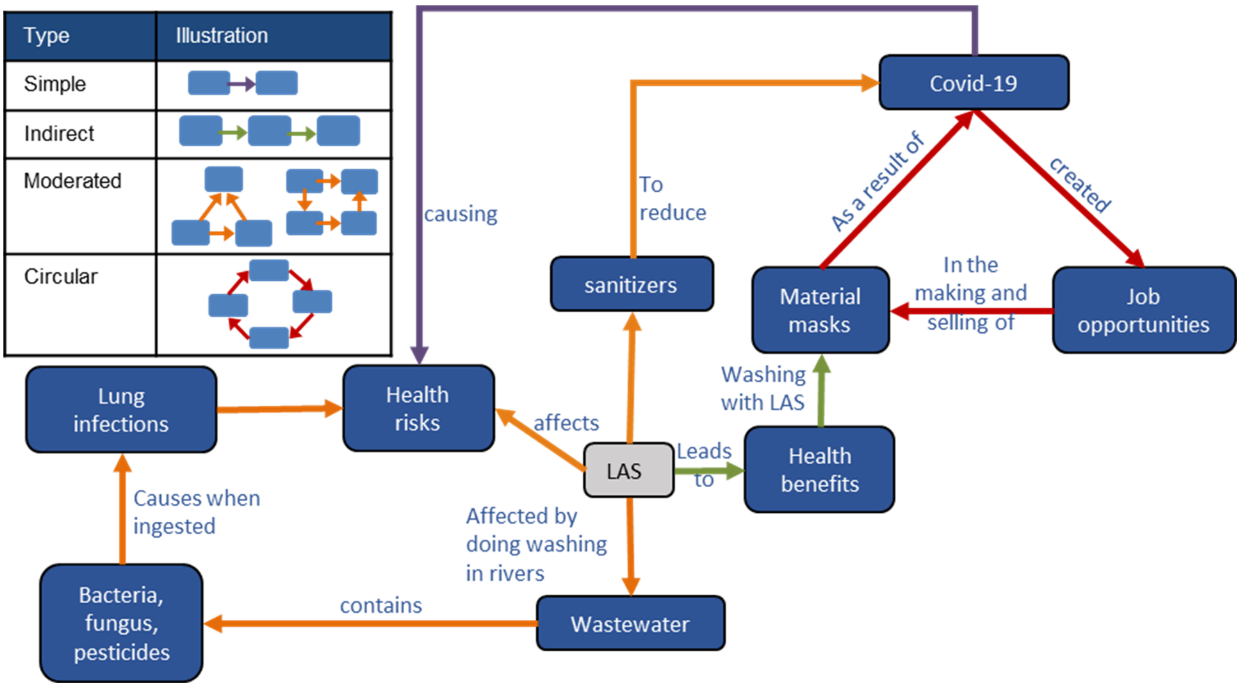


**Figure 4.** Simple, indirect, moderated, and circular loop connections are demonstrated in SOCME 24 (redrawn).

behaviors, as shown in this extract "I also learnt about the effects of detergent on the environment, society, and economics, and how these different sectors also influence each other." (Group 9). Only seven groups demonstrated holistic thinking skills for Ch2 to some extent on their SOCMEs with no evidence thereof in student reflections. Group 24 provided a clear display of multicomponent causal reasoning on their SOCME (Figure 4). Given the cognitive complexity and the representational challenge of depicting multicomponent reasoning it is not surprising that this skill was less commonly displayed.[37]

**Ch3: Identify Variables That Cause System Behaviors, Including Unique System-Level Emergent Behaviors.** Micelle formation and foaming were included in the teaching as examples of emergent behaviors at the submicroscopic level in the chemistry of LAS. However, given the complexity inherent in the intervention, the terminology of emergence was not explicitly taught. Nevertheless, we were interested to see if any SOCMEs depicted multiple variables (analytical skills) contributing to an emergent property (bridging skills). We did not assess holistic thinking skills, since students did not have the vocabulary to identify or explain emergent behaviors. In our deliberations, we were clear that simply representing an emergent property on the SOCME cannot be interpreted as understanding the concept of emergence. A property or behavior that emerges from variables at one level of granularity becomes a simple concept when viewed from another level of granularity.[49] Foaming, although an emergent property, was treated by students as a simple concept at the macroscopic level of a river system and was therefore not considered to reflect Ch3 in those instances. Thus, most groups showed no evidence of engaging with the skills associated with Ch3. However, one example in SOCME 27 demonstrated reasoning about the influence of variables exports, profit, and jobs on economic growth as an emergent property. This group's clear engagement with this bridging skill is shown in Figure 5.

