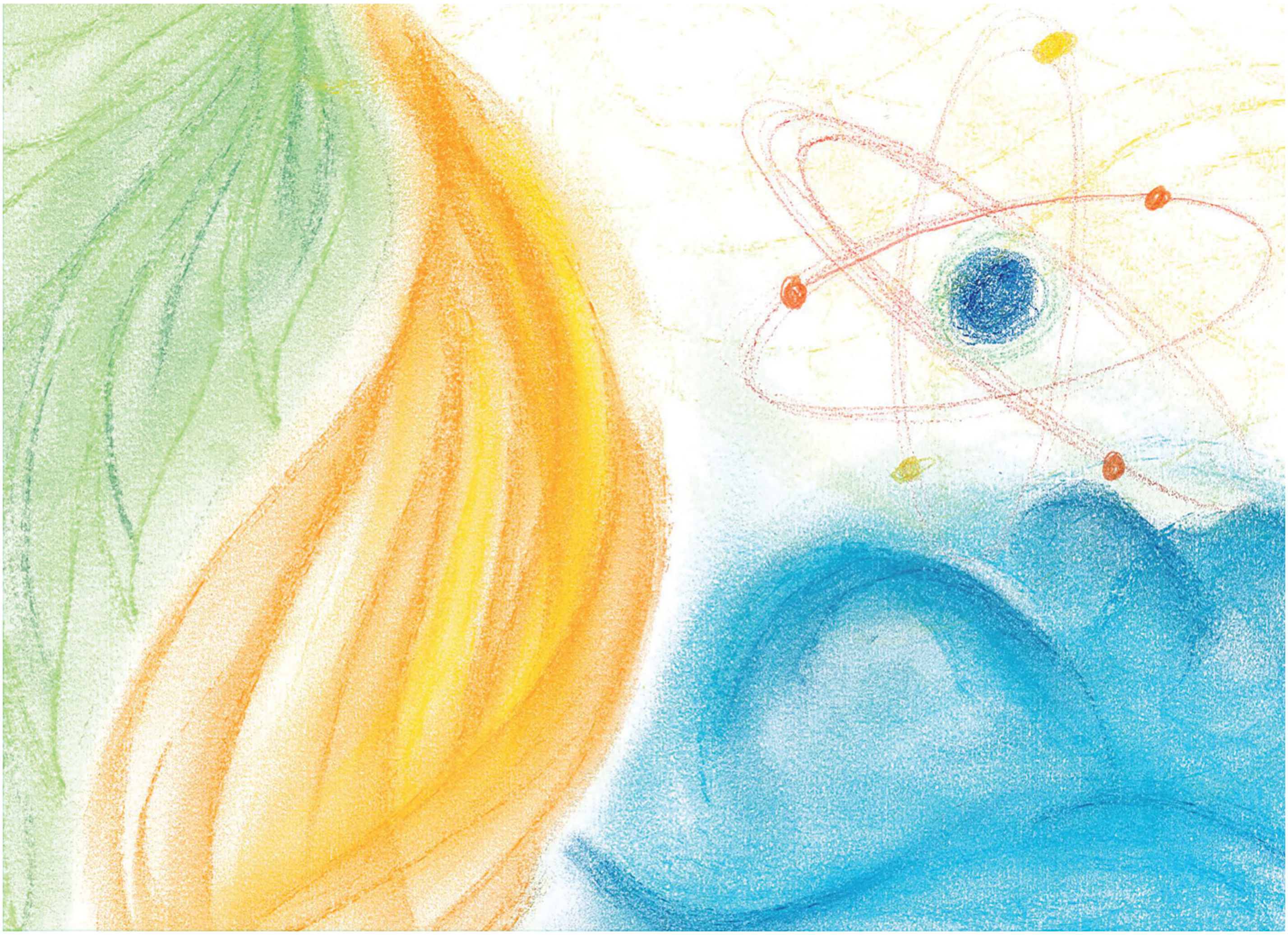

**Showcasing research from Ms Hoa Dao's laboratory, Faculty of Chemistry, Ho Chi Minh City University of Education, Ho Chi Minh City, Vietnam.**

Mainstreaming education for sustainable development in chemistry *via* a systems thinking approach: a case study on a series of lessons in the existing curriculum

This study explores systems thinking (ST) in ESD through five chemistry lessons for ninth-graders in Vietnam. Using mixed methods, results show improved ST skills, though constrained by curriculum alignment, highlighting the need for coherent, flexible integration in chemistry education.

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# Mainstreaming education for sustainable development in chemistry *via* a systems thinking approach: a case study on a series of lessons in the existing curriculum

Linh Khanh Nguyen, [ab] Binh Ngoc Thanh Huynh, [a] Khanh Hoang Gia Nguyen [c] and Hoa Thi Hoang Dao *[a]

Systems thinking (ST) has been adopted in Education for Sustainable Development (ESD) as an approach that enables learners to analyse complexity, interdependence, and multiple dimensions of sustainability issues. This paper reports a participatory action research study that developed a sequence of five consecutive ESD-integrated chemistry lessons through the ST approach and investigated its impact on the development of students' ST competence. The lessons, developed based on an adapted educational framework for teaching chemistry using a ST approach and the learning outcomes (LOs) of the local existing curriculum, were tested with 44 ninth-graders at a lower secondary school in Vietnam. Students' ST competence was assessed using a one-way repeated measures design, in which both quantitative and qualitative data were collected through written tests with open-ended questions and anecdotal records, using a methodological triangulation approach. Data from written tests were analysed using one-way ANOVA and descriptive statistics, while data from the anecdotal records were examined through deductive qualitative content analysis. The results showed a positive trend in the development of most students' ST skills (STS) across the five lessons, but the developmental trajectories differed across STS. Notably, the data revealed that strict alignment with the mandatory LOs may have constrained the development of certain STS. The results suggested that initiatives integrating chemistry lessons with ESD should continue to be implemented in other countries' national curricula, with particular attention to implementation in the form of lesson sequences, to evaluate their alignment with mandatory LOs, and to guide the use of ST in chemistry education and ensure coherence, continuity, and transformative impact.

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## Introduction

The persistent shortfall in achieving the Sustainable Development Goals (SDGs) highlights the limitations in existing sustainability efforts (Sachs *et al.*, 2024), and reinforces the need to advance Education for Sustainable Development (ESD) as a means to foster the cognitive and behavioural shifts essential for long-term transformation towards sustainability (UNESCO, 2020). According to the Sustainable Development Report 2024 (Sachs *et al.*, 2024), only 16% of the SDG targets are currently on track, while the remaining are showing limited or reverse progress. While this stagnation has been attributed to global crises (Sachs *et al.*, 2024), accelerating the achievement of the SDGs also requires behavioural change and the development of values, skills, and attitudes for responsible global engagement (UNESCO, 2020; Carmona *et al.*, 2024). In this regard, ESD has been acknowledged not only as part of SDG 4 but also as a key enabler that supports the achievement of all other SDGs by cultivating sustainability competencies (UNESCO, 2017; UNESCO, 2020). Therefore, ESD continues to require active promotion, along with the search for new context-appropriate approaches.

Chemistry education has been increasingly recognised as a fertile domain for integrating ESD (UNESCO, 2017; Sjöström and Eilks, 2018; Arifin *et al.*, 2025). Chemistry education is particularly well-suited to reflect the complexity and multidimensionality of sustainability issues (UNESCO, 2017). Moreover, chemistry education provides opportunities for students to engage with real-world problems that require multi-causal

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reasoning and interdisciplinary understanding (Council *et al.*, 2012). Therefore, chemistry education is recognised as a relevant context for engaging key ESD principles, which can support transformative objectives (UNESCO, 2017). However, ESD implementation often remains fragmented and narrowly focused, instead of advancing the holistic integration of content, pedagogy, and outcomes within formal education systems (UNESCO, 2020; Kusumaningrum *et al.*, 2023). This undermines the transformative intent of ESD and emphasises the necessity of embedding ESD within formal chemistry to ensure coherence, continuity, and transformative impact (Arifin *et al.*, 2025).

