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Sustainable from the start-an exploration of green chemistry utilizing second-year inorganic principles

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Inorganic chemistry plays a large role in the development of chemical methodologies targetting sustainable development goals such as clean energy (7), responsible consumption and production (12), and climate action (13). Catalysis, one of the 12 green chemistry principles, is ubiquitous across industry. Green chemistry developments in catalysis focus on the utilization of base metals or main group species in place of current precious metal systems. Research in this area requires a holistic approach, balancing ligand design, additives, solvent, and energy consumption in order to improve the sustainability of the system while maintaining high efficiency. The inquiry-based and gamified activities described herein are designed to integrate individuals into the green chemistry community, build confidence in green chemistry content, and explore discipline-specific applications. The activities were applied at the 2025 Canadian Chemistry Conference and Exhibition across two symposia, "*Peering into the Mist*" and "*Exploring Green Catalysis*". Similarly, two activities were implemented into a third-year inorganic chemistry course exploring green chemistry. Activity outcomes and insights are described, including commentary on challenges such as classroom silence and its relationship with student motivation.

Sustainability spotlight

We believe this work will be of interest to the green chemistry and inorganic chemistry communities, providing targeted methods to explore green chemistry and applications in modern catalyst design. The activities described incorporate components of inquiry-based learning, gamified learning, and interdisciplinary team approaches that allow junior and senior researchers to collaborate and explore modern inorganic chemistry and discipline specific green chemistry alterations. The activities, hosted at the 2025 Canadian Chemistry Conference and Exhibition (CSC) are scaffolded to provide an entrance for diverse audiences to engage with green chemistry, build green chemistry connections with general synthetic considerations, and develop discipline specific green chemistry recommendations for modern catalytic methods. The work was later extended to a third-year undergraduate inorganic chemistry course, showcasing the utility of the teaching and learning methods with various audiences. The teaching and learning methods applied in the development of the activities as well as the selected audiences reflect aspects of sustainability in quality education (4), gender equality (5), reduced inequalities (10), peace, justice and strong institutions (16), and partnerships for the goals (17), highlighting novel methods in green chemistry education for applications in conference settings, the professional's classroom, as well as undergraduate chemistry courses. The symposium design encourages interdisciplinary collaborations, fostering networking between participants, focused on emerging methods in sustainable development as well as discipline specific green chemistry recommendations in inorganic chemistry. We believe interventions such as this are critical in developing strong partnerships for the goals. Throughout the activities, flash talks, and panel discussions presented in the symposium, emerging research related to affordable and clean energy (7), responsible consumption and production (12), and climate action (13) are discussed.

Introduction

When considering green chemistry and its relationship to the 17 UN Sustainable Development Goals (SDGs), concepts such as oceanic plastic pollution, global warming, and environmental toxicity are the first concerns that come to mind. These relate directly to goals such as clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (14), and life on land (SDG 15).[1] Advances in sustainable development have been deeply rooted in environmentalism, focusing on pollution prevention, policy development, and

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government regulation.[2] Inorganic chemistry plays a significant role in advancing these SDGs, providing new opportunities to leverage transition metals and main group elements in the development of catalytic systems and new energy methods. Emerging technologies in these fields allow researchers to move away from reactionary approaches to environmental concerns, such as waste treatment and regulation, to proactive innovative approaches in which new systems tackle pollution prevention and energy consumption at the source.[2–4]

Catalysis is a burgeoning field of inorganic chemistry, represented in the 12 Principles of Green Chemistry.[5,6] The application of catalysis is ubiquitous across industry,[7] from cross-coupling reactions, heavily utilized in the pharmaceutical industry, to polymerization reactions, creating degradable plastics from renewable feedstocks; catalysts work to improve reaction mass efficiency (RME) and environmental factor (E-factor), while lowering energy consumption.[8] Research continues to improve classical catalytic systems such as Grubb's polymerization catalyst (Ru),[9] Suzuki–Miyaura cross-coupling catalysts (Pd),[10,11] and asymmetric dehydrogenation catalysts (Rh)[12] by researching base metals (Mn, Fe, Co, Ni) as a less toxic,[13–15] more abundant, and/or lower cost alternatives.[16–18] Nickel, for example, has shown significant promise as alternative systems to palladium catalyzed C–C and C–N cross-coupling reactions.[19] However, when compared to palladium systems with identical ligand frameworks and reactions conditions, nickel does not show equivalent reactivity. Watson *et al.* performed a head-to-head study comparing Ni and Pd featuring a 1,1′-*bis*(diphenylphosphino)ferrocene (dppf) ligand framework in performing a classical Suzuki–Miyaura cross-coupling reaction between aryl bromide and aryl boronic acid species.[20] Compared to Pd, the Ni system had a lower water tolerance, an unpredictable nucleophile intolerance, and was prone to protodeboronation; highlighting the need for further reaction optimization.

Approaching sustainable improvements in this sector requires a holistic approach, considering not only the metal, or main group species as a metal replacement,[21] but the ligand design,[22] solvents and substrates utilized,[23] and energy resources. With these considerations in mind, it is imperative to impart researchers with an understanding of coordination chemistry as well as green synthetic approaches and assessments. Previous surveys have indicated that crowded content and lack of knowledge in the content area are two major factors hindering the introduction of green chemistry content into undergraduate courses.[24] The learning activities described herein provide a Canadian second-year undergraduate understanding of coordination chemistry, catalysis, and green chemistry principles, challenging learners to apply their knowledge in the design of greener synthetic alternatives while balancing efficiency with sustainability. A focus is placed on structure-property relationships as they relate to ligand design to promote substitution reactions, synthetic considerations for cross-coupling reactions (ligand choice, solvent selection, reaction conditions), and introductory green chemistry applications in undergraduate synthetic laboratories. This work blends classical inorganic chemistry content with green and sustainable chemistry approaches, providing educators with specific content knowledge for ready integration of green chemistry into inorganic chemistry courses without large increases to course content.

Building partnerships for the goals: the role of equity, diversity, inclusivity, accessibility, and reconciliation in creating sustainable research spaces

Beyond the chemical considerations leveraged in the development of green alternatives, sustainable development must also consider the human aspect of green chemistry; what communities are impacted, which individuals are involved in innovation, and how do we share this wealth of knowledge, relating more deeply to goals such as quality education (4), gender equality (SDG 5), reduced inequalities (SDG 10), and peace, justice, and strong institutions (SDG 16). By developing communities of practice, we can begin to better support future sustainability leaders, creating partnerships for the goals (SDG 17).[24]

In developing communities of practice, it is imperative to incorporate principles of equity, diversity, inclusivity, accessibility, and reconciliation (EDI-AR) into platform design,[25] educational interventions, and research innovation. There is significant data driven support highlighting that diverse teams outperform homogenous teams and are associated with better problem solving and innovation.[26] For example, ethnically diverse teams have been shown to publish more and in higher impact journals.[26,27] Gender diverse scientific teams are 9.1% more likely to publish a novel paper and have 34% more citations compared to same-gendered teams.[28,29] Research by Hofstra and McFarland *et al.* similarly notes that underrepresented groups draw relations between ideas and concepts that have been traditionally missed or ignored, lending to higher levels of innovation; however, these contributions are often devalued.[30] In the context of inorganic chemistry, Simmons and Wisniewski *et al.* similarly note that advancements in base metal catalysis require collaborative innovation between experts in process development (industry) and individuals invested in exploratory science (academia) to develop future research portfolios to tackle modern problems.[31]

Chemistry conferences provide a unique platform allowing for the development of diverse communities of practice, including both underrepresented minorities as well as a blend of junior and senior researchers from industry and academia. In previous years, interactive symposium incorporating active learning techniques in place of traditional lecture methods have been valuable tools in expanding green chemistry practices.[32–34] Clapson *et al.* have highlighted the benefits of active learning and gamified learning in exploring green and inorganic chemistry at the national Canadian Chemistry Conference and Exhibition (CSC), designing symposium materials to be accessible to a blended audience of junior and senior researchers.[32,35] The Chemical Institute of Canada (CIC) Green Division continues to support interactive and workshop style symposium such as this to expand participant engagement and understanding in green chemistry as well as support partnerships for the goals.[36] The benefit of such interventions similarly includes their ready implementation into undergraduate learning environments, a topic further explored herein.