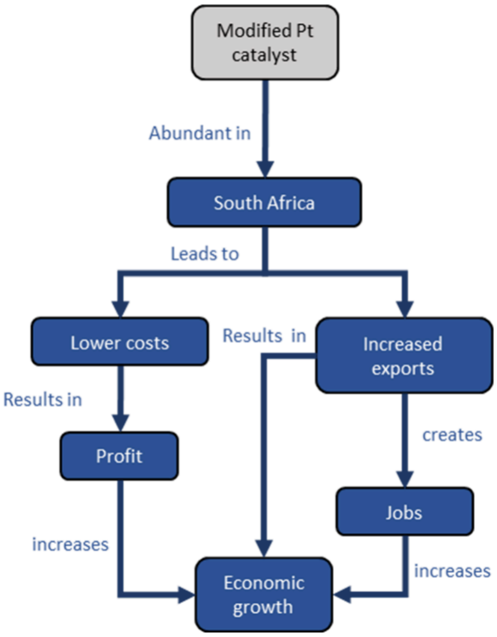


**Figure 5.** Evidence of identification of multiple variables contributing to emergent system properties, as demonstrated on SOCME 27.

**Ch4: Examine how System Behaviors Change over Time.** Dynamic systems change over time, because of changes in the components and their relationships. Observation and analysis of changes in the past behavior can lead to the identification of variables that affect the behavior of a system. Understanding the influence of these causal factors allows the system's future behavior to be predicted.[50] According to the ChEMIST table, identifying the system-level behaviors that change over time constitutes analytical skills; describing and explaining the influence of causal variables constitutes bridging skills, and using these patterns to predict future system behavior is a holistic thinking skill. Students were tasked to expand their SOCME ideas and concepts based on one of two scenarios related to the system. Thus, expansions in the SOCMEs clearly

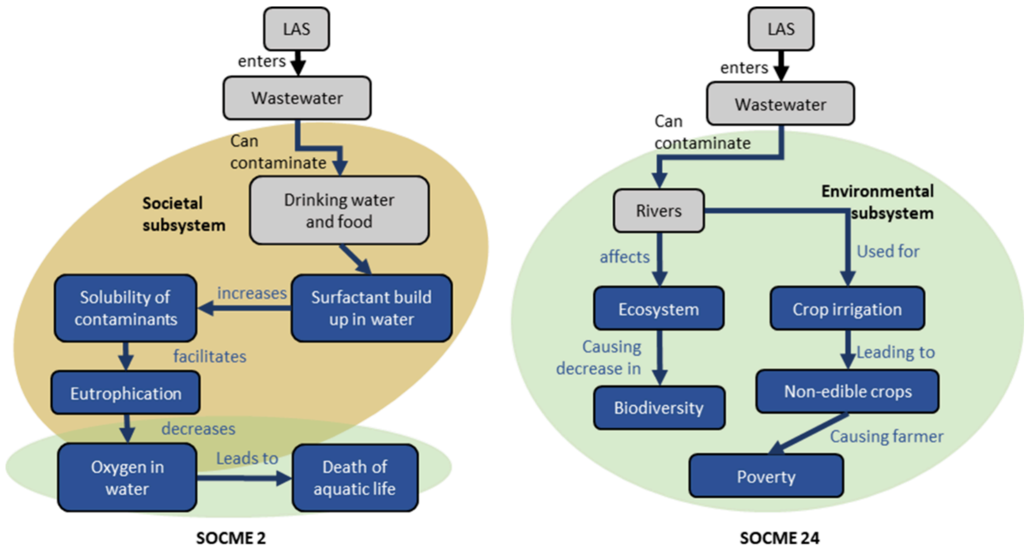


**Figure 6.** Predictions indicated on SOCME 2 and 24 within specific subsystem boundaries (redrawn)

related to one of these scenarios were interpreted as predictions and student engagement with holistic thinking skills. They could choose either to predict how $CO_2$ emitted during LAS manufacture can influence global climate patterns or how rivers with high concentrations of LAS can influence surface water sources. Beyond this task, students were not instructed to indicate variables that could change over time or how those changes would influence the system.

The SOCMEs were populated with many variables that could change over time. However, as students had not been prompted to indicate time-dependent variables or time-dependent changes and time was not mentioned explicitly, including these elements was not considered convincing evidence for Ch4. Therefore, we did not code for analytical and bridging skills in the SOCME analysis. There were no references to variables and changes over time in the reflections for any of the 13 groups.

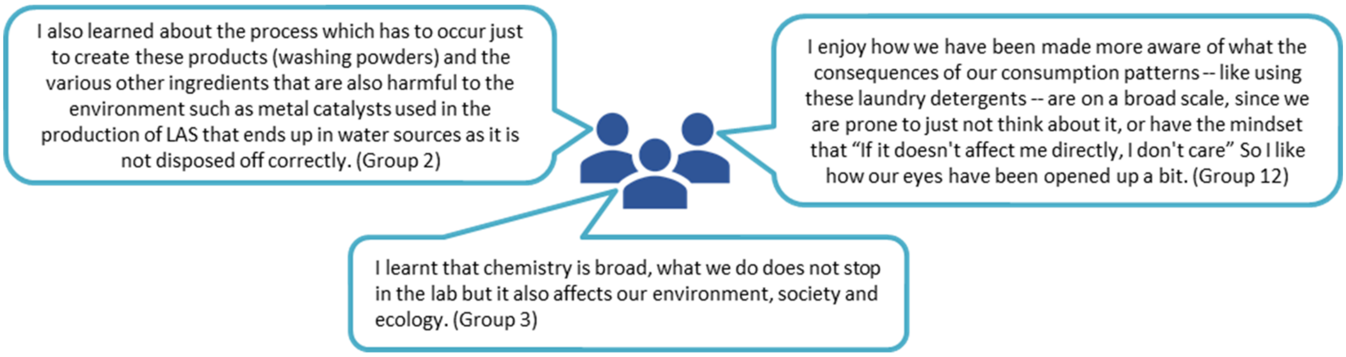
Four groups did not include expansions for either scenario in their SOCMEs. The others generally restricted their predictions to impacts on only one subsystem, which indicated a partial demonstration of holistic thinking skills within Ch4. For example, both SOCME 2 and 24 included predictions based on the effects of increased river LAS concentrations on the environmental subsystem (Figure 6). SOCME 24 also included poverty, a societal impact, but did not place this impact in the societal subsystem. When students predicted impacts on two or more subsystems on their SOCMEs, these were interpreted as a clear engagement with holistic thinking skills.