Given the growing interest in aligning chemistry education with the principles of ESD, the systems thinking (ST) approach has been proposed as a pedagogy that reflects both the interdisciplinary nature of ESD and the complexity of sustainability challenges (Rieckmann, 2018; Schuler *et al.*, 2018). In this context, ST is one of the key competencies in ESD (Arifin *et al.*, 2025), equipping students with the ability to understand interconnections, analyse dynamic systems, and engage with uncertainty (Wiek *et al.*, 2011). Moreover, ST reflects a worldview grounded in holistic, relational and contextual thinking, offering a contrast to the reductionist logic that has long dominated conventional chemistry education (Arnold and Wade, 2015). In response to the need to develop ST competence, the ST approach has been a pedagogical strategy in sustainability education (Wiek *et al.*, 2011; Demssie *et al.*, 2023). In recent years, the "Systems Thinking In Chemistry Education project" (STICE) (Mahaffy *et al.*, 2018, 2019a, 2019b; Aubrecht *et al.*, 2019; Mahaffy and Matlin, 2019; Matlin *et al.*, 2020; Keßler *et al.*, 2021) and the "Sustainability and Systems Thinking In Chemistry Education project" (SaSTICE) (Constable *et al.*, 2019; Kornfeld and Stokoe, 2019; Mahaffy *et al.*, 2019a, 2019b; Pazicni and Flynn, 2019; Szozda *et al.*, 2022; Reynders *et al.*, 2023; Talanquer and Szozda, 2024) have made profound efforts to foster the ST approach in teaching chemistry. Research publications relating to STICE and SaSTICE have been increasing, among which the educational framework for teaching chemistry using a ST approach proposed recently by Talanquer and Szozda (2024) provides a foundational guideline for researchers and practitioners in different countries to adapt and implement ST in teaching chemistry locally. Most local implementations of the ST approach in chemistry lessons came from the United States and Germany (Seher Budak and Defne Ceyhan, 2024), but it has not yet been widely implemented in some developing countries. There is thus a growing need to develop further the local implementation of the ST approach in chemistry education, inspired by recent results from the STICE project, and examine its contextual relevance within the local educational landscape, especially in developing countries.

Besides being grounded in well-developed theories, any ESD initiative must align with local contexts, including both opportunities and challenges. In many countries, education reforms have increasingly positioned ESD as a strategic focus in both policy and curricular frameworks (Zguir *et al.*, 2021; Hastangka *et al.*, 2025), laying an opportunity for the inclusion of ESD in school education. However, this integration, published in case studies around the world, remains limited to isolated lessons and lacks continuity (Zowada *et al.*, 2020; Li *et al.*, 2023; Dao *et al.*, 2024a, 2024b), thus limiting the extent to which transformative actions and awareness can be effectively promoted. Moreover, the integration of ESD into the existing curriculum usually strictly aligns with the mandatory learning outcomes (LOs), and the introduction of additional content is often restrained by time limitations (Parry and Metzger, 2023). These obstacles may hinder the mainstreaming of ESD in chemistry education. Accordingly, it is necessary to further promote the integration of ESD into chemistry education in existing mandatory curricula, face local opportunities and challenges in implementing ESD, and extend the length of the intervention to enable more meaningful and reliable evaluation of its educational impact.

The previous discussion points to the following key research problem: how can ESD-integrated chemistry education be effectively promoted through an appropriate ST approach (inspired by SaSTICE) that is formal curriculum-grounded, provides sufficient intervention duration to ensure impact, and supports the development of ST competence – one of the key ESD competencies? Accordingly, the main aim of this study is to investigate the impact of five consecutive ESD-integrated chemistry lessons, implemented through the ST approach, on students' ST competence. Our research question is: How does a SaSTICE-inspired chemistry lesson sequence support students' development of ST competence?

## Background

### Systems thinking competence in education for sustainable development

ST competence is defined as the capacity to collectively analyse complex systems across social, environmental, and economic domains at multiple scales, while accounting for cascading effects, feedback loops, and other systemic dynamics relevant to sustainability problem solving (Wiek *et al.*, 2011). This competence is critical for sustainable development by enabling stakeholders to locate leverage points, anticipate systemic shifts, and plan actions that address structural drivers instead of surface symptoms (Wiek *et al.*, 2011). Within ESD, this competence is fostered through teaching and learning processes that equip learners to map causal linkages, model dynamic scenarios and adjust actions based on system feedback, thereby strengthening the capacity to address complexity and uncertainty (Assaraf and Orion, 2005; UNESCO, 2017; Talanquer and Szozda, 2024). To enhance the practical assessment of ST competence within ESD, Karaarslan Semiz and Teksöz synthesised 12 ST skills (STS) grounded in established theoretical frameworks (Karaarslan Semiz and Teksöz, 2020), as presented in Fig. 1. These 12 STS provide behavioural indicators that support the analysis of ST competence in the ESD context (Karaarslan Semiz and Teksöz, 2020). Furthermore, the 12 STS were operationalised into an explicit assessment rubric

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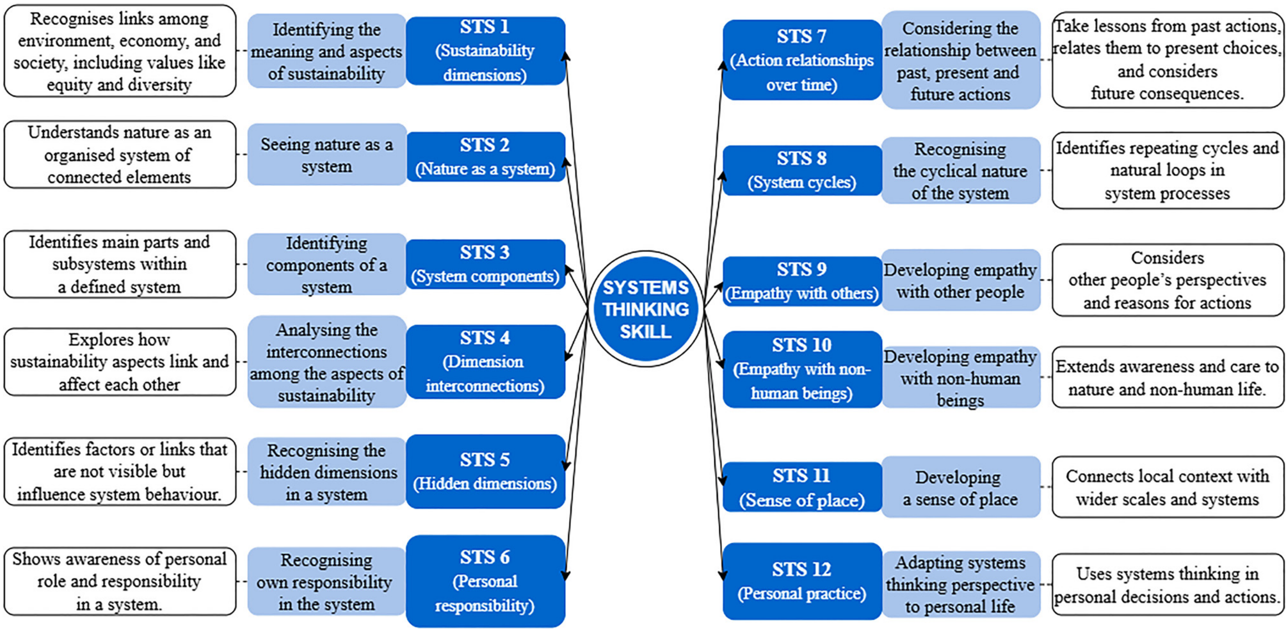


Fig. 1 Systems thinking skills and corresponding descriptions (Vare and Scott, 2007).

that enables the systematic evaluation of students' STS development, with four hierarchical levels of performance: pre-aware, emerging, developing, and mastery (Karaarslan Semiz and Teksöz, 2020).

### Systems thinking approach to ESD-integrated chemistry education

Many established instructional models and paradigms have advanced the understanding of the ST approach in education, yet they often leave gaps in how it is implemented in practice. Assaraf and Orion's (2005) hierarchical model has made a significant contribution by mapping the cognitive development of students' ST competence across eight hierarchical levels in chemistry education (Assaraf and Orion, 2005). However, its staged structure remains closely tied to a linear logic that reflects closed, mechanistic thinking, which Capra and Luisi (2014), through their systems paradigm, have criticised as inadequate for explaining complex socio-ecological phenomena (Capra and Luisi, 2014). Instead, Capra and Luisi (2014) advocate a holistic worldview that situates systems as dynamic, interdependent, and self-organising (Capra and Luisi, 2014). Orgill *et al.* (2019), as members of the STICE project, added value by defining key system characteristics and clusters of skills to guide how students describe, reason about, and analyse systems (Orgill *et al.*, 2019). While these contributions have clarified what ST is and why it is needed, they do not resolve the crucial question of how to design, implement, and assess it in practice in education – an issue that is especially critical for ESD (Vare and Scott, 2007). Talanquer and Szozda's (2024) framework, as a result of the SaSTICE project, addresses this missing link by adopting Assaraf and Orion's (2005) insight that developing ST competence requires a clear structure, embracing the holistic orientation championed by Capra and Luisi (2014), and building on the detailed system characteristics articulated by Orgill *et al.* (2019). Therefore, by combining conceptual clarity with a practical pathway – planning, implementation, and assessment – Talanquer and Szozda's framework bridges the enduring gap between theory and practice, enabling teachers to translate ST competence into teachable, measurable outcomes that align with the imperatives of sustainability-focused lesson design (Talanquer and Szozda, 2024).

