

SYNERGIZING SYSTEMS THINKING AND GREEN CHEMISTRY IN EDUCATION FOR SUSTAINABLE DEVELOPMENT CONTEXTS: A SYSTEMATIC REVIEW OF HIGHER EDUCATION CHEMISTRY CONTEXT (2021-2025)

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ABSTRAK

Synergizing sustainability principles into chemistry education at the higher education level is increasingly crucial to equip students for 21st-century challenges. Systems Thinking and Green Chemistry have been recommended as primary approaches to enhance holistic understanding and promote Education for Sustainable Development (ESD) in chemistry courses. This Systematic Literature Review (SLR) aims to examine how Systems Thinking integrated with Green Chemistry principles is applied to support sustainability education, and to explore a deeper understanding of its implementation practices in the context of higher education learning. A comprehensive search was conducted across major databases such as *Google Scholar* and the *Journal of Chemical Education*, covering studies published between 2021 and 2025. The inclusion criteria focused on research conducted by experts and discussing the application of systems thinking in chemistry learning, with a special emphasis on sustainability and green chemistry aspects. The findings indicate that the systems thinking approach addresses the complexity of chemistry in sustainability, fosters the development of critical thinking skills, and aids in integrating Education for Sustainable Development (ESD) principles into both practical and theoretical materials. These results highlight the potential of systems thinking as a framework for advancing sustainability competencies in chemistry education and provide recommendations for future curriculum development and research.

Keywords: systems thinking; green chemistry; ESD; prospective teachers; higher education

INTRODUCTION

Education for Sustainable Development (ESD) has become a key priority in addressing complex global challenges, particularly in science and chemistry education (Herranen et al., 2021). Despite the growing recognition of the importance of systems thinking and green chemistry in advancing ESD, several critical gaps remain in the literature. First, empirical evidence examining the effectiveness of integrated approaches between (ST–GC) on student learning outcomes in higher-level chemistry education is limited (M. Chen et al., 2020). Second, existing studies tend to emphasize

conceptual or theoretical discussions, with fewer studies investigating how these approaches are implemented in real-world classroom contexts. Third, most studies have been conducted in developed countries, leaving the application of ST–GC integration in developing country contexts underexplored.

Systems Thinking (ST) is a multidimensional cognitive approach characterized by an integrated set of analytical skills and reasoning strategies used to understand, interpret, and address complex phenomena (A. Z. Chen et al., 2025; MacDonald et al., 2025; Reynders et

al., 2025; Talanquer & Szozda, 2024). Systems thinking emphasizes understanding how the interacting components within a system collectively produce behavior or outcomes that cannot be fully predicted by examining each part separately (Krab-Hüsken et al., 2023; Witte & Müller, 2025). At its core, systems thinking involves viewing a system as an integrated whole, rather than simply a collection of separate and isolated components (Szozda et al., 2023; Vuorio et al., 2024). According to Szozda et al. (2023), a system is defined by at least three fundamental characteristics: (1) its components or elements, (2) the relationships or interconnections between these components, and (3) its overall purpose or function (Szozda et al., 2023).

The systems thinking framework has become increasingly relevant, as traditional teaching approaches are deemed inadequate to address contemporary global challenges. Systems thinking equips students and educators with holistic skills to analyze the interrelationships between issues and develop integrated solutions (nexuses) that can address multiple problems simultaneously (A. Z. Chen et al., 2025; Vuorio et al., 2024). Chemistry, and science more broadly, plays a central role in advancing sustainability; however, to be truly effective, education must incorporate systems thinking alongside traditional reductionist approaches (Vuorio et al., 2024). The systems perspective focuses on the dynamic network of interconnected elements that form a whole, which is crucial for understanding the emergent behavior observed in complex systems (Vuorio et al., 2024, 2025). Systems thinking is consistently recognized as one of the most fundamental competencies needed to guide societies toward a more sustainable future.

Prospective teachers need to develop this competency to effectively integrate Education for Sustainable Development (ESD) into their teaching practices (Reynders et al., 2025; Vuorio et al., 2025).