One student who contributed to SOCME 2 provided additional evidence that the intervention prompted them to make predictions. They reflected, “These practicals were able to open up my mind on how these products, although useful, can cause a lot more harm to our environment as a pollutant of our water system and consequently our marine and plant life as well as small communities”.

**Ch5: Identify Interactions between a System and Its Environment, Including the Human Components of the Environment.** In identifying a system to study, it is necessary to define the system’s boundaries by asking what relevant information will be explored. Large complex systems will likely include smaller nested components that are systems with their own boundaries at a different level of organization. These nested components are called subsystems. Defining a system’s boundaries and identifying subsystems allows one to focus on the interactions of a collection of parts within a system and how the system is influenced by or influences other systems. For this characteristic, the ChEMIST table describes analytical skills as identifying and describing appropriate system boundaries, bridging skills as a consideration of the effects of the system on other systems, and holistic thinking skills as considering the current and future influence of humans on system-level behaviors. Since our system was large, it was appropriate to explore this characteristic in terms of subsystems, delineating appropriate subsystem boundaries and considering the effects of one subsystem on another. Before constructing their SOCMEs, the home groups were tasked with adding boundaries to the given partial SOCME to delineate the economic, environmental, and societal subsystems and drawing boundaries around additional subsystem groupings. The instructions for constructing their SOCMEs were less prescriptive for drawing subsystem boundaries, but the requirement was embedded in the provided assessment rubric. Groups were simply tasked to create their own SOCME to illustrate their system knowledge for which they could use a new copy of the provided partial SOCME (Figure 2) as a starting point. The rubric prompted engagement with subsystems showing that grades would be awarded for (i) “concepts added per subsystem with subsystem boundaries”, (ii) showing clear relationships within and between subsystems, and (iii) organizing their “prediction” scenario between subsystems and creating new subsystems if necessary.

The evidence of the prevalence of thinking skills associated with this characteristic was significantly more substantial than for the previous two characteristics. Seven groups included sensible boundaries by drawing economic, environmental, and societal subsystems onto their SOCMEs, partially demonstrating analytical skills. The inclusion of poverty in the environmental subsystem (SOCME 24, Figure 6) was not considered a sensible boundary. One group added a new subsystem boundary for the industrial subsystem and, in addition to showing the three main subsystems, a clear application of analytical skills. In their reflections, students from five groups named two or three subsystems, indicating that this was part of their systems view.

The number of connections between subsystems was used to infer the extent of engagement in the bridging skills. Nine of the 13 SOCMEs demonstrated two or more relationships between



I also learned about the process which has to occur just to create these products (washing powders) and the various other ingredients that are also harmful to the environment such as metal catalysts used in the production of LAS that ends up in water sources as it is not disposed off correctly. (Group 2)

I enjoy how we have been made more aware of what the consequences of our consumption patterns -- like using these laundry detergents -- are on a broad scale, since we are prone to just not think about it, or have the mindset that "If it doesn't affect me directly, I don't care" So I like how our eyes have been opened up a bit. (Group 12)

I learnt that chemistry is broad, what we do does not stop in the lab but it also affects our environment, society and ecology. (Group 3)

**Figure 7.** Excerpts from reflections indicate human influence on various subsystems.

**Table 4. Range of Expression of the Characteristics of Systems Thinking Obtained from the Analysis of 13 Group SOCMEs and the Associated Reflections of the Group Members**

| Systems Thinking | | Analytical | | Bridging | | Holistic | |
|---|---|---|---|---|---|---|---|
| Extent of display evaluated from | | Reflections | SOCMEs | Reflections | SOCMEs | Reflections | SOCMEs |
| Ch1 System as a whole | Partial | 5 | 1 | 3 | 2 | 8 | [a] |
| | Clear | 3 | 12 | 1 | 11 | 2 | [a] |
| Ch2 Relationships | Partial | 5 | 3 | 1 | | | 2 |
| | Clear | 8 | 10 | 12 | 13 | | 5 |
| Ch3 Emergent behaviors | Partial | | 3 | | 1 | [a] | [a] |
| | Clear | | | | | [a] | [a] |
| Ch4 Behaviors over time | Partial | | [a] | | [a] | | 6 |
| | Clear | | [a] | | [a] | 1 | 3 |
| Ch5 System in its environment | Partial | 2 | | 1 | 4 | 2 | 1 |
| | Clear | 9 | 8 | | 9 | 7 | 3 |

[a] Not assessed.

pairs of subsystems. Most of these connections indicated relationships between the societal and the environmental subsystems. In their reflections, only a few students mentioned interactions between subsystems or commented on learning to analyze subsystem relationships. Holistic thinking skills were not readily shown, as only four SOCMEs included concepts relating to human influence on any subsystem. However, seven groups commented on the effects of humans on two or three subsystems in their reflections, showing clear engagement with holistic thinking skills. Three excerpts from reflections that demonstrate students' appreciation of human influence on the system are shown in Figure 7. Human influence was only presented on four of the 13 SOCME diagrams.