Moreover, Talanquer and Szozda's framework exhibits pedagogical coherence and a high degree of compatibility with the core principles of ESD (UNESCO, 2017; Talanquer and Szozda, 2024). The framework repositions chemistry education to address complex socio-environmental challenges, treating sustainability not as an add-on but as the core logic for curriculum design and learning outcomes (LOs) (Talanquer and Szozda, 2024). It balances disciplinary concepts, scientific practices, ST skills, and socio-environmental competencies (Talanquer and Szozda, 2024), reflecting ESD's focus on developing not only knowledge but also the skills, values, and attitudes necessary for transformative action (UNESCO, 2017). Additionally, the framework explicitly promotes interdisciplinarity by encouraging students to connect chemistry knowledge with insights from other aspects, fostering a more holistic understanding of complex issues (Talanquer and Szozda, 2024). Furthermore, the framework embeds formative assessment into the learning process to generate constructive feedback (Talanquer and Szozda, 2024), which aligns with UNESCO's principle that assessment should empower learners and foster transformative learning (UNESCO, 2017; Talanquer and Szozda, 2024). Despite these strengths, the framework does not yet offer a detailed structure for assessing students' ST competence, which is better operationalised through established skill sets such as the 12 STS proposed by Karaarslan Semiz and Teksöz (2020).

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Still, by coherently interweaving principles, content, pedagogy, and learning environment, the framework exemplifies a viable model for actualising ESD in practice.

### Instructional tools for the systems thinking approach to ESD-integrated chemistry education

The concept map is a student learning artefact (Szozda *et al.*, 2023) that supports learners in revisiting and reflecting on lesson content, aligning with the expectations of the Connect phase in Talanquer and Szozda's framework (2024). In the context of SaSTICE, Systems-Oriented Concept Map Extensions (SOCME) diagrams, which require learners to explicitly represent system boundaries, subsystems, and external factors when modelling complex systems, were developed as extensions of concept maps to support ST (Assaraf and Orion, 2005; MacDonald *et al.*, 2025). SOCME can be considered a unique type of concept map that groups items into subsystems (MacDonald *et al.*, 2025), so it is highly recommended to use it in lessons with the ST approach. In this article, the term ''concept map'' specifically refers to ''SOCME diagram''.

According to Novak and Cañas (2006), the concept map supports the ST approach by helping students manage cognitive load and structure complex ideas throughout the learning process. It enables students to visualise systems, organise concepts (Nesbit and Adesope, 2006), and make explicit the interconnections among system components, such as subsystems and influencing factors, represented as linked concepts (Ruiz-Primo and Shavelson, 1996). During group-based classroom activities, concept maps also encourage peer interaction and discussion, enhance critical thinking, and support the co-construction of knowledge among students across various stages of group learning, including idea generation, reflection, and integration (Ruiz-Primo and Shavelson, 1996; Van Boxtel *et al.*, 2002). However, novice students often struggle to create coherent concept maps, as their initial representations tend to be fragmented, poorly structured, or lacking meaningful integration of ideas (Ruiz-Primo and Shavelson, 1996; Kinchin *et al.*, 2000; Szozda *et al.*, 2023). Therefore, they require continued practice and formative feedback (Novak and Cañas, 2006), highlighting the need for instructional ''scaffolding'' to support their conceptual development (Szozda *et al.*, 2023; Talanquer *et al.*, 2024).

In this context, scaffolding theory, first introduced by Wood *et al.* (1976), provides structured yet flexible instructional support aligned with learners' Zones of Proximal Development (Wood *et al.*, 1976), thus supporting the implementation of the concept map in the learning process. This approach enables teachers to extend students' potential beyond what they can accomplish independently (Vygotsky and Cole, 1978; Van de Pol *et al.*, 2010). Scaffolding refers to the temporary and adaptive instructional support provided to help students accomplish tasks that would be beyond their independent capabilities (Wood *et al.*, 1976). This guidance is gradually withdrawn as competence increases, promoting autonomy for active learning, which is called fading progress (Wood *et al.*, 1976; Fosnot and Perry, 1996; Taber, 2018), and aligning with ESD's emphasis on student-centred pedagogy (UNESCO, 2017). Taken together, the integration of concept maps with intentional scaffolding strategies plays an important role in supporting the ST approach within ESD-integrated chemistry lessons by facilitating students' understanding of complex systems and promoting their gradual development of independent learning capacity. However, existing literature provides limited reference to whether scaffolding is clearly specified in ESD initiatives, particularly in supporting students' engagement with complex learning tasks and their gradual development of autonomy (Nguyen and Thai, 2023; Dao *et al.*, 2024a, 2024b; Giang and Hao, 2024; Ha, 2024).

## Research design

The case study was conducted in Ho Chi Minh City, Vietnam, from October 2024 to April 2025 and followed the participatory action research design with four phases: development, testing, evaluation, and reflection (Eilks and Ralle, 2002). Therefore, the researchers collaborated with one chemistry teacher with 15 years of experience, who was the participating practitioner in this participatory action research, to ensure the practicability of the lesson plans in a real-world educational context. In the lower secondary science curriculum, a series of biomolecules and polymers lessons in the strand ''Substances and their transformations'' encompass equivalent content to traditional chemistry. Accordingly, they were regarded as chemistry lessons for this study. The developed lesson plans were empirically tested with a class of ninth-grade students, purposively selected based on the recommendation of the participating teacher, who was responsible for teaching the class.

**Ethical considerations.** Both the students and the teacher voluntarily agreed to take part in the study. As the participants were minors in a school setting, informed consent was obtained through a designated gatekeeper, namely the classroom chemistry teacher, who signed the Participant's Consent form outlining the study purpose and procedures. Students were informed that participation was voluntary and that they could withdraw at any time without penalty. Although no formal institutional ethics approval was required in this context, essential ethical safeguards were applied. Specifically, all data were systematically de-identified prior to analysis, and appropriate procedures for data storage and reporting were implemented. As the first author implemented the instructional intervention and conducted the data collection and analysis, the study acknowledges a potential double agency inherent in classroom-based research. To minimise this risk, the second author independently analysed the dataset, providing an additional analytic perspective consistent with investigator triangulation (Carter, 2014).

All students had consistently demonstrated high academic performance and were actively engaged in extracurricular chemistry activities. Therefore, this sampling decision was made to ensure that the students had the necessary cognitive capacity for the first implementation of a newly designed lesson sequence employing a novel teaching approach. All classroom

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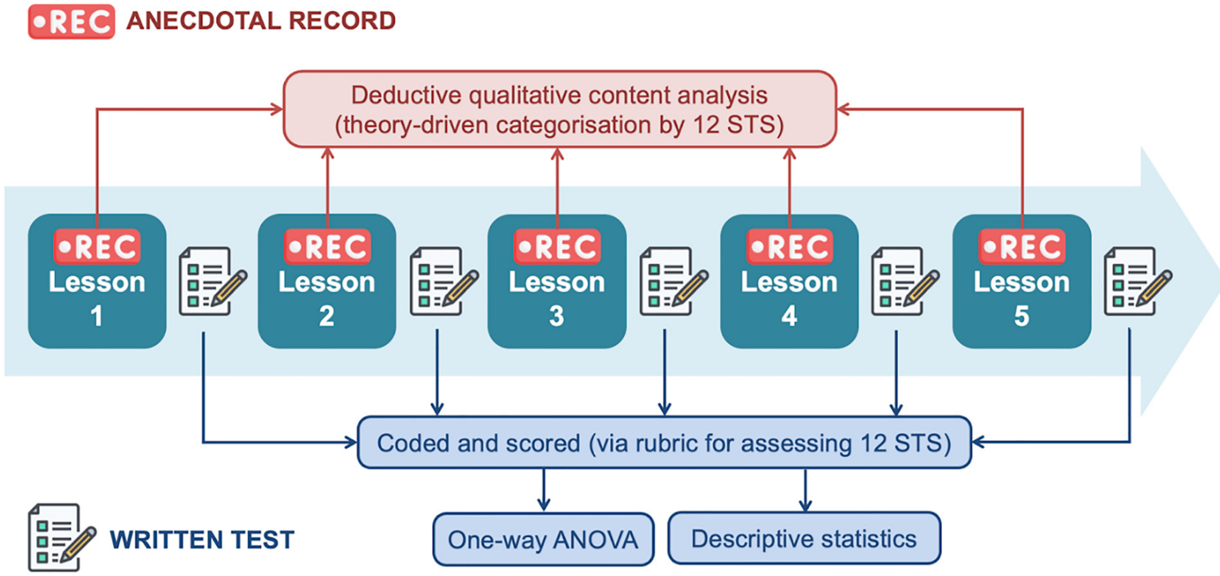


Fig. 2 Data collection and analysis methods and frameworks.

records and collected data were only used internally among the researchers with the participant's permission.