Gamification as an educational entry to green chemistry

The gamification of learning, activities implementing gaming components (leader boards, avatars, puzzles), and gamified learning, learning utilizing games (card games, board games, escape rooms), create low stakes learning environments in which participants can engage with content. The use of these strategies in undergraduate classrooms has been shown to increase student motivation, performance, and connectivity with their peers.[37] Several board games,[38–40] card games,[41–43] escape rooms,[44,45] and other activities[46–49] have been developed to explore components of green chemistry. Many of these activities are centred on a case study or centralizing theme, such as plastic pollution, incorporating board concepts to examine green chemistry applications. Utilization of discipline-specific chemistry knowledge is limited, allowing the activities to be completed without engaging with specialized course specific content. While the creation of active learning strategies accessible to interdisciplinary audiences is key in promoting green chemistry literacy and communities of practice, having discipline specific green chemistry content can help to promote its incorporation into existing courses without disrupting current learning outcomes. Exploring methods to utilize the same activities for general scientific audiences and discipline-specific audiences, such as those seen in an undergraduate classroom, allow for a combined approach, creating greater applicability for active learning interventions.

The activities described herein were implemented during two separate interactive symposia hosted by the Chemical Institute of Canada (CIC) Green Division at the 2025 Canadian Chemistry Conference and Exhibition (CSC). Symposium 1: *Peering into the Mist-The Interdisciplinary Structure of Problem Solving in Industry and Government* was cross listed with the Chemistry Education Division. The symposium intended to bridge the gap that exists between junior researchers and professional careers by introducing attendees to a variety of scientific professionals with backgrounds in industry, government, and scientific publishing who may not be represented on a typical career panel. Attendees engaged in a green chemistry focused ice–breaker activity (Activity 0) allowing for casual collaborations between senior and junior attendees. The activity was followed by a series of career presentations and an open discussion panel. A video "Peering into the Mist-what can you do with a chemistry degree?" was also shared on YouTube (167 views as of December 26, 2025) to engage members that were unable to attend the conference.[50] A total of 45 individuals attended the half-day symposium. Overall, participants demonstrated a high degree of agency and willingness to engage, likely reflecting both self-selection into the symposium and the professional context.

Feedback collected following the symposium indicated that participants perceived the format as engaging and valuable for career reflection and networking. Attendees highlighted the effectiveness of the collaborative, low-stakes activity in lowering social barriers and facilitating interaction among participants from different career stages and sectors. In particular, early-career researchers noted that the informal structure made initiating conversations with senior researchers and industry professionals feel more approachable. While no formal assessment of longer-term impacts was conducted, the feedback suggests that the symposium structure was well received and aligned with participant needs for authentic, cross-sector engagement.

Symposium 2: *Exploring Green Catalysis-The Modes, The Methods, The Targets* was cross listed with the Inorganic Division and Chemistry Education. The symposium highlighted topics in the development and application of green catalysts including base metal alternatives for precious metal catalytic systems, ligand design, greener solvents and reagents, improved chemical safety, and sustainable transformations. Activities 1–3 were interspersed between research presentations (10 minutes) and panel discussions followed by a closing round table discussion on methods to implement green chemistry into individuals' own research and teaching (Activity 4). Approximately 60 participants (40% senior researchers and educators, and 60% junior researchers) attended the half-day symposium. The symposium was divided into two sections (8:00–9:40am and 10:00–11:40am) with a coffee break at the midway. In each section there was 25–35 participants. Approximately 50% of participants attended both sessions. The flexibility of the symposium schedule, rotating activities and speakers in both sections, allowed for asynchronous engagement with individuals joining the later session. Similar to previous interactive symposia reported by Clapson *et al.* participants were highly engaged with the activities,[32,35] often reluctant to move on to the next activity if they ran out of time. Compared to previous iterations, the number of participants has continued to increase as a result of the growing popularity of interactive sessions and workshops within the Green Chemistry and Education Divisions. Of the senior researchers in attendance, we note that most were already known within the green chemistry education and green inorganic chemistry community.

Following the resounding success of the two symposia during the CSC we chose to implement activities (0 and 2) into a third-year inorganic chemistry undergraduate course (8 students). The course was focused into four main components, explorations in green inorganic chemistry, symmetry and spectroscopic analysis, main group element reactivity, and cross-coupling catalysis. The described activities were used as a primer before commencing content on green chemistry as well as a tool to promote student understanding following lecture material. Additional information on the utilization of these activities in the classroom setting is detailed in the discussion.

Activities

Activity 0-Peering into the Mist: a murder mystery to build partnerships for the goals

Activity 0-Peering into the Mist was intentionally designed to place participants in an unfamiliar and partially ambiguous problem space. Rather than presenting a well-defined task with a single correct solution, the activity mirrors the uncertainty, incomplete information, and competing perspectives characteristic of real-world sustainability challenges. Participants are required to make sense of evolving evidence, negotiate differing interpretations, and arrive at defensible conclusions without the reassurance of procedural certainty.