### Summary of Systems Thinking Characteristics Displayed

The range of expression of the characteristics of Systems thinking outlined in the ChEMIST table was mapped out in Table 4. This overview revealed that all 13 groups engaged with the first, second, and fifth characteristics to some extent, very few groups displayed systems thinking skills associated with Ch3, and most groups demonstrated engagement with Ch4, but only in predicting future system behavior as tasked. The limited engagement with characteristics 3 and 4 may be attributed to the conceptual difficulty of these characteristics and the instructional design that did not require an understanding of the concepts underlying these characteristics. These skills would need to be intentionally developed with more time. Furthermore, students need to be given the language for communicating this understanding and the tools to display this thinking.

For Systems Thinking characteristics 1, 2, and 5, most groups demonstrated thinking skills at all three levels, the analytical and holistic levels and the bridging level, where both the parts and the whole are considered together. This is encouraging given that their prior chemistry training has focused on the parts in isolation.

### RQ2: To What Extent Does the Activity Elicit a Display of the Core Systems Thinking in Chemistry Education Components of Mechanistic Reasoning, a Context-Based Focus, and a Sustainable Action Perspective?

Three codes emerged from the initial inductive coding of the reflections that were not accounted for in the ChEMIST table. These were "Sustainability matters", "Ownership" and "Chemistry is relevant" (SI Table 6). The codes resonated with two of the core components of Systems Thinking proposed by Talanquer, namely "a sustainable action perspective" and "a context-based focus", prompting engagement with our second research question to explore all three components.[2] Figure 8 summarizes the coding framework that we used to explore the display of Systems Thinking from 34 groups (84 participants) to answer our second research question.

**1. Mechanistic Reasoning.** To develop mechanistic reasoning students should learn to think about the processes that contribute to cause-and-effect interactions to build chemical rationales to support their explanations.[2] Although the reflection questions did not require or even prompt students to reproduce this learning, many reflections showed that students appreciated learning what was happening at a molecular level, and based on the guided inquiry design of the first contact session, students engaged with these processes concerning LAS. The following answers to the prompts "What did you enjoy?", and "What did you learn?" illustrate this appreciation: ". . . learning about the properties of detergents

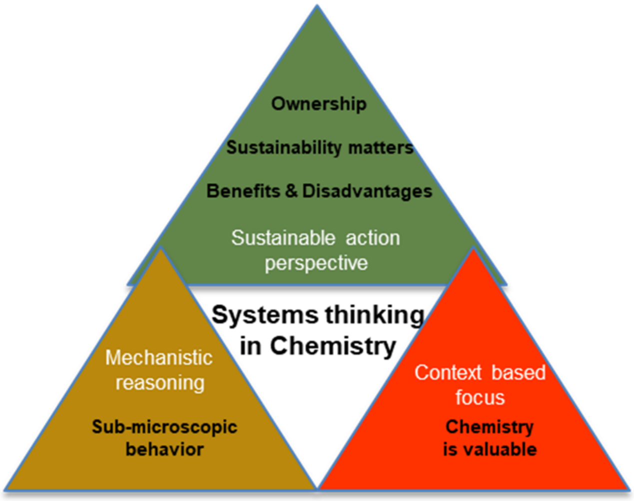
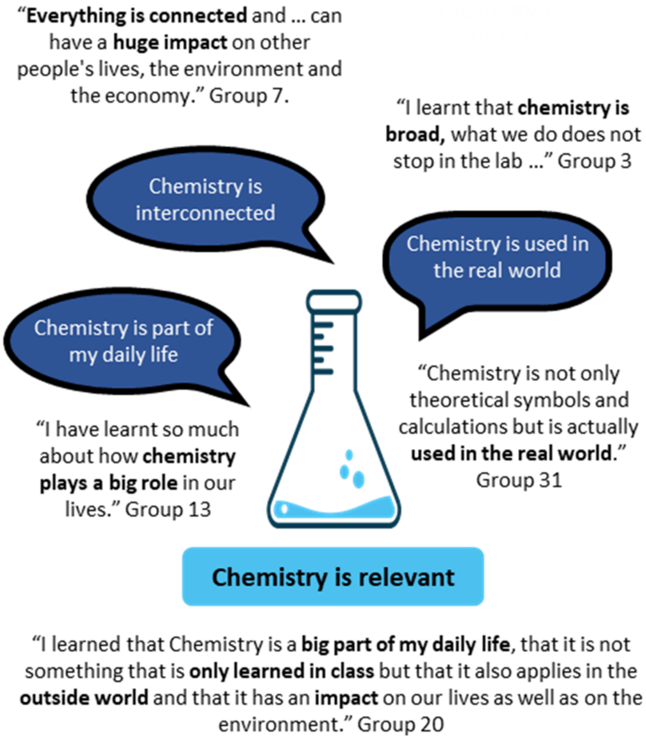


**Figure 8.** Components for deductive coding of the intervention according to Talanquer's framework for Chemical Systems Thinking.