Fig. 2 summarises the design, methods and instruments used to evaluate how the designed lesson sequence develops students' ST competence, which is the study's research question. A one-way repeated measures approach (Verma, 2015) was conducted across five data collection points to assess students' ST competence. Such a design enhanced statistical precision by eliminating between-subject variability, as each participant serves as their own control (Verma, 2015). Thus, the design provided robust evidence of how ST competence developed progressively in response to extended ESD-based instruction. It directly addressed limitations in prior short-duration trials, which had highlighted the need for extended teaching time to support deeper conceptual growth (Dao *et al.*, 2024a, 2024b). Moreover, the data were collected during and after each lesson, *via* two research instruments with triangulation through a mixed-methods design: written tests and anecdotal records. While the written tests captured students' individual reasoning after each lesson, but were limited by students' ability to express ideas or by test effects (Fraenkel *et al.*, 2011; Hubbard *et al.*, 2017), the anecdotal records provided real-time, situated evidence of learning through behaviour (Fraenkel *et al.*, 2011) such as discussion, argumentation, and collaborative problem-solving during the whole classroom session. Hence, the combination of these two data sources helped validate findings, reduce bias, and offer a more holistic picture of student learning (Patton, 1999; Creswell and Clark, 2017).

The written tests, each including some open-ended questions, were purposefully developed to assess specific indicators within the 12 STS (Karaarslan Semiz and Teksöz, 2020; Ekselsa *et al.*, 2023) as well as ensuring the appropriateness to each lesson topic, the learning content, and the educational context. In each test, one question requires students to fully identify and comprehensively analyse the explored system learned in the lesson, then another question(s) requires students to position themselves within the system by proposing practical measures and real-life scenarios. While the overall assessment intent remained consistent across the lesson sequence, variations occurred in the level of scaffolding provided in specific lessons. In particular, guiding prompts were incorporated and subsequently faded in Lesson 4, and remained removed in the final lesson. Across all lessons, the primary variation in the written tests was related to the specific system context referenced in each lesson, related to biomolecules and polymers (see more details in the SI). To better capture students' learning potential and responsiveness to support, dynamic assessment (Elliott *et al.*, 2018) (*i.e.*, data collected from the previous tests are used as a reference for designing the next test) was incorporated into the written test design, aligning with the spirit of the participatory action research design (Bradbury, 2015). The content validity evidence was obtained by asking for comments from authors of the research team, as well as the secondary school teacher who participated in the study. Students' responses were coded directly according to the coding manual developed by Karaarslan Semiz and Teksöz (2020). The coding and scoring process was conducted independently by the first and second authors, and interrater reliability was assessed using Cohen's Kappa coefficient (Cohen, 1960). To examine whether there were statistically significant differences across the five measurement points, one-way ANOVA was applied. Besides that, descriptive statistics were also used to provide an overall view of the data distribution.

The anecdotal records were collected during each classroom session by the first author, who acted as a participant observer, following qualitative observation principles that emphasise objectivity, detail, and non-evaluative recording of behavior (Fraenkel *et al.*, 2011). Any behaviour deemed relevant, such as group activities, concept mapping, or classroom debates, was recorded, and all notes were documented immediately after

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each lesson to ensure accuracy in accordance with standard practices in educational research observation (Cohen *et al.*, 2002). To ensure consistency and theoretical alignment, the observation process was guided by predefined criteria based on the 12 skills of the STS framework (Karaarslan Semiz and Teksöz, 2020), which helped enhance the construct validity and interpretive coherence of the analysis (Cohen *et al.*, 2002). The study then applied deductive qualitative content analysis, using this theory-driven coding scheme to categorise (Elo and Kyngäs, 2008) and interpret student behaviours in relation to each targeted STS skill (Karaarslan Semiz and Teksöz, 2020). Taken together, findings from both data sources were compared and triangulated to enhance interpretive validity and deepen understanding of students' ST competence.

## Teaching intervention

As suggested by Talanquer and Szozda (2024), the original educational framework is modified (Fig. 3) to better align with the local General Education Curriculum, since its mandatory LOs and time allocations allow only limited flexibility (MOET, 2018). Adherence to mandatory LOs ensured that chemistry learning was not sacrificed, as ST skills developed through students' engagement with core concepts embedded within the lesson design. In the planning stage, the sequence of phases is intentionally restructured by placing the Define phase at the beginning, emphasising that the starting point of lesson planning must be the mandatory LOs, which drive the decision of selecting suitable socio-environmental issues in the Contextualise phase. In addition, identifying the subsystems of each lesson's system in the Focus phase also has to be aligned with the LOs to avoid digression and ensure consistency with the pre-defined lesson duration. As a result, implementing ESD-integrated chemistry education does not require adding new content but instead focuses on reorienting how existing content is approached – making it feasible and practical within the current teaching structure. Finally, the teacher designs the lessons according to the learning sequence suggested in the Implement stage, with four main learning activities, each of which may align effectively with the development of the STS due to their potential correspondences in characteristics and pedagogical intent (Fig. 3, see more details in the SI). To guide students in constructing concept maps that closely align with their progressive engagement with the scientific content, a scaffolding strategy is devised as follows:

• In the first two lessons (fully scaffolded), students received explicit guidance in constructing concept maps. The teacher provided fully pre-constructed maps, leaving only the component boxes blank. After learning the content of each subsystem, students reviewed their understanding through short guiding questions, which the teacher used to support them in identifying key components and adding these to their group concept maps during the Map out and Zoom in phases. Subsequently, to help students recognise connections among components across subsystems and identify emerging or hidden components in the Zoom out and Connect phases, the teacher directly guided students through a sequence of guiding questions, with each question explicitly targeting a specific relationship or component.

• In the following two lessons (partially scaffolded), instructional support was gradually reduced. The teacher intentionally continued to provide pre-constructed concept maps with the component boxes left blank within each subsystem. In some cases, entire subsystems were left without predefined component boxes. Across all four phases, after learning the relevant

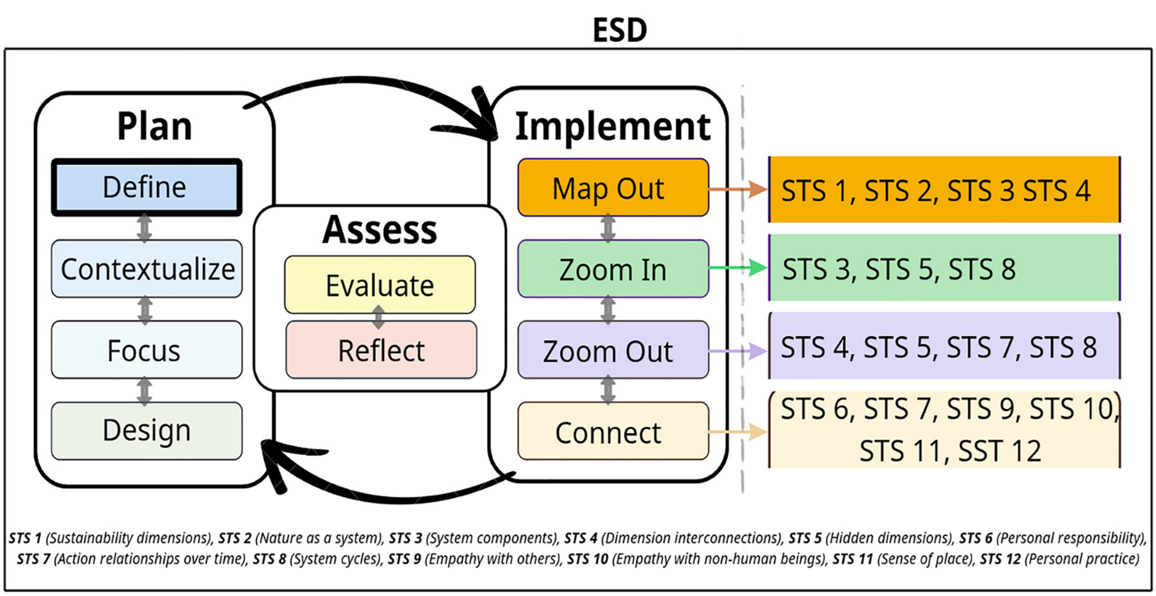


Fig. 3 Theoretical framework of the teaching intervention adapted from Educational Framework for Teaching Chemistry Using a Systems Thinking Approach (Talanquer and Szozda, 2024) and twelve systems thinking skills (Karaarslan Semiz and Teksöz, 2020).