ESD is an educational framework designed to embed sustainability principles into teaching and learning processes across all levels of education (Vuorio et al., 2024). The primary goal of Education for Sustainable Development (ESD) is to foster a deeper understanding of the interconnectedness of environmental, social, and economic issues, thereby empowering individuals to make informed decisions and take responsible actions towards a more sustainable future (Vuorio et al., 2024). ESD is characterized by a holistic and interdisciplinary approach that integrates subject-specific knowledge with the broader context of sustainability and effective pedagogical practices (Reynders et al., 2025; Vuorio et al., 2025). ESD also emphasizes the development of key competencies that support ST, which are considered essential for understanding complex and interrelated issues.

However, the application of ST in chemistry education should not be limited to treating it as an abstract cognitive skill. Instead, ST needs to be integrated into concrete disciplinary practices, and green chemistry provides a very broad and meaningful context for this integration. ST offers a powerful framework for understanding complex chemical and environmental systems by highlighting the relationships, feedback loops, and interdependencies among their components (Krab-Hüsken et al., 2023; Reynders et al., 2025; Talanquer & Szozda, 2024). In chemistry education, this perspective allows students to go beyond isolated facts or reactions and begin to understand how

chemical processes affect and are affected by larger systems (Krab-Hüsken et al., 2023; Reynders et al., 2025). By integrating ST into learning, students are encouraged to analyze problems holistically, anticipate system behavior, and project the consequences of chemical decisions at multiple levels. (Reynders et al., 2025). This approach strengthens students's ability to connect molecular-level understanding to broader issues of global transformation, in line with the goals of ESD, which emphasizes critical learning, interdisciplinary perspectives, and action-oriented engagement (A. Z. Chen et al., 2025; Vuorio et al., 2024). In this study, the integration of ST and GC is examined through the lens of ESD competencies, specifically systems thinking and related sustainability competencies, which serve as analytical criteria to evaluate how learning practices support holistic understanding and sustainability oriented decision making with CheMIST Table, SOLO taxonomy, or concept maps. GC represents a disciplinary framework grounded in sustainability principles that provides an ideal context for operationalizing systems thinking competencies.

Witte et al. (2025) note that Green Chemistry (GC) was formally introduced in 1998 by Paul Anastas and John Warner, who conceptualized it through twelve guiding principles aimed at shaping the design, production, and practical use of chemical products (Witte & Müller, 2025). Essentially, the main goal is to reduce waste production, increase energy efficiency, and replace hazardous chemicals with safer options at every stage of a product's life cycle, from initial design to final disposal (Araripe & Zuin Zeidler, 2024; Witte & Müller, 2025). In contemporary chemistry education, GC plays a vital role, especially

when integrated with ecological perspectives and STEM. This approach offers a structured way to connect fundamental chemical knowledge to pressing global challenges, including climate change and sustainable energy solutions. Furthermore, GC principles enable students to critically examine the complexities and trade-offs inherent in chemical design processes (D'eon & Silverman, 2023; Vuorio et al., 2025).

The synergy between ST and GC is essential, as it directly reinforces the competencies promoted by ESD, including boundary setting, scenario analysis, critical reflection, and participatory decision-making. (Dilip & Kerr, 2024). By placing chemistry education within the dynamic interaction between environmental, social, and economic systems, students and prospective teachers can critically evaluate the sustainability of chemical processes and products in a real-world context. Recent studies show that combining systems thinking with GC principles can improve students' ability to address sustainability dilemmas, anticipate unintended consequences, and identify leverage points for transformative change (Constable, 2021; Witte & Müller, 2025). Therefore, the integration of ST and GC not only deepens disciplinary understanding but also operationalizes the broader objectives of ESD.

Based on this conceptual framework, this systematic review aims to analyze the ways in which ST and GC have been implemented together in higher education to achieve ESD goals. To organize the analysis, this study answers three main questions: (1) in what forms are ST and GC implemented in teaching practices; (2) what are the barriers, constraints, or contextual factors that influence the successful

integration of ST and GC at the university level; and (3) what gaps remain in the existing literature, and what directions are

METHOD

To maintain transparency and methodological rigor, this review was conducted in accordance with the PRISMA 2020 framework. A protocol was established in advance, clearly outlining the study objectives, inclusion criteria, search procedures, screening steps, and data synthesis approach (Page et al., 2021). This methodological approach facilitates comprehensive, transparent, and reproducible integration of previous studies at the intersection of ST, GC, and sustainability education, while minimizing potential bias (Julian et al., 2019). The search was conducted in Google Scholar and ScienceDirect, covering publications from 2021 to 2025, with searches conducted between November 11 and November 18, 2025.