"**Everything is connected** and ... can have a **huge impact** on other people's lives, the environment and the economy." Group 7.

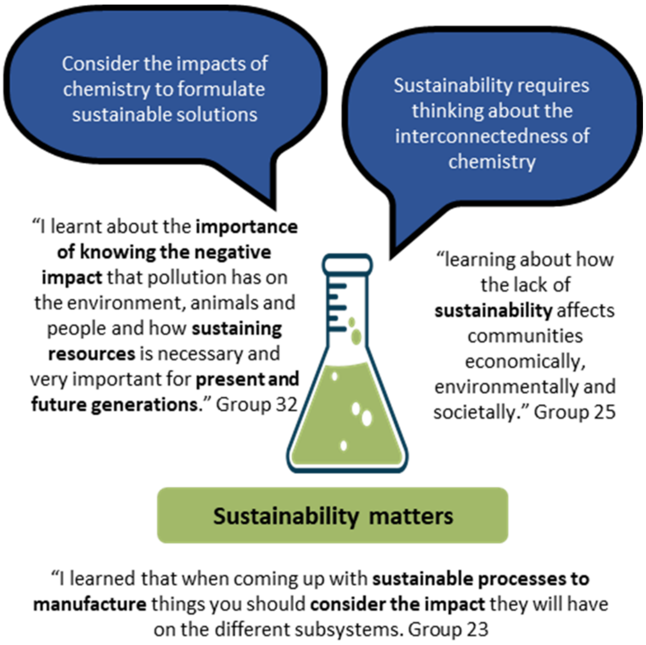
"I learnt that **chemistry is broad,** what we do does not stop in the lab ..." Group 3

"I have learnt so much about how **chemistry plays a big role** in our lives." Group 13

"Chemistry is not only theoretical symbols and calculations but is actually **used in the real world.**" Group 31

"I learned that Chemistry is a **big part of my daily life**, that it is not something that is **only learned in class** but that it also applies in the **outside world** and that it has an **impact** on our lives as well as on the environment." Group 20

**Figure 9.** Students' reflections showed a developing appreciation of chemistry and its relevance as they recognized that chemistry is part of their daily life; it is interconnected and used in the real world.



"I learnt about the **importance of knowing the negative impact** that pollution has on the environment, animals and people and how **sustaining resources** is necessary and very important for **present and future generations.**" Group 32

"learning about how the lack of **sustainability** affects communities economically, environmentally and societally." Group 25

"I learned that when coming up with **sustainable processes to manufacture** things you should **consider the impact** they will have on the different subsystems. Group 23

**Figure 10.** Students' reflections showed a developing awareness that sustainability matters and requires thinking about the impacts of chemistry for sustainability.

which play a big role when removing dirt from clothes since it explains how detergent transforms itself into different forms until it reaches a point where it can remove dirt." (Group 19); "··· found it very useful to understand how detergents work in theory and chemically" (Group 7); "I learned about LAS, how it affects the rivers and foaming related matters. . . where it is manufactured and how" (Group 5). Students from 16 of the 34 groups commented on learning the chemistry that explains the macroscopic outcomes in the synthesis or function of surfactants.

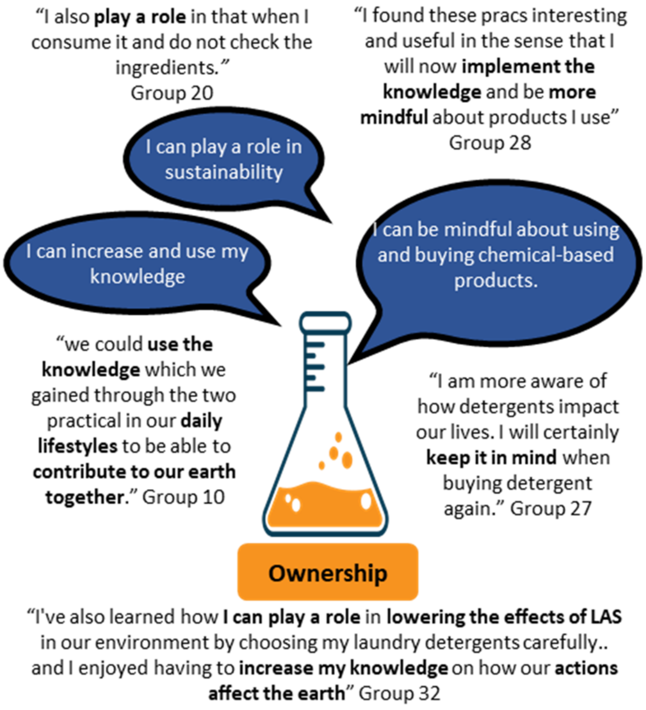
**2. Context-Based Focus.** One of the goals of the intervention design was to engage students in the relevance of chemistry in our modern society and cultivate an appreciation for chemistry. The intervention materials were made contextually relevant through examples drawn from the local chemical industry, pollution of a nearby river system, links to the recent COVID pandemic, and research into the effects on a local rural population and general human health. Analysis of students' reflections revealed that they valued learning chemistry in context. Comments from ten groups highlighted that they now realized that chemistry is applied beyond the classroom or a laboratory, that it encompasses much more than just calculations and reactions, that it impacts their everyday lives and the real world and influences many spheres of which they were previously unaware (Figure 9). The relevance of chemistry to the context was noticed.