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Table 1 The instructional sequence across five lessons following a scaffolding strategy

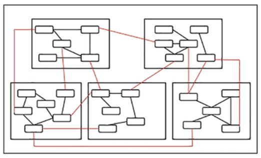
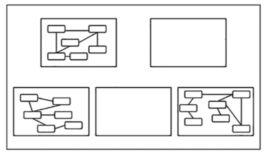
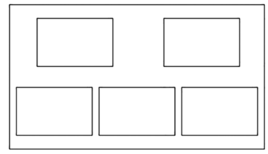
| | Fully scaffolded | | Partially scaffolded | | Minimally scaffolded |
|---|---|---|---|---|---|
| | Lesson 1: lipid and fat (90 minutes) | Lesson 2: glucose and saccharose (90 minutes) | Lesson 3: starch and cellulose (90 minutes) | Lesson 4: protein (90 minutes) | Lesson 5: polymer (90 minutes) |
| Pre-design concept map |  | |  | |  |
| Map out | The lesson started with "Premature ageing in youth," guiding students to identify subsystems through open-ended questions. | The lesson began with a game, "Cutting sugar from meals", students predicted sugar-containing foods lead to the introduction of the issue "cutting sugar from meals". Then, the teacher used open-ended questions to guide students in identifying subsystems. | The lesson began with the issue of "No-carb diet trend", the teacher used open-ended questions to guide students in identifying subsystems. | The lesson began with the issue of "High-protein diet trend", the teacher used open-ended questions to guide students in identifying subsystems. | The lesson began with the issue "The Battle of Survival Materials", in which students predicted the durability of different materials in various environmental conditions, which led to the introduction of the issue "plastic overuse". Then, the teacher used open-ended questions to guide students in identifying subsystems. |
| Zoom in | • Applications in the human body: food: students explored the concepts, molecular structures, and chemical bonds of different types of fats, then categorised them into specific groups with practical examples.<br>• Fat metabolism in the body: students explored the mechanism of fat metabolism in the human body.<br>• Chemical behaviour of fats: students explored the underlying nature of the properties and the saponification reaction of fats. | • The natural sources, and structures of glucose and saccharose: students explored the molecular structures and chemical bonds of glucose and saccharose, as well as naturally occurring products.<br>• Chemical and physical behaviours of glucose and saccharose: students explored the underlying nature of the properties of glucose and saccharose.<br>• Sugar metabolism in the body: students explored the mechanism of sugar metabolism in the human body. | • The structures of starch and cellulose: students explored the concepts, molecular structures, and chemical bonds of starch and cellulose, as well as their naturally occurring products.<br>• Chemical and physical behaviours of starch and cellulose: students explored the underlying nature of the properties of starch and cellulose.<br>• Starch metabolism in the body: students explored the mechanism of starch metabolism in the human body. | • The structures of proteins: students explored the molecular structures and chemical bonds of proteins, as well as their natural states.<br>• Chemical and physical behaviours of proteins: students explored the underlying nature of the properties of proteins.<br>• Protein metabolism in the body: students explored the mechanism of protein metabolism in the human body.<br>• Silk materials: students explored the origin of silk and nylon fibres. | • The structures of polymers and polyethylene: students explored the concepts, molecular structures, and chemical bonds of polymers and polyethylene.<br>• The chemical properties of polyethylene: students explored the underlying nature of the properties of polyethylene.<br>• Some natural cycles in the environment: students explored the natural decomposition cycles, waste dispersion, and biological food chains. |
| Zoom out | Students analyse types of (traditional and industrial) fats in conjunction with the fat metabolism process in the human body to infer issues related to fat consumption in health. They also examined the molecular structure of fats to reason about environmental pollution caused by fat residues. | Students analyse the molecular structures to explain the chemical and physical behaviours of glucose and saccharose; then, combine them to explain their real-life applications; combine with sugar metabolism in the body to infer issues for sugar consumption in health. In addition, students infer economic and environmental aspects when considering methods of cultivating sugar-containing foods. | Students analyse the molecular structures to explain chemical and physical behaviours of starch and cellulose; then, combine them to explain their real-life applications; combine with starch metabolism in the body to infer issues for starch consumption in health. In addition, students infer economic and environmental aspects when considering methods of cultivating starch-containing foods. | Students analyse the structures to explain the chemical and physical behaviours of proteins, and in conjunction with the protein metabolism process in the human body, to infer the role of protein in health. Additionally, analyse the structures, chemical and physical behaviours of proteins in conjunction with types of silks to distinguish between natural silk and nylon fibre. | Students analyse the structure to explain the chemical properties of polyethylene; then, combine them to explain and categorise its various applications; combine with some natural cycles to infer the issue of plastic pollution in the environment. |


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Table 1 (*continued*)

| | Fully scaffolded | | Partially scaffolded | | Minimally scaffolded |
|---|---|---|---|---|---|
| | Lesson 1: lipid and fat (90 minutes) | Lesson 2: glucose and saccharose (90 minutes) | Lesson 3: starch and cellulose (90 minutes) | Lesson 4: protein (90 minutes) | Lesson 5: polymer (90 minutes) |
| Connect | Students positioned themselves within the system to propose and make decisions on individual or collective actions for the responsible use of fats. | Students positioned themselves within the system to propose and make decisions on individual or collective actions for the responsible use of sugars. | Students positioned themselves within the system to propose and make decisions on individual or collective actions for the responsible use of starch. | Students just explain the issue introduced at the beginning of the lesson. | Students positioned themselves within the system to propose and make decisions on individual or collective actions for the responsible use of polyethylene. |

content, students engaged in group discussion and self-review to identify key components, complete the subsystems, and establish relationships among components. This process was implemented progressively as students moved from one subsystem to another. After each subsystem, students presented their developing concept maps, and the teacher provided feedback by posing guiding questions to support students in recognising components and relationships that were missing or challenging.

• In the final lesson (minimally scaffolded), students independently constructed concept maps based on the content learned in class. The provided concept maps included only predefined but unlabelled subsystem areas, with no component boxes specified. During the Map out phase, the teacher and students collaboratively labelled the subsystems to ensure that the content to be explored within each subsystem was appropriately aligned with the LOs. After learning the content of each subsystem, students worked collaboratively in groups to construct their concept maps. Subsequently, students presented their maps, and the teacher offered support by prompting the addition of relevant information where necessary.

The five lesson plans were designed in accordance with the adapted educational framework, as presented in Table 1. These lessons were selected based on their pedagogical coherence and their potential relevance to the goals of ESD (UNESCO, 2017; MOET, 2018). As these five lessons are consecutively positioned within the official curriculum (see the SI for the mandatory LOs of those topics), they allow for repeated exposure without being interrupted by unrelated instructional content. Furthermore, the lessons are tightly interconnected in terms of both content and instructional logic, linking topics from food to materials, with all themes revolving around SDG 12 – Ensure sustainable consumption and production patterns (UNESCO, 2017) and SDG 2 – End hunger, achieve food security and improved nutrition, and promote sustainable agriculture (UNESCO, 2017), thereby supporting the progressive development of systems thinking in a coherent manner.

Notably, the mandatory LOs of Lesson 4 limit the full implementation in the Connect phase. The LOs centred around the molecular structure of proteins and their related chemical and physical properties, with only a brief reference to "the role of proteins in the human body" (MOET, 2018), making it difficult to extend the lesson to broader themes such as responsible consumption. Moreover, to maintain appropriate classroom time and avoid deviating from the required outcomes, the teacher had to keep a strong focus on the specified content. Although the lesson was designed in alignment with the framework for developing ST competence and a real-world issue was appropriately connected, the requirements of the Connect stage were still not as fully implemented as in the other lessons.