Studies were selected using predetermined inclusion criteria to ensure relevance and methodological quality. The screening process was based on an adapted version of the PICO framework tailored to the context of educational research (Johnson & Hennessy, 2019):

- **Population:** Research focusing on students or educators in higher education.
- **Intervention:** Research involving the application or analysis of ST, GC, and/or ESD in teaching practices, curriculum design, laboratory teaching, or professional training initiatives. Studies discussing GC outside the scope of education are excluded.
- **Comparison group:** No specific comparison group is required.

recommended for curriculum improvement and pedagogical innovation at the intersection of ST, GC, and ESD?

- **Outcomes:** Study documenting educational outcomes (including knowledge mastery, skill development, and attitude changes), teaching approaches, and barriers or drivers related to ST and GC in relation to ESD.
- **Publication period:** Articles published between 2021 and 2025.

Overall, these criteria allow for the inclusion of diverse and relevant studies that explore the intersection and integration of ST, GC, and ESD. Article identification and screening were conducted according to the PRISMA framework. As shown in the PRISMA 2020 flow diagram (**Figure 1**), this process includes the stages of record identification, screening, eligibility assessment, and final study inclusion in the systematic review.

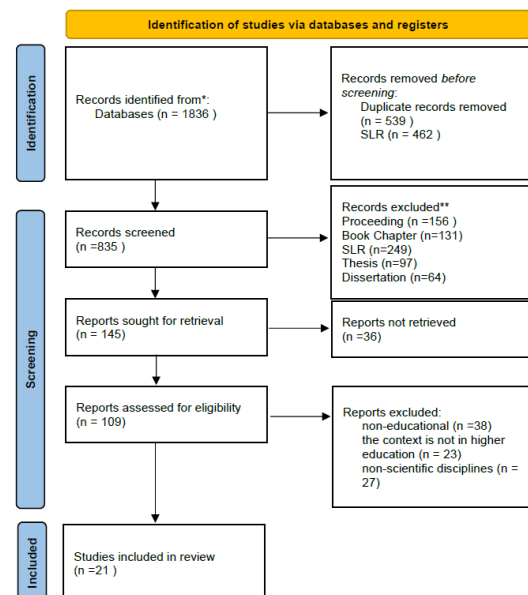


Figure 1 PRISMA 2020 Flow diagram

A systematic literature search was conducted in databases such as Google Scholar and ScienceDirect, with the help of the Publish or Perish tool, using the

keywords ST, GC, and ESD. The initial search yielded 1,836 records. After removing duplicates and applying a screening process, 21 studies were considered eligible based on the established inclusion criteria.

The selected studies were analyzed using a thematic approach, identifying key

patterns and recurring themes across the studies. The data were categorized into several analytical aspects, including learning approaches, teaching activities, learning tools, and the goals of systems thinking in teaching. This categorization process allowed the studies to be systematically compared and synthesized.

RESULT AND DISCUSSION

A review of 21 eligible studies highlights a heterogeneous but uneven research landscape. Although the studies cover a wide range of regions, most are concentrated in developed countries, particularly North America, with limited representation from developing countries such as Indonesia, South Africa, and Thailand. This imbalance highlights the need for broader research in regions facing urgent sustainability challenges.

The studies employed diverse data collection methods, including analysis of student-generated artifacts (e.g., SOCME and SMCM), interviews, classroom observations, and surveys. This methodological diversity reflects the early and exploratory phase of research on ST–GC–ESD integration, suggesting a need for greater methodological cohesion to support systematic comparison.

Overall, these findings reveal research gaps and contextual variations that influence how ST and GC are implemented in educational settings. Therefore, the following section focuses on identifying and analyzing the main pedagogical strategies used to implement ST–GC–ESD integration in various educational contexts. This section examines the main instructional approaches used to develop ST while integrating GC into ESD-oriented chemistry education. Findings show that ST is not developed through a single

pedagogical model, but rather through complementary strategies that vary in depth and focus of integration.