**3. Sustainable Action Perspective.** Talanquer described a sustainable action perspective as the ability to critically analyze complex interactions between socio-environmental systems and engage in global sustainability by taking responsible action.[2] To develop such a perspective, students must recognize that sustainability matters. The code "Sustainability matters" was applied whenever students reflected that they learned that sustainability is important or is a goal to pursue. Students from 10 of the 34 groups made such comments. Their reflections revealed that they appreciated the importance of considering the impacts and interconnectedness of chemistry for sustainability (Figure 10). One student from Group 2 claimed to have "learnt more about how people can live more sustainable lives." Another student claimed to have learned "a bit about the everyday use of chemistry and the impact it has on the economy, society, and environment, as well as the sustainability of certain resources" (Group 19). The student of Group 23, who commented on sustainable manufacturing as shown in Figure 10, also stated: "I learnt that LAS has different effects on the environment, society and economy and [the need to] allow researchers to find more sustainable products."

In developing a sustainable action perspective, students need to learn that the risks of chemical activity be considered alongside the benefits of chemical products.[6,51,52] These considerations are an important reflexive application of chemistry understanding in decision-making to design more sustainable products and processes.[2] Students from six groups commented on the risks and benefits of chemistry. Examples include: "To see how LAS can be a huge benefit to society and the economy but at the same time have many disadvantages to the environment. It was interesting to weigh up all the advantages and disadvantages." (Group 28) and "I learned how our daily habits can actually impact the environment and lead to global warming. Therefore, I should try to avoid those issues." (Group 8)

The ultimate goal of educating individuals to look at the world with a sustainable-action perspective is to engage in value-driven decision-making and be motivated to take action toward global sustainability.[2] To achieve this goal, Systems Thinking needs to be developed, as assessed above, but the students in our chemistry classes also need to grow a sense of ownership or a willingness to contribute to solving problems. The code "attitude of ownership" that emerged from the data was applied when students reflected on how they would act to contribute to a more sustainable future. Students from 12 of the 34 groups gave examples of intended behavioral changes for sustainability as a result of the intervention. Some expressed an intent to change how they use laundry detergents or to use ecofriendly options to be more sustainable. Others referred to being more mindful when using chemical products in general. A student from Group 2 mentioned that "these practicals gave me reason to evaluate my own use of chemical based products and what alternatives there are for me to use to improve my life and if they would improve sustainability as a whole...". Other excerpts showing the development of an attitude of ownership are shown in Figure 11.

These findings suggest that the context-based focus and the sustainable action perspective were at the forefront of the student experience and that they valued learning about chemical processes at the molecular level, an understanding of which is necessary for mechanistic reasoning. While not all students commented on all three components of systems thinking, the intervention design included the core components and elicited references to them in the students' reflections on their learning experience.



"I also **play a role** in that when I consume it and do not check the ingredients." Group 20

"I found these pracs interesting and useful in the sense that I will now **implement the knowledge** and be **more mindful** about products I use" Group 28

"we could **use the knowledge** which we gained through the two practical in our **daily lifestyles** to be able to **contribute to our earth together**." Group 10

"I am more aware of how detergents impact our lives. I will certainly **keep it in mind** when buying detergent again." Group 27

"I've also learned how **I can play a role** in **lowering the effects of LAS** in our environment by choosing my laundry detergents carefully.. and I enjoyed having to **increase my knowledge** on how our **actions affect the earth**" Group 32