# Results and findings

### Written test

Repeated measures ANOVA presented in Table 2 revealed statistically significant changes across the 12 STS. The $F$-values ranged from 40.739 to 233.579 with all $p$-values $< 0.05$, suggesting that the observed improvements in student performance are unlikely to have occurred by chance. Partial eta-squared ($\eta^2$) values ranged from 0.484 to 0.845, representing large effect sizes (Cohen, 1988). Observed power values ranged from 0.984 to 1.000, reflecting a high probability of detecting true effects given the sample size and observed variances (Lakens, 2013). The largest statistical differences were observed in STS 2 ($F$ = 233.579, $\eta^2$ = 0.845, power = 1.000), STS 8 ($F$ = 143.656, $\eta^2$ = 0.786, power = 1.000), and STS 5 ($F$ = 110.362, $\eta^2$ = 0.764, power = 1.000). While these values suggest strong statistical evidence of change, they may reflect notable improvements at certain points rather than a steady progression across the entire intervention (Field, 2024). Similarly, large effect sizes and high statistical power were also found for STS 4, STS 6, STS 7, and STS 11 ($\eta^2$ = 0.645–0.710), indicating stable differences in performance across lessons. STS 1, STS 10, STS 3, and STS 12 demonstrated moderate but statistically meaningful differences ($\eta^2$ = 0.484–0.606; power $\approx$ 1.000), further supporting the robustness of the observed changes. In contrast, STS 9 showed no statistically significant change ($F$ = 0.000, $\eta^2$ = 0.000) because this skill could not be assessed across the sequence *via* the written tests. Taken together, these results suggest that the intervention contributed to statistically reliable differences across most of the 12 STS. However, confirming developmental progression requires further analysis of change patterns, such as trends in mean scores or triangulation with qualitative data (Lakens, 2013; Field, 2024).

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Table 2 Repeated measures ANOVA results for each systems thinking skill (STS) across Lessons 1–5, Cohen's $\kappa$ = 0.83

| | Df | *F*-Value | Sig. (p) | $\eta^2$ (partial eta$^2$) | Power |
|---|---|---|---|---|---|
| **STS 1** (Sustainability dimensions) | 3.298 | 55.535 | 0.000 | 0.564 | 0.984 |
| **STS 2** (Nature as a system) | 1.645 | 233.579 | 0.000 | 0.845 | 1.000 |
| **STS 3** (System components) | 4 | 40.375 | 0.000 | 0.484 | 1.000 |
| **STS 4** (Dimension interconnections) | 2.537 | 98.751 | 0.000 | 0.710 | 1.000 |
| **STS 5** (Hidden dimensions) | 2.167 | 110.362 | 0.000 | 0.764 | 1.000 |
| **STS 6** (Personal responsibility) | 1.645 | 73.876 | 0.000 | 0.645 | 1.000 |
| **STS 7** (Action relationships over time) | 2.600 | 88.479 | 0.000 | 0.673 | 1.000 |
| **STS 8** (System cycles) | 1.965 | 143.656 | 0.000 | 0.786 | 1.000 |
| **STS 9** (Empathy with others) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **STS 10** (Empathy with non-human beings) | 2.284 | 66.062 | 0.000 | 0.606 | 1.000 |
| **STS 11** (Sense of place) | 2.665 | 89.976 | 0.000 | 0.685 | 1.000 |
| **STS 12** (Personal practice) | 2.475 | 40.739 | 0.000 | 0.487 | 1.000 |

Note: df (degrees of freedom: number of independent values used to estimate variance), *F*-value (a ratio indicating whether there is a significant difference between group means relative to within-group variability) (Verma, 2015), *p*-value (tests whether the difference is statistically reliable – $p < 0.05$ supports rejecting the hypothesis H0) (Verma, 2015), partial eta squared ($\eta^2$) (a measure of effect size indicating the proportion of total variance in the dependent variable that is attributable to a particular factor, partialling out other effects) (Verma, 2015), and observed statistical power (the probability that the test correctly rejects a false null hypothesis, i.e., detects a true effect if one exists) (Verma, 2015).

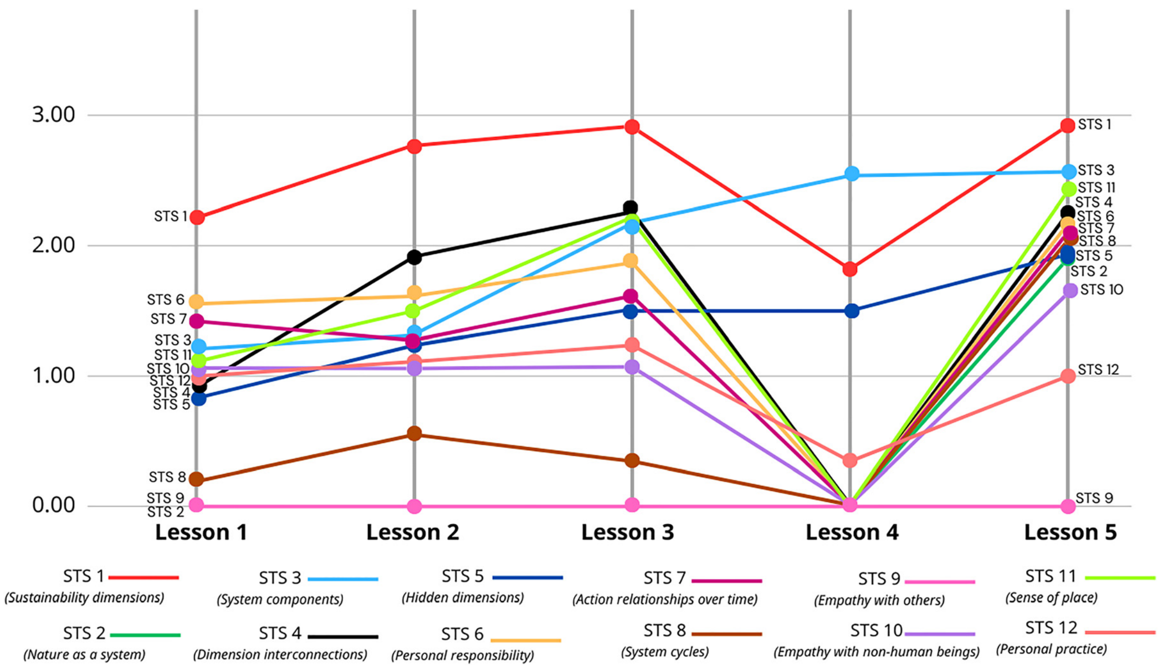


Fig. 4 Scores of students' 12 STS.

Fig. 4 presents in detail the results of students' ST competence across the five lessons, showing a positive trend for most STS. Most STS showed a gradual shift from lower level (in Lesson 1) to more advanced level (in Lesson 3). Notably, Lesson 5 demonstrated the most substantial improvements, with many mean scores of STS above 2 out of 3. Especially for STS 1 (Sustainability dimensions), the mean score in Lesson 5 reached 2.95, which is close to the maximum level. Most students were able to identify relevant sustainability aspects within a given context. For example, a student wrote:

"Since plastics cannot participate in natural decomposition, they stay in the environment, spread everywhere, enter food chains, and harm organisms. This not only affects ecosystems but also human health. However, plastic is very cheap and easy to use, so people still use it a lot, which leads to more environmental pollution. Using too much plastic causes long-term issues."

Specifically, several notable findings were observed. STS 1 (Sustainability dimensions) demonstrated a high level of performance from the first lesson and remained the most developed skill by Lesson 5. STS 3 (System components) demonstrated a consistent upward trend across the five lessons, with mean scores gradually increasing over time. In contrast, STS 12 (Personal practice) consistently remained at a relatively low level throughout the sequence, with mean scores below 1.25. Besides, STS 8 (System cycles) remained underdeveloped in the first four lessons (with mean scores below 0.51), but showed a marked increase in the final lesson

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(mean score = 1.95). Similarly, STS 2 (Nature as a system) was entirely absent during the first four lessons, yet demonstrated clear emergence in Lesson 5, with a mean score of 1.88. Notably, with the exception of STS 3 (System components) and STS 5 (Hidden dimensions), most skills declined in Lesson 4 before recovering in Lesson 5. Lastly, STS 9 (Empathy with others) was not demonstrated in any lesson, suggesting the need to cross-reference with anecdotal records to determine whether this absence resulted from a lack of instructional opportunity or from limitations in the assessment instrument.

**Anecdotal record**

We observed clear development in students' ST competence over the course of five lessons, evidenced through 12 STS. The changes observed across the five lessons are summarised in Table 3. Selected raw excerpts from the anecdotal evidence are provided in the SI.

This observation revealed uneven levels of participation in learning activities, as some students were minimally involved in class tasks. Even during group work, they rarely took the initiative to express their own perspectives. As a result, although the anecdotal records produced notable findings, they did not fully capture the performance of all students in the class, which can be better reflected through individual written tests.