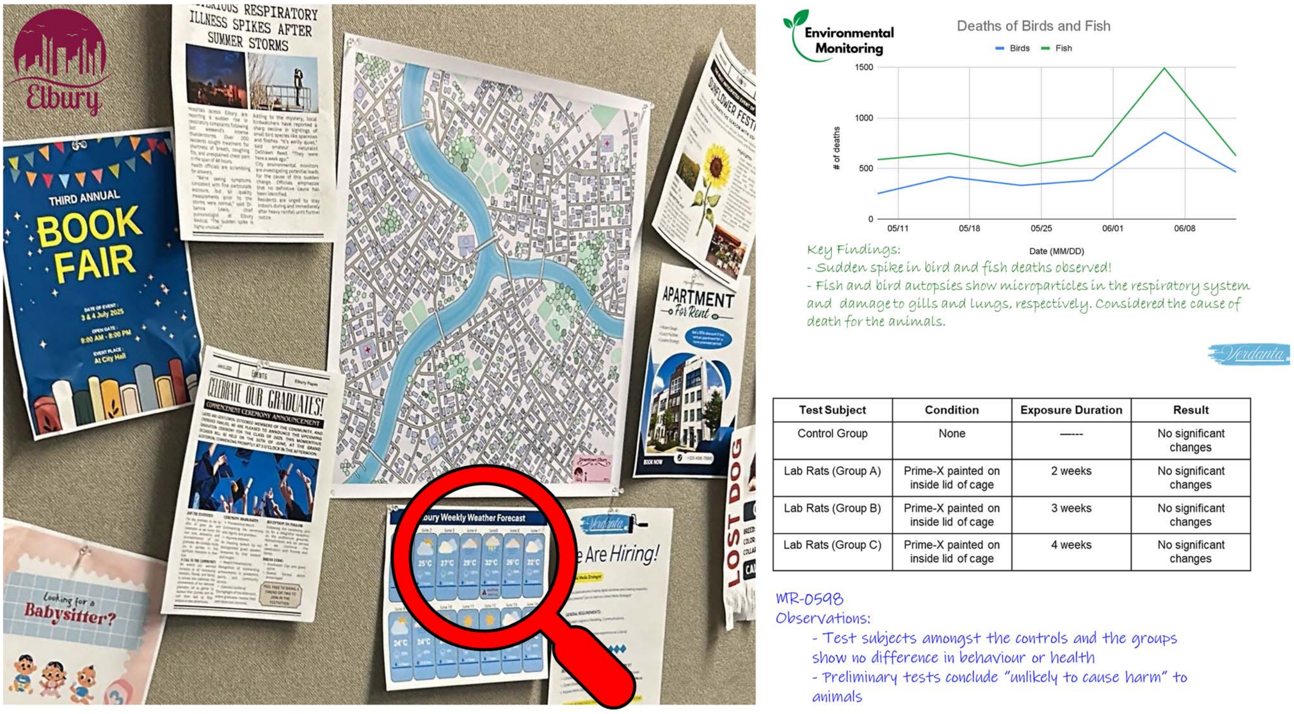
The activity (40 minutes) provided a structure for engaging participants in collaborative investigation of a complex sustainability scenario. Participants are provided with an activity booklet, outlining the goals of the activity and key terminology, alongside access to a community board which contained clues required to solve the "sustainability mystery" (Fig. 1). Participants were asked to form groups of 4–6 and everyone was provided with a role envelope. Inside of each envelope is a character role (CEO, technician, politician, *etc.*) alongside data and evidence that can be used to solve the mystery. By sharing their clues with one another participants can solve the mystery by determining the cause of the sustainability failure and identifying the responsible individuals. Preventative actions that could be implemented by companies in the future were proposed and defended by participants.

Learning objectives:

- Collaborate with diverse senior and junior researchers to solve a scientific problem.
- Utilize methods in systems thinking to analyse environmental challenges and crises.
- Engage with key ideas related to systems thinking, hotspot analysis,[51] and environmental transformations of pollutants as they arise in the scenario.
- Interpret a complex system and propose a defensible solution to the presented problem(s).

Reflections*:* Activity 0 was facilitated with a light-touch approach, in which facilitators prompted discussion and clarification without directing participant conclusions utilizing an inquiry-based approach.[52] A central community board was used to display shared contextual information and encourage physical movement, cross-group interaction, and the synthesis of distributed evidence. Participants were required to actively seek out information, manipulate physical artifacts, and engage with materials beyond their immediate role envelope, reinforcing the collaborative and exploratory nature of the task. By requiring participants to move, observe, and interact with shared resources, the activity externalized cognition and reduced reliance on purely internal or individual reasoning. Groups were ideally composed of participants who did not know one another well, further encouraging participants to negotiate communication styles, confidence levels, and agency within the group.

During the symposium implementation, Activity 0 was met with a high level of engagement and sustained participation. Participants readily entered the narrative, interacted extensively with both role-specific and shared materials, and engaged in active discussion throughout the session. Informal feedback from both academic participants and invited industry professionals indicated that the activity was perceived as engaging, meaningful, and conducive to authentic conversation across career stages. Observations suggested that the success of the activity was strongly influenced by participant buy-in and group composition. Groups that included a mix of experience levels and comfort with open-ended discussion tended to navigate the ambiguity of the scenario more productively.[53–55] In professional and symposium settings, the level of agency afforded by the



Key Findings:
- Sudden spike in bird and fish deaths observed!
- Fish and bird autopsies show microparticles in the respiratory system and damage to gills and lungs, respectively. Considered the cause of death for the animals.

Test Subject	Condition	Exposure Duration	Result
Control Group	None	------	No significant changes
Lab Rats (Group A)	Prime-X painted on inside lid of cage	2 weeks	No significant changes
Lab Rats (Group B)	Prime-X painted on inside lid of cage	3 weeks	No significant changes
Lab Rats (Group C)	Prime-X painted on inside lid of cage	4 weeks	No significant changes

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Observations:
- Test subjects amongst the controls and the groups show no difference in behaviour or health
- Preliminary tests conclude "unlikely to cause harm" to animals

Fig. 1 Cropped image of the community board clues provided during Activity 0, highlighting key information on acid rain using the magnifying glass (left). Example information provided to participants in their role envelopes (right).

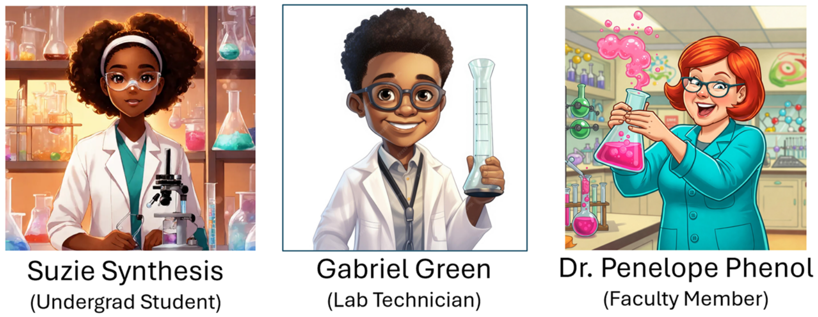
activity appeared well calibrated, with participants supporting one another in synthesizing information and articulating perspectives.

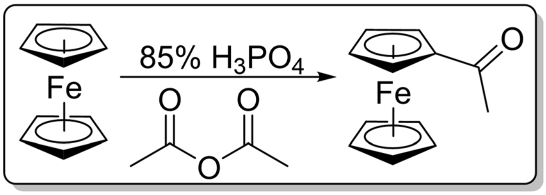
Higher cognitive skills are required from students to draw relationships between activity materials and content knowledge.[56] In groups with heterogeneous knowledge skills, such as undergraduate classroom settings, students benefit from additional facilitator guidance.[57] When introduced into a third-year inorganic classroom, students benefited from clearer articulation of task goals and more explicit prompts to guide evidence synthesis and discussion. Future iterations would benefit from embedding additional guiding questions or structured prompts within role envelopes to provide a guide without undermining the intentional use of uncertainty. These observations highlight the importance of balancing productive ambiguity with appropriate support, particularly when working with less experienced learners.[58]

Activity 1-our role: exploring individuals' roles in developing sustainable alternatives

Chemistry research has led to extraordinary achievements tackling global sustainability challenges; however, research and teaching laboratories also lead to significant waste and CO_2 production.[59–61] Recognizing these obstacles, initiatives such as My Green Lab®[62] and the Laboratory Efficiency Assessment Framework (LEAF)[63] provide toolkits for implementing sustainable laboratory methods into academic laboratories including methods in plastic reduction,[64] improved water efficiency, and energy efficiency.[65,66] Acting as global role models, universities must meet the call to action in improving laboratory sustainability.[67] This also included providing students with opportunities to not only learn green chemistry principles and utilize green metrics, but how to implement chemistry content knowledge to propose green alterations to current processes.