Six main patterns emerge. Collaborative learning based on system mapping strengthens students' understanding of the relationships between elements and system boundaries (Talanquer & Szozda, 2024). Project and case-based learning places chemistry concepts in real-world sustainability challenges, requiring learners to analyze trade-offs and consider the perspectives of various stakeholders (Araripe & Zuin Zeidler, 2024; Krab-Hüsken et al., 2023). Digital simulations enhance system modeling and learner autonomy, while green laboratory practices implement GC principles through environmentally responsible experiments (Bopegedera, 2025; A. Z. Chen et al., 2025). Data-driven and visualization-based approaches further support dynamic systems analysis and the identification of leverage points (Szozda et al., 2024).

Importantly, these approaches differ in the extent to which they develop higher-order competencies aligned with ESD. Some emphasize conceptual systems awareness, while others promote critical reflection, anticipatory thinking, and sustainability-oriented decision-making. **Table 1** summarizes these pedagogical patterns and their contribution to ST development.

Table 1. Learning approaches in operationalizing ST

Approachs	Ref.	Activity	Learning Tools	Purpose ST
Collaborative + System Mapping	1,2,3,4,5,6,7,8, 9,10	Group discussion, system map creation, presentation	SOCMEs, SMCM, SOCKit, CmapTools, Miro	System visualization, relationship analysis
Project-Based Learning	11,12,13,14	Project workshops, mentoring, trials, presentations	Project templates, models, rubrics	Complex problem solving, trade-off analysis
Case-Based Learning	9,15,16	Real case analysis, dilemma discussion, multi-stakeholder perspective	SDGs cards, pie charts, "Four E" framework	Business-industry systems analysis, conflict identification
Blended Learning Digital	17,7,12,10	Online modules, quizzes, simulations, self-paced learning	Xerte platform, DOC simulation, spreadsheet	Systemic self-learning, data analysis and prediction
Green Experimental	14,18,19, 20	Modification experiments, green metrics evaluation, comparative analysis	Lab equipment, green metric calculator	Understanding chemical process systems, impact evaluation
Data & Visualization Driven	1,4,8,12, 18, 21	Dataset analysis, simulation, pattern interpretation	DOC simulation, KCVS, graphing tools	Systemic data analysis, understanding dynamic systems

Note: 1 (Talanquer & Szozda, 2024); 2 (Reynders et al., 2025); 3 (MacDonald et al., 2025); 4 (Szozda et al., 2023); 5 (Vuorio et al., 2025); 6 (D'eon & Silverman, 2023); 7 (Ridley et al., 2024); 8 (Szozda et al., 2024); 9 (Araripe & Zuin Zeidler, 2024); 10 (Fors et al., 2023); 11 (Krab-Hüsken et al., 2023); 12 (Mahaffy et al., 2024); 13 (Wisudawati & Barke, 2024); 14 (Andrew et al., 2022); 15 (Dilip & Kerr, 2024); 16 (Reynders et al., 2023); 17 (A. Z. Chen et al., 2025); 18 (Bopegedera, 2025); 19 (Constable, 2021); 20 (Bruce et al., 2023); 21 (Vuorio et al., 2024).

The literature highlights collaborative system mapping as a key pedagogical strategy for developing systems thinking (ST) in chemistry education. By visually representing the relationships between chemical concepts and broader social, economic, and environmental contexts, this approach helps students move from fragmented knowledge to a more holistic systems perspective (Bruce et al., 2023; MacDonald et al., 2025; Ridley et al., 2024).

A tool often used in this approach is the SOCME extension, which models complex systems by mapping core chemical reactions alongside interacting subsystems, including material and energy inputs and outputs, as well as desired and undesired consequences (Bruce et al., 2023; Vuorio et al., 2025). SOCME also connects

basic chemical principles, such as stoichiometry and GC, with global sustainability challenges and SDGs. By organizing systems into smaller subsystems and exploring them sequentially, SOCME also helps manage cognitive load while promoting a deeper understanding of the system (Bruce et al., 2023; D'eon & Silverman, 2023).