**Figure 11.** Reflection excerpts indicate a developing attitude of ownership of the problem.

## DISCUSSION

An intervention was designed to address the five characteristics of Systems Thinking for chemistry education outlined by York and Orgill and was implemented in a large (1039) first-year general chemistry course for science majors, mediated by teaching assistants new to systems thinking. In this context, we investigated how thinking skills associated with these five characteristics were elicited in student groups' SOCME diagrams and reflections on their learning experience. Our analysis provided good evidence for students' engagement with the thinking skills of characteristics 1, 2, and 5. Seeing the system as a whole requires thinking about how the parts are organized (Ch1) and related (Ch2) but also involves the delineation of the boundaries of subsystems and the relationships between related systems (Ch5). Holme commented that in a general chemistry large class setting, systems thinking was likely to focus largely on system components but demonstrated the utility of SOCMEs to prompt students to extend those connections in a small group setting.[43] This intervention centered around the use of SOCMEs in a large class setting, likely resulted in the extensive connections depicted in most of the SOCME diagrams.[34] In our study (Table 4), most groups generally included chemistry concepts on a macroscopic level and their impacts on their SOCMEs, but omitted concepts on a submicroscopic level. These represented two levels of granularity associated with bridging skills (Ch1). All groups demonstrated bridging skills by showing cause and effect propositions or cyclic connections on their SOCMEs, but only five groups demonstrated multicomponent causal reasoning, representing holistic thinking skills (Ch2). These findings match those of Szozda et al.[37] who reported that Ch1 and 2 were readily demonstrated but that few examples of microscopic concepts and no relationships at the level of multicomponent causal reasoning were included in student's systems maps. It has been noted that SOCMEs become more sophisticated when they are constructed over a longer time as students develop a better understanding of the system[42] as evidenced by the SOCMEs prepared by fourth-year students throughout their Green Chemistry course.[41] The scaffolding provided in this intervention, including a partial SOCME, a two week interval between sessions during which individual's understanding of their subsystem could mature, and guidance from teaching assistants, would have enabled our first-year students to prepare moderately sophisticated SOCMEs in only 60 min.

Despite their reductionist training,[53] most groups engaged in holistic thinking skills in addition to the more analytical skills for characteristics 1, 2, and 5. In our design, the role of human action was implicit, conforming to the "humanized" version of chemistry teaching,[51] yet was something that students reflected on explicitly (holistic thinking skills). In addition, for Ch5, there was evidence that all groups considered both parts of the system and the whole system simultaneously, here termed "bridging skills".

The characteristics associated with Ch3 (causal variables and emergence) and Ch4 (change over time) were less evident in both the SOCMEs and the reflections. These skills are associated with higher-order thinking, requiring concentration and effort.[14,54] Given the short time frame allocated for the activity, the learning objectives for these characteristics were limited to (i) explaining the underlying chemistry of particular emergent processes (micelle formation and foaming) and predicting the impact of a given scenario. Nine out of 13 groups responded to the direct prompt to predict system changes based on a given scenario representing holistic thinking skills (Ch4). However, there was no evidence of deeper engagement with dynamic thinking skills or that they would have engaged in unprompted temporal thinking. Using a wider variety of tasks Szozda et al.[37] could elicit Systems Thinking skills aligned with Ch3 and Ch4 but also found that these skills were less readily demonstrated than those associated with the other characteristics. The skills associated with Ch3 and Ch4 would need to be intentionally developed with more time as students would need to be given a vocabulary to conceptualize emergence and ways of depicting dynamic system processes.[55]

The detailed exploration of the Systems Thinking skills elicited by the intervention from the perspective of the ChEMIST table was complemented by a study of the students' experience of the intervention using Talanquer's proposed core components of Systems Thinking for Chemistry. Exploring our second research question through this framework showed that the chemical processes used to illustrate emergence at the submicroscopic level were both understood and valued. These processes, captured in worksheets and concept maps in the first session of the intervention, were not added to the group SOCME diagrams. However, students in many groups commented that they valued this learning, providing evidence that they appreciated the mechanistic reasoning approach, the first core component in Talanquer's framework. Students were not explicitly prompted to show their mechanistic thinking and their mechanistic reasoning skills were not assessed, yet their reflections showed they appreciated learning about what was happening at the molecular level, which aligns with aspects of a mechanistic reasoning approach.

The second core component, "a context-based focus", was inherent in the intervention design. This focus was assimilated by the students, as revealed during inductive coding. The code "Chemistry is relevant" emerged from students' reflections that they could see the relevance and applications of chemistry to their lives and in their world. Students in other recent studies have given similar feedback with realizing the role chemistry can play in addressing challenges and solving problems.[19,41] The third component in Talanquer's framework, "a sustainable-action perspective", is partly addressed in ChEMIST table Ch5 under the more holistic thinking skills dealing with human action on the system. However, a sustainable action perspective includes attitudes as well as skills, and this component provided an appropriate theme to accommodate emergent codes, "Sustainability matters" and "Ownership", reflecting that students valued sustainability and owned the responsibility to take sustainable actions. Wisudawati and Bark propose that teaching systems thinking using locally relevant contexts will likely promote an ownership attitude.[56] Talanquer suggested that it would be a major challenge to develop a sustainable action perspective based on data from a task that included chemistry in a sustainability context that was not explicitly developed to elicit systems thinking.[2] Our findings and other recent studies[39,41] suggest that interventions designed to promote systems thinking according to his framework can mitigate this challenge and cultivate a sustainable action perspective. In answering RQ2, we can conclude that aspects of the three core components were present in student reflections, representing an important summary of what the students valued in the learning experience. We would have missed these insights if we had restricted our study to only answering our first research question.

Whereas discussions of issues related to sustainability can leave people demoralized and defeated because the Sustainable Development Goals (SDGs) can look so unattainable when studying a system in detail, references to opportunities for personal action in the data indicate that students felt empowered through the intervention.[57,58] The groups embraced the conclusions of the intervention, reflecting hope rather than defeat, with some pointing to the potential for designing more sustainable products or processes, suggesting that incorporating sustainability considerations in a chemistry course can change the image of the discipline to being part of the solution and not only a problem. Some students recognized that their learning of Systems Thinking and their sense of responsibility to act more sustainably were transferable to other contexts, thus indicating that for them we met the goals of the STICE agenda.