In this activity, participants gathered in groups of 4–6 members. Everyone randomly selected a character role; undergraduate student, teaching assistant, laboratory technician, faculty member/lab director, or health and safety officer (Fig. 2). All participants were given a copy of an undergraduate inorganic chemistry laboratory experiment focused on the synthesis of acetylcyclopentadienyl(cyclopentadienyl)iron(II) from ferrocene utilizing a Brønsted acid catalyzed Friedel–Crafts aromatic substitution reaction.[68] Participants reviewed the experiment from the perspective of their various roles, leveraging systems thinking to propose alterations to the laboratory or laboratory space to improve the sustainability of the experiment (20 minutes). Participants were provided with tools such as the





1. What are the "non-sustainable" elements of this experiment?
2. What changes would you make to make the experiment procedure itself more sustainable?
3. What changes would you make to make the experimental space itself more sustainable?
4. What changes would you make beyond the experiment procedure and space in the interest of sustainability?

I. Synthesis and Isolation of Crude $Fe(C_5H_5)(C_5H_4COCH_3)$

Perform in a fumehood.

Add 1 mL of 85% phosphoric acid dropwise to a stirring mixture of 1.73 g of ferrocene and 8.2 mL of acetic anhydride in a small Erlenmeyer flask. Use a $CaCl_2$ drying tube to protect the solution. The reaction is heated in a boiling water bath for 10 minutes, and then the mixture is poured onto approximately 20 g of ice in a large beaker. After the ice has melted, $NaHCO_3$ is added until CO_2 no longer forms, and the solution is neutral. The solution is cooled in an ice bath for 30 minutes and the product is allowed to precipitate. The solid is isolated by vacuum filtration and washed with water until the washings are pale orange. The crude solid is dried in air for 15 minutes before being isolated from the vacuum filtration apparatus.

Fig. 2 Visual of the five stakeholders in Activity 1, part 1 of the experimental procedure, and the guiding questions given to participants.

twelve green chemistry principles, the Beyond Benign Greener Solvent Guide,[69] and an environmental health and safety (EHS) assessment and life cycle analysis (LCA) of common organic solvents.[70] Participants were challenged by the facilitator to not only consider the chemical aspects of sustainability, but also EDI-AR for teaching and learning in the laboratory space.[71–73]

Learning objectives:

- Utilize systems thinking to adopt alternative perspectives when exploring green chemistry considerations, challenging one's own definitions of green chemistry and sustainability.
- Apply current green chemistry tools to adapt existing resources to be "greener" through changes to chemistry, infrastructure, policies and mindset.
- Collaborate with an interdisciplinary team in developing sustainable laboratory processes and procedures, considering both chemistry and EDI-AR.

Reflections: Activity 1, Our Role, was designed using an inquiry-based approach in which participants can collaborate to provide several complementary sustainability perspectives. Utilizing systems thinking, participants explore green chemistry alterations to an undergraduate inorganic chemistry experiment from the point of view of different stakeholders. Roles were chosen to encourage participants to engage with broader perspectives while gaining a better understanding of how they may be able to influence their own laboratory practices at their home institutions.

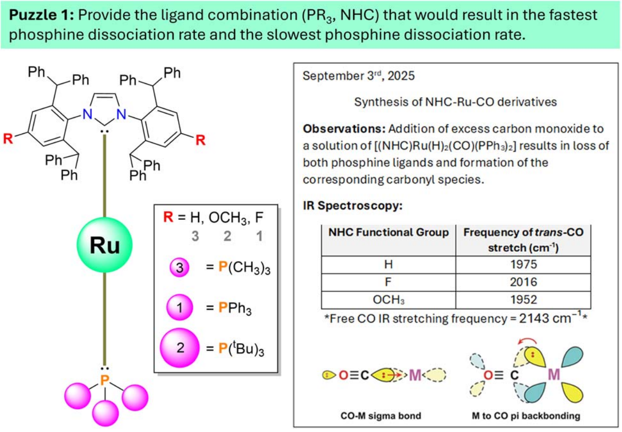
Recommendations on how to improve the laboratory were categorized as follows: alterations to experimental procedure, alterations to the experimental space, alterations beyond procedure and space. Most participants comments were focused on alterations to the experimental procedure including key themes such as reducing the experimental scale (reducing waste and improving safety), substituting reagents for greener alternatives (replacing dichloromethane with ethyl acetate), selecting low solvent purification methods (recrystallization *vs.* column chromatography), and introducing methods to monitor the reaction. These themes reflect introductory knowledge on green chemistry principles such as preventing waste, safer solvents and reaction conditions, and increasing energy efficiency. Few examples considered specific inorganic chemistry related alterations or alterations to improve green metrics, for example, replacing phosphoric acid with a Lewis acid catalyst as a means to lower acidification potential,[74] highlighting a need for more discipline-specific green chemistry education.

Improvements to the laboratory space included ensuring personal protective equipment (PPE) requirements correlate with the potential hazards, adding signage indicating the importance of proper waste disposal, and matching academic procedures to current industrial standards. For example, a dichloromethane ban was instituted in the United States limiting its utilization in industrial applications. While the ban did not include academic laboratories, it promoted researchers and educators to look for sustainable alternatives.[75] In a similar vein, participants recommended improving the sustainability of the laboratory by including green chemistry content into the lecture and lab manual. This included providing an overview on green chemistry as well as generating experimental questions challenging students to consider the sustainability of the experimental procedure. These comments reflect current green chemistry education practices, exploring systems thinking and the 12 green chemistry principles,[76] but could be expanded to include a deeper understanding of green metrics and discipline-specific knowledge.

Activity 2-a sustainability puzzle: leveraging second-year inorganic principles for sustainable catalyst design

Escape room activities are a popular gamified teaching tool, allowing students to apply their course knowledge in a novel learning environment. The puzzle-based nature of the activities alongside associated locks creates opportunities for educators to embed both lecture and laboratory skills while providing immediate feedback to participants.[77,78] The puzzles herein are designed to challenge participants understanding of coordination chemistry, ligand design, and relative effects on common inorganic transformations while incorporating green chemistry design principles.

Puzzle 1-dissociative mechanisms. Participants are provided with a box containing three laminated N-heterocyclic carbene (NHC) derivatives (R = H, OCH_3, F),[79] three 3D phosphine ligand representations (PR_3, where R = CH_3, Ph, ^{t}Bu), and a bead on a dowel representing the metal (Ru) and associated bonds to ligands *trans* to one another (Fig. 3). Conference attendees were provided with a workbook and activity sheet detailing the goals of the puzzle as well as key background information on the *trans*-effect, d-orbital back bonding, Tolman's electronic parameter, cone angle, bite angle, and ligand substitution mechanisms (associative and dissociative).[80,81] The inclusion of ample background information assisted in providing context for participants that did not have a background in inorganic chemistry. Although some information may be truncated, we believe these definitions and examples are required to provide participants with the prerequisite knowledge to solve the puzzle. Students in the inorganic II course, however, were provided with significantly less information and


Puzzle 1: Provide the ligand combination (PR_3, NHC) that would result in the fastest phosphine dissociation rate and the slowest phosphine dissociation rate.