Collaborative systems mapping places the visualization of interconnections as a central mechanism for building shared systems understanding. Approaches such as jigsaw puzzles, pairwork, and small-group collaboration enable students to combine insights from economic, social, and environmental subsystems into integrated system representations (Fors et al., 2023; MacDonald et al., 2025; Szozda et al., 2023, 2024; Talanquer & Szozda, 2024;

Vuorio et al., 2025). This collaborative engagement encourages the exchange of perspectives and facilitates the recognition of emergent system properties, resulting in more coherent maps with explicit causal structures (Dilip & Kerr, 2024; Szozda et al., 2024).

System relationships are typically represented through mapping techniques that depict causal, indirect, and cyclic connections, while subsystem boundaries are visually distinguished using elements such as color-coded regions (MacDonald et al., 2025; Reynders et al., 2025; Szozda et al., 2023; Vuorio et al., 2025). Digital platforms such as SOCKit support the mapping process through automated layout, and learning outcomes are often assessed using frameworks such as the SOLO taxonomy or the ChEMIST model to capture increasing levels of systemic complexity (A. Z. Chen et al., 2025; MacDonald et al., 2025; Reynders et al., 2025).

Nevertheless, several challenges remain, including students' difficulty connecting macroscopic phenomena to submicroscopic mechanisms, persistent linear reasoning that limits recognition of feedback loops, and the potential dilution of detailed analysis in collaborative settings (Szozda et al., 2023, 2024). Despite these limitations, collaborative systems mapping remains one of the most comprehensive approaches to fostering ST, as it integrates chemical knowledge with the broader socio-economic and environmental systems in which it operates.

Evidence from the reviewed studies suggests that project-based learning (PjBL) is a powerful strategy for developing students' capacity to address complex issues at the intersection of chemistry and sustainability. By engaging students in

authentic projects, this approach shifts learning from abstract theoretical understanding toward active problem investigation, solution development, and critical evaluation of potential consequences, often requiring explicit consideration of sustainability trade-offs (Andrew et al., 2022; Bopegedera, 2025; Krab-Hüsken et al., 2023; Mahaffy et al., 2024).

The projects described in the literature vary in focus but share a systems-oriented perspective. Examples include redesigning pharmaceutical synthesis processes to reduce waste and environmental hazards, climate change initiatives supported by system-visualization tools such as SOCKit, conceptual-model-guided environmental problem solving in chemical engineering education, and projects connecting global CO₂ emissions with local ocean acidification effects (Andrew et al., 2022; Mahaffy et al., 2024; Krab-Hüsken et al., 2023; Wisudawati & Barke, 2024).

Across these learning activities, trade-off analysis becomes a central component of the learning process. Students are required to evaluate competing priorities—such as balancing safety and economic feasibility in green synthesis or considering the environmental impacts of energy policies. When combined with ST frameworks and conceptual models, PjBL promotes holistic reasoning and helps students develop the critical competencies needed for responsible decision-making in complex sustainability contexts.

Case-based learning (CBL) is often used to connect theoretical concepts of GC and ST with practical sustainability challenges (Araripe & Zuin Zeidler, 2024; Dilip & Kerr, 2024; Fors et al., 2023). By engaging students in complex real-world

scenarios, CBL encourages them to analyze chemical problems from multiple stakeholder perspectives while considering broader ethical and sustainability implications.

Three main forms of CBL emerge from the reviewed studies. The first, called “case hacking,” involves reinterpreting existing industry cases through a sustainability-oriented framework, encouraging students to question corporate narratives and incorporating alternative sources such as NGO reports or industry data (Reynders et al., 2023). The second approach develops new cases from contemporary socio-environmental issues, including plastic waste and plant-based food alternatives, encouraging students to assess conflicting stakeholder interests (Araripe & Zuin Zeidler, 2024). The third approach views industrial practices and chemical products as analytical cases, enabling interdisciplinary evaluation of sustainability challenges related to substances such as PFAS and BPA (Dilip & Kerr, 2024).

Together, these strategies highlight the potential of CBL to foster critical analysis, ethical reflection, and systems-oriented reasoning, thereby strengthening students’ understanding of the complex relationships linking chemistry, society, and sustainability (Araripe & Zuin Zeidler, 2024; Dilip & Kerr, 2024; Reynders et al., 2023).