## Discussion

This study contributes empirical insights into how a SaSTICE-inspired chemistry lesson sequence can support the development of students' ST competence within ESD-integrated chemistry education – a promising field that remains under-researched (Pazicni and Flynn, 2019; Kusumaningrum *et al.*, 2023). To address the research question, the intervention was developed based on the adapted Talanquer and Szozda's framework (2024) (in the SaSTICE project), combined with 12 STS proposed by Karaarslan Semiz and Teksöz (2020), scaffolding strategies and concept map tools. A one-way repeated measures design was employed, and data collected from written tests and anecdotal records were triangulated to give a more in-depth understanding of how students' ST competence can be formed and developed in sequence of ESD-integrated chemistry lessons.

Both data from written tests and anecdotal records provide compelling evidence of students' progressive development in most STS from Lessons 1–3, and most STS reached high levels in Lesson 5. This demonstrates the effectiveness of the lesson sequence, which might be attributed to two interrelated components: a structured instructional framework (Talanquer and Szozda, 2024) and strategically designed scaffolding (Taber, 2018). The adapted framework supported teachers in integrating ESD by aligning with mandatory LOs and allocated lesson time, while maintaining pedagogical coherence. As a result, although no additional content was incorporated beyond the mandatory LOs, students could still develop most STS effectively within each lesson. In parallel, scaffolding strategies played an important role in gradually supporting students to engage step by step with STS. Initial results showed that most STS appeared at a low level at the start, confirming that scaffolding was necessary. Conversely, the presence of well-structured scaffolding in the early stages might allow students to gradually and smoothly build this competence without becoming overwhelmed. In addition, the concept map, supported by scaffolding, also might serve as a practical visual tool that helps students structure lesson content, position themselves within the system and examine factors more actively during the Connect phase. Thus, this combination demonstrated a positive impact on students' development of ST competence. However, there are some important points to note about how certain STS developed.

Findings on some STS development in this study align with previous research. The most positive developmental trend was observed in STS 1 (Sustainability dimensions) and STS 3 (System components), aligning with the findings of Ekselsa *et al.*, (2023). Our study also revealed that STS 1 consistently demonstrated a high level of performance from the first lesson, which may suggest that this skill is relatively easy to develop and had already begun to emerge before. The lesson sequence mainly served to further sharpen this skill. Although Semiz and Teksöz did not examine the developmental trajectories of individual STS, they noted that these two skills represent the lowest-order cognitive demands and are therefore more easily developed by students (Ekselsa *et al.*, 2023). In contrast, STS 12 (Personal practice) was not fully evident across the three-week, five-lesson intervention. This is also the STS that Karaarslan Semiz and Teksöz (2020) identified as the most challenging for students to develop. Although the lessons were intentionally designed to support the Connect phase by engaging students with sustainability issues and encouraging movement toward transformative actions, opportunities to observe and assess such transformation were inherently constrained within the classroom setting. Consequently, this finding highlights the need for further exploration of how the development of STS 12 may be supported and examined in broader learning contexts beyond the classroom.

A noticeable shift in students' developmental trend emerged in Lessons 4 and 5, which may be attributed to the strict adherence to the LOs of the local General Education Curriculum and the change in scaffolded supports as dynamic assessment (Elliott *et al.*, 2018). In Lesson 4, as evidenced by both written test results and the anecdotal records, except for STS 3 (System components) and STS 5 (Hidden dimensions), most of the STS were weakly expressed. Firstly, the limited scope of the mandatory LOs and the time allocated for each lesson constrained opportunities for students to position themselves within the system in order to reflect and engage in informed decision-making as in other lessons. They just constructed systems based on the mandatory LOs and connected system components to explain the issue introduced at the beginning of the lesson in the Connect phase. As a result, the development of most STS was hindered. Secondly, throughout Lessons 1–3, support was made explicit during both instruction and assessment to help students build foundational understanding and reasoning confidence, which contributed to a steady upward

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Table 3 Observing changes in students' STS across the five lessons

| STS | Observed changes in students across five lessons |
|---|---|
| **STS 1** (sustainability dimensions) | **Lesson 1:** Relying on teacher prompts and model maps, students were able to effectively identify relevant sustainability aspects in the Zoom out and Connect phase, within the context of the lesson.<br>**Lesson 2:** Students began independently proposing ideas related to sustainability aspects during the Map Out activity, within the context of the lesson. They continued to effectively identify these aspects during the Zoom Out and Connect phases.<br>**Lesson 4:** Students independently identified sustainability aspects, but these were incomplete and did not encompass all key dimensions as in other lessons.<br>**Lessons 3 and 5:** Students actively identified new sustainability aspects while making connections in the Zoom Out phase. Some students posed cross-lesson questions, indicating an expanded systems perspective. |
| **STS 2** (nature as a system) | **Lessons 1–4:** Nature was mentioned only as background or consequence, without being seen as the system, as when students just said waste oil polluted water and harmed fish.<br>**Lesson 5:** Some students began to recognise the interactions between nature and human behaviour. Some of them described how plastic waste from humans goes into nature and harms animals and water, showing that everything in nature is connected. |
| **STS 3** (system components) | **Lesson 1:** In the Zoom in phase, although the teacher directly guided students in identifying system components of each subsystem, many still found it challenging to recognise all relevant components. Their concept map was fragmented and lacked clear organisation.<br>**Lessons 2 and 3:** In the Zoom in phase, some students began independently organising components into concept maps. They identified the components of each subsystem more completely, and their concept map demonstrated improved logical organisation.<br>**Lessons 4 and 5:** Students gradually took primary responsibility for system structuring, with the teacher providing only feedback. |
| **STS 4** (dimension interconnections) | **Lesson 1:** The relationships between aspects of sustainability that students identified were often fragmented or unclear. They just mentioned environmental or health aspects as isolated factors.<br>**Lesson 2:** Some students began forming reasoned connections between aspects of sustainability. They gradually became able to simply point out that the health factor was related to economic concerns in food consumption, based on the teacher's guiding questions.<br>**Lessons 3 and 5:** In the Zoom out and Connect phase, argumentation integrating sustainability aspects became more common. They engaged in more active discussions and made efforts to consider multiple aspects of a given issue, such as food consumption or plastic use.<br>**Lesson 4:** Students just focused on the health-related aspect. |
| **STS 5** (hidden dimensions) | **Lesson 1:** In the Zoom out phase, most students were only able to identify some hidden aspects by recording the teacher-guided information, including molecular bonding or metabolic pathways at the cellular level, as well as additional aspects not initially present in the lesson context, such as pollution, economic concerns, and health impacts.<br>**Lessons 2–5:** In the Zoom out phase, some students began exploring deeper system layers through indirect relationships. As they connected the subsystems, they began to identify additional aspects that were not initially present in the context of the lesson, such as pollution, economic concerns, or health impacts. |
| **STS 6** (personal responsibility) | **Lesson 1:** In the Connect phase, most students' proposed solutions were general and not linked to specific personal contexts.<br>**Lessons 2, 3, and 5:** In the Connect phase, students began offering solutions grounded in their own or their family's contexts. Some students also consider others' situations, such as questioning whether eating cereal in the morning would be suitable for a worker, showing awareness of different needs in decision-making.<br>**Lesson 4:** In the Connect phase, students had not yet had the opportunity to place themselves within the system for reflection. |
| **STS 7** (action relationships over time) | **Lessons 1 and 2:** In the Zoom out and Connect phase, most students just offered descriptive explanations, often focusing on imagined future scenarios related to the issue. Only a few students began to make simple decisions by reflecting on past experiences to suggest actions for the future. However, they did not consider the present and gave no clear reasons for their choices.<br>**Lessons 3 and 5:** In the Zoom out and Connect phase, some students clearly reflected on past lessons or their own experiences to draw lessons for making more sustainable choices in the future, and even considered their present situation.<br>**Lesson 4:** In the Zoom out and Connect phase, students only reflected on the context of the lesson and gave explanations related to it within systems, which shows reflection on the past. They had not yet had the opportunity to consider the present or the future. |
| **STS 8** (system cycles) | **Lesson 1:** Natural cycles were rarely mentioned.<br>**Lessons 2–4:** Limited progress in the Zoom in, Zoom out and Connect phase; only some students just identified basic feedback loops in food consumption, but without a clear explanation.<br>**Lesson 5:** Students described natural cycles more clearly in the Zoom in phase, such as decomposition, food chains, and biological–social interactions. |
| **STS 9** (empathy with others) | **Lesson 1:** At first, students rejected different system perspectives from other students, leading to arguments and unwillingness to compromise in the Zoom out and Connect phase. The teacher stepped in to help them recognise and respect others' viewpoints.<br>**Lessons 2–5:** Students gradually became more open to others' views and began to respond by exploring ideas rather than rejecting them in the Zoom out and Connect phase. The number of students engaging in system analysis during debate activities gradually increased across the lessons. |
| **STS 10** (empathy with non-human beings) | **Lessons 1–4:** Limited emotional expression toward living organisms or ecosystems. Some students began to express concern about environmental harm caused by food production processes.<br>**Lesson 5:** Most students showed greater emotional engagement, using empathetic language toward animals and natural habitats. Such as, some students expressed concern for animals losing their habitats. |