September 3rd, 2025

Synthesis of NHC-Ru-CO derivatives

Observations: Addition of excess carbon monoxide to a solution of $[(NHC)Ru(H)_2(CO)(PPh_3)_2]$ results in loss of both phosphine ligands and formation of the corresponding carbonyl species.

IR Spectroscopy:

NHC Functional Group	Frequency of *trans*-CO stretch (cm^{-1})
H	1975
F	2016
OCH_3	1952

Free CO IR stretching frequency = 2143 cm^{-1}

Fig. 3 Diagram of the tactile components included in puzzle 1 (left). Example laboratory notebook clue provided to the inorganic II students (right).

instead more ambiguous clues and hints as they had previously learned this content in a prerequisite course.

Learning objectives:

- Explain how steric and electronic properties affect relative ligand–metal bond strength through the *trans*-effect.
- Rationalize donicity and steric trends utilizing inorganic spectroscopic data.
- Predict relative reaction rates of ligand dissociation pathways.

To solve the puzzle, participants needed to pair the various NHC and phosphine ligands together and move the metal bead up or down the dowel to represent the relative metal–ligand bond lengths as a function of ligand donicity and sterics. For example, a more strongly donating NHC (R = OCH_3) would form a stronger (shorter) bond with the Ru. Alternatively, phosphine ligands with a large cone angle (R = ^{t}Bu) would result in a longer (weaker) metal–ligand bond. The rate of ligand dissociation following a dissociative mechanism is related to the strength of the metal–ligand bonds *trans* to one another. A stronger NHC donor would weaken the metal-phosphine bond allowing for faster dissociation rates.[81]

Puzzle 2-considerations in experimental design for Suzuki–Miyaura cross-coupling. Cross-coupling reactions make up approximately 12% of all reactions performed by pharmaceutical companies,[82] representing an area of industry that could greatly benefit from the introduction of green chemistry. Compared to other cross-coupling mechanisms, the Suzuki–Miyaura cross-coupling reaction has milder reaction conditions, utilizing safer reagents, more common nucleophiles such as boronic acids, and is generally more environmentally friendly.[82,83] More recently research has focused on methods to perform cross-coupling reactions in water as a greener solvent.[84] Similarly, base metals such as Ni[85–87] and Fe[88–92] show promise as more abundant and less toxic alternatives to palladium based systems. Puzzle 2 explores the opportunities and challenges in implementing green chemistry alterations to industrial transformations, showcasing the balance required to create efficient and sustainable catalysts.

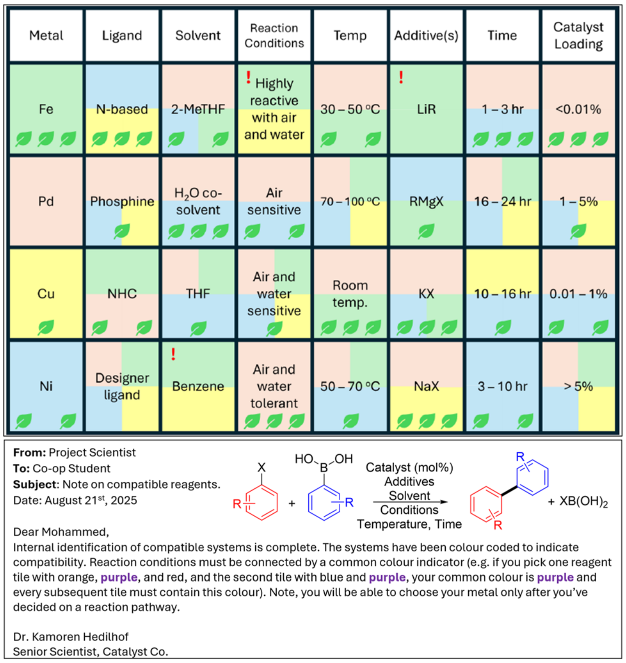
Learning objectives:

- Leverage knowledge on hard-soft acid base theory, coordination geometry, and solubility to pair metals with compatible ligand designs and reaction conditions.
- Utilize knowledge on common cross-coupling mechanisms (Suzuki–Miyaura, Kumada, Negishi)[83] and metal reactivity (oxidative addition, transmetalation, reductive elimination) to select complementary additives.
- Balance green chemistry alternatives (solvents, energy input, chemical safety) with catalyst function to determine a feasible catalyst design.
- Discuss the barriers in applying sustainable alternatives while maintaining chemical functionality.

Symposium participants and inorganic II students were provided with a workbook with green chemistry resources such as the 12 principles of green chemistry, transition metal abundance, green solvent guides, the EHS and LCA information for common organic solvents, and several catalyst examples utilizing the metals and ligands showcased in the puzzle materials. The puzzle materials consist of two tables, one in which the leaves and the colours of the metals are obscured (A), and the other as presented in Fig. 4(B). Participants were challenged to make their ligand, solvent, additive, and reaction condition selections utilizing table A before revealing table B to assess the greenness of their selection.

All participants, before revealing table B, selected Ni or Fe (catalyst loading 0.01 mol%) as the metal centre combined with a phosphine ligand and potassium salt as the additive, utilizing water as a solvent under ambient conditions stirring for 1–3 hours. Once table B was revealed, participants immediately understood they were unable to select Fe as the metal centre without having to implement harsher reaction conditions. Many participants, especially students in inorganic II, tried to still utilize Ni as the metal centre. While many ligand combinations and reaction conditions that are developed for Pd can be applied to Ni, these complexes still suffer from lower turnover frequencies (TOF), higher catalyst loadings, and lower air/water tolerance.[20,87] Overall, Pd paired with a phosphine ligand is the greenest synthesis due to its water tolerance and lower catalyst loading. This conclusion sparked conversations between participants on the balance of green *versus* efficiency, with questions such as "if nickel is greener and cheaper but requires double the amount compared to palladium, is it really sustainable?".

Puzzle 3-green catalyst design for N_2O reduction. Similar to puzzle 2, this puzzle explores concepts in ligand design, metal selection, and the balance of green chemistry interventions and desired catalyst performance. N_2O, a by-product of industrial fertilizers, is an atmospheric pollutant responsible for ozone



Metal	Ligand	Solvent	Reaction Conditions	Temp	Additive(s)	Time	Catalyst Loading
Fe 🍃🍃🍃	N-based 🍃🍃🍃	2-MeTHF 🍃🍃	! Highly reactive with air and water	30 – 50 °C 🍃🍃	! LiR	1 – 3 hr 🍃🍃🍃	<0.01% 🍃🍃🍃
Pd	Phosphine 🍃	H_2O co-solvent 🍃🍃🍃	Air sensitive 🍃🍃	70 – 100 °C	RMgX 🍃	16 – 24 hr	1 – 5% 🍃
Cu 🍃	NHC 🍃🍃	THF 🍃	Air and water sensitive 🍃	Room temp. 🍃🍃🍃	KX 🍃🍃🍃	10 – 16 hr 🍃	0.01 – 1% 🍃🍃
Ni 🍃🍃	Designer ligand	! Benzene	Air and water tolerant 🍃🍃🍃	50 – 70 °C 🍃	NaX 🍃🍃🍃	3 – 10 hr 🍃🍃	> 5%

From: Project Scientist
To: Co-op Student
Subject: Note on compatible reagents.
Date: August 21st, 2025

Dear Mohammed,
Internal identification of compatible systems is complete. The systems have been colour coded to indicate compatibility. Reaction conditions must be connected by a common colour indicator (e.g. if you pick one reagent tile with orange, **purple**, and red, and the second tile with blue and **purple**, your common colour is **purple** and every subsequent tile must contain this colour). Note, you will be able to choose your metal only after you've decided on a reaction pathway.