The digital blended learning approach has been proven effective in promoting student learning independence by integrating interactive platforms, online simulations, and carefully selected digital resources. This type of learning environment supports flexible and independent learning while helping students connect chemistry concepts to the

ever-evolving real-world context outside the classroom (A. Z. Chen et al., 2025; Fors et al., 2023; Mahaffy et al., 2024; Ridley et al., 2024).

An illustrative example is The Biorefinery Experience developed by Ridley et al. (2024), a simulation-based learning platform built using Xerte. This activity invites students to redesign a Brazilian sugarcane biorefinery using authentic data while evaluating alternative climate change scenarios. Designed as a three- to four-hour independent task, this simulation encourages temporal thinking and systems-level analysis. Student responses showed significant learning gains, with 97% reporting that the activity supported their ability to apply ST to real-world sustainability challenges (Ridley et al., 2024).

Mahaffy et al. (2024) demonstrated a comparable strategy through the use of online climate simulators, including the KCVS Design Our Climate Simulator (DOCs) and En-ROADS. These tools enable students to translate the broad challenge of global emissions reduction into manageable strategies while examining the outcomes of alternative policy pathways using complex systems models. These activities encourage critical analysis and inquiry-based learning. (Mahaffy et al., 2024). Complementary digital approaches include structured online modules designed to support self-directed learning. Reynders et al. (2023), for example, introduced an online SOCME module that combined multimedia content, quizzes, and virtual exercises, while Chen et al. (2025) developed a Systems Thinking (STEM) Enrichment Module that provided curated resources for self-directed exploration (Bopegedera, 2025; A. Z. Chen et al., 2025). These modules incorporate

reflective and collaborative elements that encourage students to take greater responsibility for their learning process.

Collectively, these digital tools shift the learning environment from passive knowledge delivery to active engagement. By experimenting with variables, analyzing system responses, and reflecting on the results, students develop stronger autonomy and systems thinking skills needed to address complex sustainability issues (A. Z. Chen et al., 2025; Fors et al., 2023; Mahaffy et al., 2024; Ridley et al., 2024).

Integrating GC principles into laboratory instruction is generally achieved through two complementary experimental strategies (Andrew et al., 2022; Bopegedera, 2025). The first strategy focuses on replacing traditional experiments with more environmentally friendly alternatives in introductory laboratory curricula. Examples include replacing the conventional copper cycle with copper extraction from malachite using safer reagents, and using simple materials such as paper cups and household substances in calorimetry and titration experiments to minimize hazardous waste without compromising core learning outcomes (Bopegedera, 2025).

The second strategy involves redesigning existing chemical syntheses as instructional case studies. In the case of the bupropion hydrochloride synthesis, hazardous solvents such as NMP and DCM were replaced by bio-based alternatives such as cyrene and ethyl acetate, while elemental bromine was replaced with N-bromosuccinimide, reducing waste production by 66% (Andrew et al., 2022).

This redesigned experiment requires students to critically evaluate chemical processes through structured tasks and the

use of green chemistry metrics, including the E-factor and Process Mass Intensity (PMI). By assessing improvements and examining considerations related to solvent safety and energy use, the laboratory activity becomes an opportunity for active learning that emphasizes the principles of sustainable chemical design (Bopegedera, 2025; Reynders et al., 2023).

A data driven and visualization oriented learning approach supports the development of systemic thinking by transforming abstract datasets into meaningful visual representations. For example, analyzing atmospheric CO₂ records from the Mauna Loa Observatory allows students to identify long-term trends, climate-related shifts, and planetary boundary issues, while also exploring the historical relationship between CO₂ concentrations and global temperature increases (D'eon & Silverman, 2023).

These analytical activities are complemented by system mapping exercises that highlight conceptual relationships and reveal common linear thinking patterns among students, as well as interactive simulations such as Build a Planet and Design Our Climate Simulator, which allow learners to experiment with variables that influence climate systems (Andrew et al., 2022; Mahaffy et al., 2024; Wisudawati & Barke, 2024). The ST-based framework connects these activities through a “zoom in” and “zoom out” perspective, linking processes at the molecular level to broader environmental systems (Talanquer & Szozda, 2024).