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Table 3 (*continued*)

| STS | Observed changes in students across five lessons |
|---|---|
| **STS 11** (sense of place) | **Lesson 1**: Most students struggled to clearly integrate multiple perspectives related to themselves in the Connect phase. When considering food consumption, they often focused only on the health aspect.<br>**Lessons 2, 3, and 5**: Some students more clearly integrated personal circumstances, cultural habits, and economic conditions into their system analysis.<br>**Lesson 4**: Students had limited opportunities to bring in diverse perspectives when discussing the context of the lesson, as they merely focused on explaining the issue itself in the Connect phase. |
| **STS 12** (personal practice) | **Lessons 1–3 and 5**: Some students expressing intentions related to personal behaviour, showing a desire to change and maintain a healthier lifestyle in the Connect phase. However, no clear development was observed, as they only articulated intentions without taking specific actions.<br>**Lesson 4**: Students had no opportunity to engage in making decisions on individual or collective actions regarding the responsible use of protein in the Connect phase.<br>**Lesson 5**: A few observable behavioural changes were noted in the classroom, such as using plastic bottles or eating deep-fried foods sold at the school gate. |

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trend in their performance. Lesson 4, by contrast, used only two questions to examine students' independent performance. The lower results at this stage might therefore stem from both the lesson design and the assessment tool. In Lesson 5, an additional support component was explicitly incorporated through dynamic assessment, allowing guided feedback during evaluation. This adjustment enabled students to express their reasoning more effectively, revealing learning potential consistent with the principles of dynamic assessment (Elliott *et al.*, 2018). With these data, it is uncertain to determine which factor really affects this developmental trend; hence, the above arguments suggest that future controlled research to investigate the effect of each factor (LOs and scaffolded support) on students' development of ST competence is necessary.

The strict adherence to the LOs may also limit the development of STS 2 (Nature as a system) and STS 8 (System cycles) in the first four lessons. Regarding STS 2, students' focus on responsible consumption led them to perceive nature merely as an external factor, as the LOs centred primarily on human health and personal well-being. By contrast, Lesson 5, which emphasised environmental implications more prominently, provided greater space for students to recognise humans as embedded within ecological systems, contributing to clearer development of STS 2. STS 8 also showed slow development, with consistently low scores across the first four lessons. This may be because the learning outcomes framed processes in a linear manner, which did not prompt students to trace recursive effects or consider how outcomes can feed back into the system. Only a few students were able to recognise feedback loops when considering the system as a whole. This result is consistent with the observations of Ekselsa *et al.* (2023), who noted that these skills are particularly challenging to develop. This shows that while some STS can develop readily, others remain more difficult to foster and tend to develop more slowly under mandatory LOs. Therefore, future research could examine the development of these STS across different lessons, as well as across different national education curricula.

Some limitations of the assessment instrument suggest that the written test alone may not be sufficient to capture the full students' STS. A notable observation is that the performance trends of most STS in five lessons were generally consistent across both data sources, except for STS 9 (Empathy with others). STS 9 was not evident in students' written responses across all five lessons but was observed in the anecdotal records, possibly because the assessment question did not explicitly require students to consider others' perspectives and only referred to humans indirectly. This might also suggest that the ability to view issues from others' perspectives is difficult to assess comprehensively through written tests alone. Therefore, it is important to strengthen assessment practices that focus on each individual student and reinforce the essential role of triangulating quantitative and qualitative data sources.

As a result, the lesson sequence can be considered successful in integrating core principles of ESD, as demonstrated through multiple strands of evidence. Integrating ESD within the boundaries of the program's mandatory LOs may pose certain constraints; however, the results still indicate positive signals, as a key condition is that the program's outcomes must be achieved and aligned with students' actual learning capacity. Therefore, the results of this study support the need for implementing ESD-integrated chemistry lesson sequences, as they help strengthen students' sustainability competence without necessarily requiring extensive additional content beyond the existing curriculum, given that both time and students' cognitive capacity are limited. As shown in this study, only one lesson was clearly constrained by the LOs and the limited support provided by the written test. Accordingly, the development of this competence should be maintained through multiple successive lessons; hence, it is recommended that ESD be embedded throughout the teaching process, whether through a few lessons or many, to frame how ST is applied into chemistry education and ensure sustained impact.

# Conclusion

This study presents a participatory action research on the integration of ESD into chemistry education through the ST approach. The research team designed a SaSTICE-inspired

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chemistry lesson sequence and tested it on a sample of Grade 9 students ($N$ = 44) to examine the development of students' ST competence. The findings highlight the positive progression of students' ST competence throughout the lesson sequence. Notably, this competence was progressively cultivated across the five lessons, following a gradual trajectory that balanced cognitive demands with student readiness. This steady progression not only prevented cognitive overload but also enabled students to internalise and independently extend their ST capabilities, aligning with the long-term objective of nurturing autonomous, sustainability-oriented learners. Importantly, the results also address a previously identified gap in ESD implementation: the need for structured chemistry lesson sequences that allow students to gradually develop key competencies over time, rather than through isolated or fragmented interventions.

However, the study still has limitations. First, the sample was limited to students with relatively high academic performance, which may restrict the generalizability of the findings to broader student populations, particularly those with lower academic readiness. Second, while responsible action (STS 12 – Personal practice) is a core element of ESD, the study was unable to assess whether students translated their learning into actual behaviours due to the absence of authentic, real-world contexts. Future research should address this by incorporating opportunities for students to demonstrate and consolidate this competency through situated learning experiences. Third, across the first four lessons, some STS remained at relatively low levels before rising sharply in Lesson 5. This pattern may have been influenced by the lesson content itself rather than only by teaching or assessment factors. Future studies should therefore include a control group to clarify whether the observed changes stem from instructional effects or from differences in lesson content. Finally, this study focused solely on assessing ST competence, which represents only one dimension of the broader set of ESD competencies. Future research should aim to evaluate a more diverse range of competencies to provide a more comprehensive understanding of students' development within ESD.

To our knowledge, this study is among the earliest studies to apply the results of the SaSTICE project to investigate the ESD-chemistry education integration using the ST approach. Its contribution lies not only in the conceptual alignment of ESD with existing curriculum content, but also in the concrete design and implementation of a structured five-lesson chemistry sequence. By grounding the intervention in the Talanquer and Szozda framework (2024), with 12 STS (Karaarslan Semiz and Teksöz, 2020) and employing a repeated measures design (Verma, 2015) with triangulated data sources, this study offers evidence of how ST competence can develop progressively within an ESD-integrated chemistry sequence. We strongly recommend that future research explore the use of the ST approach to integrate ESD across different student populations, in order to further advance the implementation of ESD and the application of results from STICE and SaSTICE projects in diverse educational contexts. Moreover, chemistry-ESD integrating initiatives should continue to be implemented in other countries' national curricula, with particular attention to the design and empirical investigation of chemistry lesson sequences, in order to evaluate their alignment with curricular goals, to support the application of ST in chemistry education, and ensure coherence, continuity, and transformative impact.

## Author contributions

Linh Khanh Nguyen: conceptualisation, data curation, formal analysis, investigation, methodology, resources, validation, visualisation, and writing – original draft. Binh Ngoc Thanh Huynh: formal analysis, methodology, resources, validation, and writing – review and editing. Khanh Hoang Gia Nguyen: conceptualisation, methodology, resources, supervision, validation, visualisation, and writing – review and editing. Hoa Thi Hoang Dao: conceptualisation, methodology, project administration, resources, supervision, validation, and writing – review and editing.

## Conflicts of interest

There are no conflicts to declare.

## Data availability

Data for this article are available at Google Drive at https://docs.google.com/spreadsheets/d/1YKUnGL8vnXmlawOOzkTxztSKGWSDTdhu7vWnFdcGuVw/edit?gid=0#gid=0. Data collected from human participants, described in Table 3, are not available for confidentiality reasons.

Supplementary information (SI) includes the full research instruments, detailed examples, and selected raw excerpts from students' responses and classroom observations. See DOI: https://doi.org/10.1039/d5rp00450k.

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