Dr. Kamoren Hedilhof
Senior Scientist, Catalyst Co.

Fig. 4 Image of the reaction component selection chart revealing the metal colour coding and number of associated leaves (level of sustainability) for each selection (top). Example email clue provided to the inorganic II students (bottom).

depletion.[93] The transformation of environmental pollutants such as N_2O or CO_2 into value-added materials has been a topic of interest for several decades. Piers *et al.* previously reported a series of iridium PCP carbene complexes capable of activating N_2O.[94–96] Participants compare the donicity[97] and resulting reactivity of the pincer ligands with several extrapolated metal combinations including nickel,[98,99] cobalt,[100,101] and iron.[102,103]

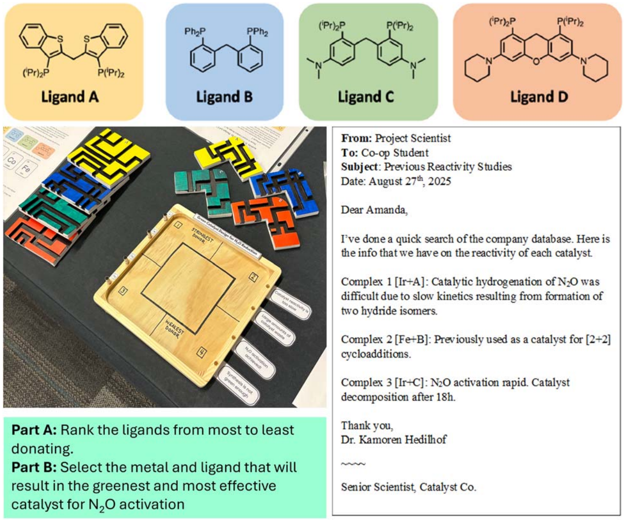
Learning objectives:

- Apply knowledge of the Tolman Electronic Parameter and the effects of electron-withdrawing and electron-donating functional groups to rank relative ligand donicity.
- Exemplify the differences in complex reactivity between alternating metal and ligand selections.
- Emphasize the cyclical process of alternating ligand design, metal combination, and green chemistry considerations in catalyst development.

Within the activity workbook, participants are provided with the synthetic routes for each of the PCP pincer ligands, the C≡O stretching frequencies for each associated carbonyl complex, and general notes on known reactivity of each ligand on varying metals. This puzzle was completed in two steps. First, participants needed to utilize the maze corner pieces (each colour coded to represent a different ligand) and the IR data provided to organize the ligands from most to least donating (Fig. 5). Second participants must choose the greenest ligand and metal combination that leads to the desired reactivity. Initially, most participants selected the dimethylamine derivatized *ortho*-phenylene ligand, C, as the greenest ligand due to the short number of synthetic steps. However, the notes suggest that the resulting catalyst decomposes upon activation of N_2O, resulting in greater waste and lower efficiency.

Participants must balance the described reactivity and synthetic knowledge to choose the most reasonable design (iridium with ligand B). Overall, participants were readily able to grasp the concepts within the puzzle but struggled to use the puzzle pieces themselves. It is very important when preparing the central tiles that there is no way for alternative metals to achieve the same outcome as the correct answer. Facilitators also found it relevant to indicate to participants how the puzzle pieces should be oriented and how the metal pegs can move, although it was mentioned in the workbook. Each piece has an associated ligand letter in the top lefthand corner. The letters should be oriented in readable format within the maze.

Reflections: Symposium attendees enthusiastically assembled the tactile materials within each puzzle. Attendees often returned to the workbook to look for additional information, discussing content together. Several attendees had previous experience with chemistry educational escape rooms, or other active learning techniques. Most symposium participants completed the puzzles within 20–30 minutes. Conversely, students in the inorganic II class required significant prompting to open the puzzle boxes and utilize the materials within. Rather, students focused on reading the workbook and attempting to decipher the puzzle answers from there. There was less communication between team members, mainly relying on the better performing students to lead the way. This was the students' first experience with an educational escape room activity. It is unclear whether this hesitancy is related to the novelty of the educational tool, a lack of student understanding, or a lack of motivation. We note that the differences in prerequisite information in the student workbook compared to the symposium workbook may have resulted in decreased student comprehension, requiring additional content recall. However, struggling with problems has been shown to lead to deeper cognitive processing overall,[104] highlighting an important balance between challenging student knowledge and facilitator guidance.



Part A: Rank the ligands from most to least donating.
Part B: Select the metal and ligand that will result in the greenest and most effective catalyst for N_2O activation

From: Project Scientist
To: Co-op Student
Subject: Previous Reactivity Studies
Date: August 27th, 2025

Dear Amanda,

I've done a quick search of the company database. Here is the info that we have on the reactivity of each catalyst.

Complex 1 [Ir+A]: Catalytic hydrogenation of N_2O was difficult due to slow kinetics resulting from formation of two hydride isomers.

Complex 2 [Fe+B]: Previously used as a catalyst for [2+2] cycloadditions.

Complex 3 [Ir+C]: N_2O activation rapid. Catalyst decomposition after 18h.