Through this approach, students develop the ability to interpret complex data patterns, understand dynamic system interactions, and predict future changes, equipping them with the analytical competencies needed to address climate-

related sustainability challenges (Bopegedera, 2025; Mahaffy et al., 2024; Talanquer & Szozda, 2024).

The reviewed studies used a variety of assessment methods to evaluate learning outcomes, including concept-based tests, rubric-based evaluation of systems maps like SOCME, reflective writing, and structured interviews. Some studies adopted established frameworks such as the SOLO taxonomy and the ChEMIST Table to assess the complexity of systems thinking. However, the diversity of assessment approaches highlights the lack of a standardized instrument for measuring systems thinking competency. Future research would benefit from the development of more consistent and validated assessment tools to enable better comparisons across studies and strengthen the evidence base.

The diversity of the reviewed studies, in terms of research design, sample size, and educational context, limits the generalizability of the findings. While some studies involved large cohorts and structured interventions, others were based on small-scale implementations or exploratory designs. This variation underscores the need for more rigorous, longitudinal studies to better understand the long-term impact of ST–GC integration in chemistry education.

In chemistry education focused on sustainability, GC plays a key role as an approach that prioritizes the prevention of environmental damage through the application of safer and more efficient chemical practices (Andrew et al., 2022; Reynders et al., 2023). However, addressing the complexity of sustainability issues requires GC to be positioned within a broader systemic perspective that integrates scientific, social, and ethical

considerations. ST supports this integration by providing analytical tools to analyze the causal relationships and broader implications of chemical activities in interconnected systems (Szozda et al., 2023, 2024). Based on this perspective, the next section explores how GC is implemented in educational practice and how the combined integration of ST, GC, and ESD promotes a more comprehensive understanding of sustainability.

In chemistry education, GC is integrated through pedagogical strategies that connect core chemistry knowledge to current sustainability challenges (Araripe & Zuin Zeidler, 2024; Bopegedera, 2025; Reynders et al., 2025; Ridley et al., 2024). The curriculum design integrates topics such as plastic pollution and the sustainability implications of plant-based food systems, while laboratory practices are adapted to more environmentally friendly formats through the replacement of hazardous reagents and the application of modern analytical techniques (Andrew et al., 2022; Araripe & Zuin Zeidler, 2024; Bopegedera, 2025).

Industrial case studies are further explored using critical approaches such as "case hacking," which encourages students to evaluate sustainability trade-offs and identify potential greenwashing. Visualization tools, including SOCME and interactive digital platforms, support this process by illustrating the complex interrelationships between chemical processes and broader sustainability systems (Bruce et al., 2023; Reynders et al., 2023).

GC principles are operationalized in educational activities through the application of several key principles particularly the third, fifth, sixth, seventh, and ninth principles which emphasize waste

prevention and atom efficiency (Andrew et al., 2022; Bopegedera, 2025; Bruce et al., 2023; Constable, 2021; D'eon & Silverman, 2023; Ridley et al., 2024). Students apply quantitative indicators such as the E-factor and Process Mass Intensity to assess the environmental performance of various synthesis pathways. Concepts related to renewable feedstocks and green catalysis are also introduced through case studies involving biorefineries and material substitution (Andrew et al., 2022).

At the same time, these learning activities reveal the practical complexities of sustainable chemical design, including trade-offs between chemical safety and energy efficiency, as illustrated in the case of bupropion synthesis (Andrew et al., 2022; D'eon & Silverman, 2023).

The application of GC in chemistry education presents several significant challenges. Students often experience conceptual difficulties in interpreting complex systems and connecting macroscopic observations to submicroscopic mechanisms (Szoza et al., 2023, 2024). Furthermore, densely structured curricula and limited teaching resources can limit opportunities for meaningful integration, while assessing systems thinking competencies remains methodologically complex and potentially subjective (Bopegedera, 2025; Vuorio et al., 2025).

One of the most demanding pedagogical challenges is helping students identify sustainability considerations and avoid "regrettable offsets." This difficulty becomes even more pronounced when discussing sensitive issues or working with incomplete industrial data, which can limit the depth of analysis possible in educational settings (Dilip & Kerr, 2024; Reynders et al., 2023).