## Limitations of the Study and Implications for Research and Teaching

the two data sources used for this study were necessary to explore students' engagement with Systems Thinking. Students made their engagement with systems thinking explicit by depicting the organization and relationships between system components in their SOCME diagrams as well as as they documented their reflections on their learning experience. The SOCMEs generally provided stronger evidence of analytical skills and bridging skills to some extent. In contrast, the reflections provided more evidence for bridging and holistic thinking skills, with some evidence of analytical skills. Thus, both forms of evidence were needed to evaluate engagement with Systems Thinking. Other researchers have shown that SOCMEs can be very useful for helping students make connections between chemistry, the environment, and the economy[40] and to display the benefits and disadvantages of chemicals,[23] but have cautioned against using SOCMEs alone to assess Systems Thinking.[19,40]

It is important to note that the reflection prompts were very open, and the responses thus represented what was foremost in the students' minds from their experience of the intervention. This approach was feasible to implement on a large scale, with the 84 reflections coded representing approximately 10% of the population. It is also noted that the lack of prompts via interviews or more specific prompts for the reflections means that students reported only what first came to mind and other learning may have been missed. Thus, the map of what was demonstrated does not reflect the full picture of what was learned. Interviews would have enriched our study of the students' experience.

The study presents the learning and values expressed shortly after the intervention. A follow-up study could explore the durability of the learning, particularly concerning their recognition of the contribution that chemistry should make to sustainability for those who do not take any further chemistry courses.

The study findings are context-dependent, i.e., the intervention design and the learning environment. The findings cannot readily be generalized or transferred to other situations. Yet, our study of a large scale intervention revealed findings similar to those of studies conducted with much smaller groups regarding the characteristics of systems thinking most readily elicited and the development of a sustainable action perspective through Systems Thinking interventions. Typically students apply quick heuristic rules to make decisions, but can expand and deepen their thinking when prompted.[2] It is noted that in the many studies of systems thinking the students responded appropriately to the prompts as they did in this intervention. The challenge for all contexts is likely to be that Systems Thinking must be prompted regularly so that it becomes a habit. Our recommendation is to prompt Systems Thinking regularly in subsequent activities or over a course to build a habit of engaging students in deeper thinking, where they have to consider advanced dimensions, which include emergence, extended temporal thinking, and complex dynamic interactions.

The value this study contributes is the demonstration that a single add-on intervention can elicit appropriate learning and the development of Systems Thinking even in a large scale course that necessitates the mediation of learning by teaching assistants not skilled in Systems Thinking. It also showed the value of combining both frameworks to contextualize Systems Thinking in chemistry education.

## CONCLUSIONS

Chemistry is important for addressing the SDGs, yet many people do not associate chemistry with the sustainability agenda. Nonchemistry major students in our large general chemistry classes often view chemistry as a barrier to overcome and not a resource to tackle global problems. This view of chemistry was improved by including an activity directed toward sustainability that developed Systems Thinking. Despite no specific reflection prompts, more than half of the groups either foregrounded the importance of sustainability in the context of learning chemistry or suggested actions they would take as individuals to live more sustainably or both. These embody the core values behind the STICE agenda and point to developing future professionals who will contribute to sustainability.

We explored the demonstration of Systems Thinking skills and attitudes elicited by an activity in a large first-year chemistry course, employing two Systems Thinking frameworks. A modified form of the ChEMIST table, with analytical to holistic dimensions, helped to map the range of Systems Thinking skills that students demonstrated. This analysis revealed that System Thinking characteristics Ch1, viewing a system as a whole as well as identifying its parts, Ch2, organizing the system into a framework of relationships, and Ch5, identifying boundaries or relationships between connected systems, including the role of humans, were readily demonstrated. Thus, our study supports the extrapolation of findings from small scale interventions to a large scale setting when similar pedagogical approaches are used. Furthermore, the three core components of Systems Thinking for chemistry were met. Students valued learning the mechanistic reasoning for surfactant action, the context-based focus, and the sustainable action perspective. This stand-alone intervention oriented chemistry as a science for sustainability in the students' minds.

Balancing sustainability concerns with hope inspired the students to make a difference where possible. To meet the goals of STICE, it is important to engage students' hearts and minds to embrace the sustainability agenda in addition to developing Systems Thinking characteristics.

Circumventing the obstacle of slow curriculum reform processes, we have demonstrated that an appropriately designed Systems Thinking activity in a large general chemistry course can lead to meaningful learning of chemistry and experiences. The investment of laboratory time for the activity was good for the image of chemistry and inspired action toward a sustainable future.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.4c01048.

Intervention description: context, schedule, a full description of the activities, constructive criticism from students and subsequent modifications to the intervention design, and changes to the intervention compared to the published design (PDF, DOCX)

Codebook for qualitative analysis, examples of high and low-scoring SOCMEs, and comparison of the outcome space for the reflections of the subset 13 groups with the full sample (PDF, DOCX)

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### Notes

The authors declare no competing financial interest.

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