Thank you,
Dr. Kamoren Hedilhof

~~~~

Senior Scientist, Catalyst Co.

Fig. 5 Image of the puzzle board and maze tiles (left). Each coloured maze tile represents one of the ligands (top). A ligand to be paired with a metal is placed in the centre of the board. The metals are represented by wooden pegs on the side of the puzzle board. The correct answer will allow the peg to move through the maze to the label "N_2O activation". Example email clue provided to inorganic II students (right).

Activity 3-keywords: a waste and hazard reduction puzzle

Activity 3 represents an entry level introduction to green chemistry content before approaching discipline-specific materials. It is best implemented as a review tool to assess participants' understanding of preliminary green chemistry content such as applications of the 12 green chemistry principles, understanding definitions of green chemistry metrics, and modern themes in catalysis.[105] Here participants answer a series of green chemistry and catalysis focused questions with multiple choice style answers. Instead of listing answers as A, B, C, D, answers are correlated to a letter and colour (Fig. 6). The goal is for participants to spell out a key word or phrase utilizing the correct answers. This method provides students with internal feedback on the correctness of their answer without having to wait for facilitator feedback.

Learning objectives:

- Expose participants to metrics relevant to chemical safety-such as LD_{50}, solvent flash points, and safety data sheets.
- Expose participants to questions and metrics that pertain to reaction efficiency-such as atom economy, turnover number, and turnover frequency.
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- Expose participants to questions and metrics that pertain to waste reduction-such as E-factor and atom economy.

Reflections: The activity required little facilitator intervention, taking participants approximately 10–15 minutes to complete. The main point of confusion was the colour coding associated with the tiles. There are four different colours (red, blue, yellow, and green) each associated with a different keyword. To solve the puzzle, participants must not only select the correct answer, but the colours for each answer must be the same. For example, if a team has selected the green keyword (indicated by small green stickers on the question tiles) they must use only green letter tiles to select an answer. This activity nuance is not directly stated in the activity instructions, acting as an additional puzzle component. To simplify the activity for future audiences, we recommend mentioning the colour coding in the instructions. Facilitators noted that small groups of junior symposium attendees (2 people) and attendees wishing to participate alone (only student attendees), often elected to perform activity 3 before attempting the other activities.

We theorize that junior participants and solo participants are more drawn to this activity as it required minimal discipline-specific knowledge and can be performed without needing to engage in larger group discussions. In this sense, activity 3 acts as a low stakes entry point for attendees who are beginning to build their green chemistry network.

Activity 4-research in action: a discussion on current green chemistry research

Activity 4 was designed to highlight current research in green and sustainable chemistry while supporting community-building and professional engagement across career stages. Unlike earlier activities in the symposium, activity 4 emphasized exposure and discussion rather than structured problem-solving or task completion.

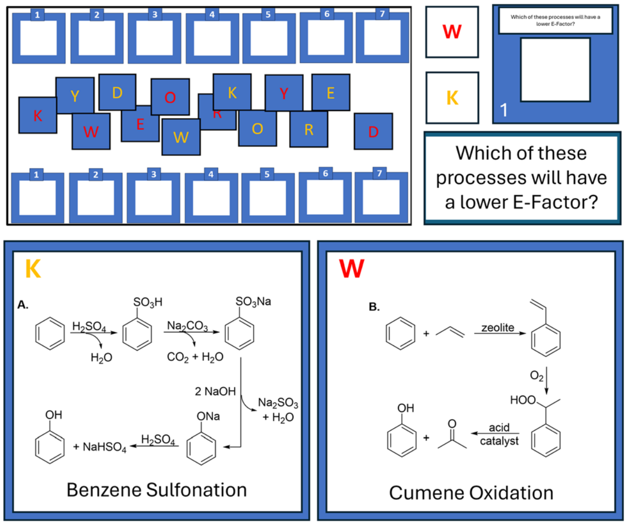

Fig. 6 Example of the activity set-up (top left). Two letter tiles and the associated question tile with question below (top right). The two possible answers for the question represented on the lettered tiles (bottom) adapted from.[106]

Learning objectives:

- Expose participants to contemporary research directions in green chemistry and catalysis.
- Provide visibility for emerging researchers within the community.
- Create space for dialogue between speakers and symposium participants.

Reflections: Activity 4 was separated into two parts. Part 1 (8:30–9:30 am) incorporated 10 minute presentations from green chemistry and inorganic chemistry researchers followed by a 30 minute panel discussion. Speakers included Zhen Dai (Assistant Professor, McGill University), Nelson Rutajoga (PhD Candidate, University of Ottawa), and Gillian Thomas (Assistant Professor, University of Leeds) speaking on organocatalytic peptide coacervates as green microreactors for aldol additions in water, a diagnostic hydrogen generation method for evaluating remediation capabilities of novel TiO_2-based catalysts under visible light, and expedited reaction optimization where transfer learning meets high-throughput experimentation, respectively.[36] Presentations were well received by audience members with later panel discussion questions focusing on methods for green chemistry implementation into research and project specific content.

Part 2 of the activity (11:00–11:40 am) was focused on facilitating round table discussions on methods to implement green chemistry learnings into personal research and education practices. Worksheets were provided to each participant as a conversational prompt and take-home material, focusing on methods to introduce green chemistry into inorganic and materials research as well as chemistry education. As previously discussed by Clapson *et al.* the worksheets explored themes such as research positionality, content and research goals, challenges and opportunities, as well as available resources for continuous learning.[35] To better facilitate the round table discussions, tables were organized into themes for each worksheet with 2–8 participants in each group. A facilitator was assigned to each table to supplement conversations with guided prompts and content knowledge. Compared to previous years, we found the addition of a facilitator resulted in deeper and more engaging conversations on green and sustainable chemistry inclusion into research environments. Participants interested in green chemistry education readily engaged with one another without significant intervention by facilitators, perhaps reflecting the collaborative nature noted for many educators interested in improving their teaching and learning practices.

Discussion

This work contributes design-oriented insight into the implementation of inquiry-based, gamified green chemistry activities across professional and educational contexts. Across symposium and classroom implementations, we observed that activity features such as open-ended problems and shared physical artifacts supported collaborative reasoning, but that the degree of facilitation and explicit framing required varied substantially with participant experience. These observations suggest that successful transfer of sustainability-focused activities from symposium to classroom depends less on altering activity mechanics and more on calibrating ambiguity, task framing, and facilitator intervention to the intended audience.

Following the founding of the CIC Green Division in July 2024, incorporation of interactive symposia and workshops into the Green Division programming boomed. Of the eight symposia hosted at the 2025 CSC, four leveraged active learning techniques. Two symposia, "*Peering into the Mist*" and "*Exploring Green Catalysis*" utilized gamified learning to explore concepts in sustainable development, considering both green chemistry and EDI-AR. These symposia provided the primary implementation contexts through which the design insights described in this discussion were observed. Throughout the design and implementation of the activities described, the goal was to engage interdisciplinary audiences in sustainable and green chemistry thinking while providing avenues to explore discipline-specific applications. To expand the utility of this work, we aimed to provide a low-stakes entry for individuals to begin to grow their communities of practice while simultaneously creating an easily implementable tool for chemistry educators to integrate green chemistry into their course work without content crowding. Overall, the activities can be categorized as follows based on generalized learning objectives:

1. Integrating individuals into green chemistry communities:

- Activity 0-a narrative entry to sustainable and green chemistry leveraging systems thinking.
- Activity 1-engaging with alternative perspectives to enhance laboratory sustainability.

2. Building confidence in green chemistry applications:

- Activity 3-keyword matching as content reinforcement and consolidation.
- Activity 4-exploring modern applications of green chemistry in research and design.

3. Engaging with discipline-specific design:

- Activity 1-when utilized to explore specific alterations to laboratory procedures.
- Activity 2-a high-fidelity design case or exemplar integrating discipline-specific knowledge.

At the conference, the activities were split across two symposia. The "*Peering into the Mist*" symposium was designed to bridge the gap between junior chemists and professional careers through a sustainability lens. Attendees were provided with the opportunity to engage with a variety of professionals in both academia, industry, and government, working to build stronger communities of practice and reduce barriers for later career transitions. Activity 0 acted as a communication tool, allowing participants to network while engaging with key components of sustainable development. Overall, the symposium drew approximately 60 participants. The activity sparked community discussions, creating ample opportunities for networking and engagement.