In sustainability-oriented chemistry education, the integration of ST and GC within the ESD framework shifts instruction from fragmented content delivery toward the contextual analysis of complex systems (Talanquer & Szoza, 2024). This integration is supported through a deliberately structured curriculum that links fundamental chemical concepts with GC principles and the SDGs, often facilitated by visualization tools such as SOCME to represent the interconnected environmental and socio-economic impacts of chemical processes (Bruce et al., 2023; MacDonald et al., 2025). Real world engagement is further strengthened through the critical examination of industrial case studies and the implementation of green laboratory practices.

Although the benefits of integrating green chemistry into laboratory instruction have been reported, findings across studies are not entirely consistent. Some studies report significant improvements in students' ability to evaluate sustainability considerations and apply green chemistry metrics (Andrew et al., 2022; Bopegedera, 2025), while others highlight persistent difficulties in connecting experimental procedures to broader systems-level understanding (Szoza et al., 2023, 2024). This inconsistency may be due to differences in instructional design, intervention duration, and the level of support provided during laboratory activities. In particular, shorter interventions or those that provide less explicit guidance on systems thinking tend to produce more fragmented understanding.

Such integration is necessary because sustainability challenges are inherently multidimensional and cannot be thoroughly addressed through reductionist perspectives alone (Vuorio et al., 2024; Bruce et al.,

2023). ST offers a holistic analytical lens that helps students evaluate systemic consequences and anticipate long-term effects, thereby reducing the risk of regrettable substitutions in chemical design (Constable, 2021; Talanquer & Szozda, 2024). Ultimately, combining ESD, ST, and GC strengthens the relevance of chemistry education while preparing graduates with the competencies required to navigate complex sustainability issues.

The literature highlights several core dimensions for sustainability-oriented chemistry education, including a holistic systems understanding, critical analysis of sustainability considerations, a life cycle perspective, and attention to social justice considerations (Constable, 2021; Wisudawati & Barke, 2024). These priorities mark a transformative shift in chemistry education, where educators act as facilitators, sustainability principles are embedded in the core curriculum, and students are encouraged to view chemistry as a discipline capable of generating sustainable solutions (Andrew et al., 2022; Bopegedera, 2025).

Despite growing interest in integrating ST, GC, and ESD, significant

gaps remain. Current research often lacks robust and long-term assessments of ST competencies, while students often struggle to understand dynamic and complex systems. Furthermore, curriculum integration remains fragmented, particularly in laboratory activities and CBL-based instruction, and the social and economic dimensions of ESD remain insufficiently addressed.

Addressing this gap requires the development of ESD-oriented learning models that foster systems thinking among pre-service teachers, particularly in chemistry topics such as extraction. Student-centered strategies particularly CBL and collaborative systems mapping offer a promising direction. This approach is consistent with the Higher Education Curriculum Development Guidelines (2024), which recommend active learning methods such as case-based instruction, collaborative learning, project-based learning, and simulations (Kusumawardani, 2024). Therefore, integrating CBL with collaborative systems mapping aligns pedagogical practices with national higher education curriculum policies.

CONCLUSION

The findings of this systematic review indicate that the integration of ST and GC in chemistry education is primarily implemented through collaborative learning, project-based activities, and digital systems mapping tools that help students examine the relationship between chemical concepts and sustainability challenges at various scales. Despite this progress, several barriers remain, including conceptual difficulties among students, curriculum constraints, limitations in contextual learning materials, and the lack

of standardized methods for assessing systems thinking competencies.

This study has several limitations. First, the review only considered articles published from 2021 to 2025 and sourced from selected databases, which may lead to publication bias and the omission of relevant studies not indexed in these databases. Second, the inclusion criteria were limited to English-language publications, potentially overlooking important research from non-English-speaking regions. Third, variations in study

design, sample size, and teaching context among the included studies reduce the ability to directly compare results and limit the generalizability of the findings. Therefore, these limitations should be taken into account when interpreting the results of this review.

The literature further highlights important research gaps, particularly in the validation of assessment instruments, the

design of interdisciplinary instructional models, and the incorporation of socio-economic perspectives into ESD. Addressing these gaps will require future studies to develop innovative pedagogical approaches and ESD-based curriculum designs that integrate GC principles with systems thinking to prepare chemistry educators capable of addressing sustainability challenges.

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