The development of catalysts for the sustainable transformation of small molecules to value-added chemicals is a key component included in the 12 principles of green chemistry. In the development of green catalytic systems, there are three general research themes: (1) sustainable transformations-catalysts that improve known commercial transformations but incorporating greener or safer additives, solvents, and reaction conditions, (2) green catalyst development-working to create greener catalysts through improved ligand synthesis, application of base metals, or the application of main group catalytic species, and (3) sustainable targets-catalyst development to target sustainable transformations such as waste valorisation. The "*Exploring Green Catalysis*" symposium, cross listed with the Inorganic and Chemistry Education Divisions, was designed to introduce individuals to green catalyst development utilizing first principles explored in second-year inorganic chemistry courses at Canadian institutions. The target audience was a blend of early career and established researchers from inorganic and education backgrounds interested in novel methods to integrate green chemistry into the classroom or to explore modern research methods to incorporate green chemistry recommendations into their own research. The symposium and activities were well-received. Participants were excited to engage with the activity contents in team problem solving. Groups benefitted from interacting with diverse team members. In several cases, senior researchers helped to guide junior colleagues in collective problem solving similar to what is often observed in a research group meeting. Overall, the symposia served as a model for how the activities may be integrated into a classroom setting.

Following their success at the 2025 CSC, activities 0 and 2 were implemented in a third-year inorganic chemistry course (inorganic II, 8 students). The course is focused on four main components, explorations in green inorganic chemistry, symmetry and spectroscopic analysis, main group element reactivity, and cross-coupling catalysis. Green Chemistry is the first topic covered within the course. Inorganic I, a second-year undergraduate course focused on coordination chemistry, molecular orbital theory, spectroscopic methods, and preliminary mechanisms is a prerequisite for inorganic II. Students are expected to have a generalized understanding of ligand design, ligand substitution mechanisms, and infrared spectroscopy (IR) stemming from the prerequisite material. Activity 0, Peering into the Mist, was utilized as a primer activity at the beginning of the semester before commencing the green inorganic chemistry content. It was implemented during the first 50 minute lecture. Six of eight students were in attendance; therefore, each student received a unique role for the activity. A brief introduction was given to the students highlighting that the goals of the activity were to determine the sustainability concern and its cause as well as identify the individual(s) responsible. Students initially formed two groups and started sharing their unique clues and information. Student groups were hesitant to approach one another or engage with the community content information posted on the whiteboard at the front of the room. The instructor needed to prompt students to engage with all the activity information. Surprisingly, students started to explore the entire classroom for clues, attempting to utilize non-activity materials including university promotional posters, despite these items not being near the activity materials and present in the classroom before the arrival of the instructor. These actions highlighted a lack of student understanding on the goals of the activity and how to categorize data. At the end of the activity, the instructor provided a debriefing, prompting student discussion on sustainability considerations, including how the fictional industry may improve their sustainability practices to avoid similar failures.

In the subsequent three lectures students explored concepts such as systems thinking,[107,108] and two-eyed seeing,[109] common green metrics, including how to perform a truncated life cycle assessment,[110] as well as examples of green chemistry initiatives in modern inorganic chemistry such as CO_2 conversion, and nickel-based cross-coupling catalysis. During the final lecture, students performed a self-assessment rating their understanding of the green chemistry content followed by a series of exam style questions. Students had the option to perform the self-assessment as a group but could not utilize their lecture notes. Self-assessments were graded based on participation and students were provided with the answer key following the activity. The lecture slides are included in the SI.

Activity 2 was implemented during the subsequent lecture. All eight students participated. Students, in two teams, had 40 minutes to solve the three puzzles. Students were provided with an alternative workbook to symposium participants, with reduced background information and more escape room-like hints and clues. A truncated workbook was provided as students were expected to have the prerequisite knowledge of the material. As seen with the facilitation of Activity 0, students were hesitant to engage with one another as well as the tactile puzzle components. Rather students selected to read the workbook in detail and required prompting to engage with the other materials. Several students struggled to recall prerequisite content knowledge, relying heavily on their stronger performing peers to guide discussion and puzzle solution. Two students did not engage in discussion at all. As a large group, the class was able to complete the activity. A debriefing on the puzzle content and solution was provided during the subsequent lecture. Following the activity, students were asked to complete an assignment focused on green inorganic chemistry. Similarly, content questions on green inorganic chemistry were included in midterm 1 and the final exam. Analysis of examination and assessment outcomes, student self-assessments, and student engagement with the green chemistry activities is underway. The study will be repeated over several semesters and included in a subsequent publication assessing the outcomes of gamified learning on student understanding of green inorganic chemistry.

Translation of activities to large classroom audiences

As is true for many active learning techniques, utilization of these methods in large classroom settings (>100 students) can be a challenge. Many of these obstacles are related to the classroom layout, lecture halls compared to tables, which limit the ability for students to engage in conversation and manipulate tactile components. The availability of facilitators and the complexity of the activity can also be a limiting factor. Of the activities described herein, we believe that Activity 0-Peering into the Mist and Activity 1-our role can be readily implemented into large classrooms with inflexible seating arrangements. Both of these activities are heavily conversation based, allowing student to talk with nearby colleagues. Similarly, the activity materials can be provided to participant as online documents (downloadable *via* laptop or phone) creating an easily accessed tool. Activity debriefing can be performed as a classroom, allowing all students to engage.

Activities 2-a sustainability puzzle and Activity 3-keywords are better suited for classroom spaces with tables. The activities are easily prepared and facilitated, allowing for multiple copies to be distributed. We recommend students participate in groups no larger than 4 so that all participants are able to engage with the tactile materials and following discussions. Similar escape room-style activities have been successfully implemented during tutorial sections (50 minutes) with upwards of 50 students.[111–114] To implement activities such as this in a lecture-style classroom, facilitators may consider placing the several copies of tactile components, such as puzzle materials, at the front of the room for students to approach and engage with, while conversation takes place seated.

Classroom silence and student motivation-challenges in active learning implementation

Active learning in undergraduate classrooms has been shown to increase student motivation and learning outcomes.[115–117] As active learning and inquiry-based learning techniques become more popular in education, students must engage more deeply with content, building a capacity for independent inquiry and continuous critical thinking.[118] Educators must balance their instructional methods to provide students with the prerequisite knowledge to tackle complex problems without reducing opportunities for independent thinking. An emerging challenge in classrooms incorporating active learning techniques is classroom silence, an unwillingness of students to engage with the educator or the learning materials.[119] Classroom silence has been correlated negatively with instructional effectiveness and positively with student loafing.[119] Student loafing, or "free-riding" behaviour, is a phenomenon in which students exert less effort and showcase reduced motivation when working in team environments,[120] often directly influenced by student learning motivations,[121] competency,[119,122] emotional relationships between peers and educators, as well as collective identity.[119,120,122]The large difference in participant engagement between the symposium setting and the Inorganic II course may be a result of classroom silence. In a conference setting participants self-select to engage with symposia and their contents, the motivation to attend, learn, and engage is already present. However, in the classroom setting, students are required to engage with green chemistry content regardless of their driving motivations. Among the 8 students in inorganic II there already existed a large difference in student performance from previous courses, possibly leading to increased classroom silence as seen during the activities' implementation.

We believe that increasing student familiarity with active learning tools such as gamification and enhancing the relevance and applicability of green chemistry and inorganic content will help to improve classroom silence. We also emphasize the importance of curating inclusive learning environments where students can engage with one another without fear of reprisal for their content knowledge or perceived lack of knowledge.

Future perspectives

Creating opportunities for chemistry educators and researchers to engage with green chemistry content through novel platforms continues to showcase benefits in conference settings. Providing an environment in which individuals can engage with research, literature, and fundamentals of both green chemistry and discipline-specific knowledge allows community members to deepen their understanding while building communities of practice. We envision that interactive symposia, incorporating active learning techniques such as gamification, will continue to be utilized to share green chemistry content, leveraging the benefits of active learning.

Despite the proven utility of active learning interventions on learning, students perceive traditional lecturing as more beneficial to their understanding.[115] Group learning activities similar encounter challenges associated with student motivation and perceived learning. Deslauriers *et al.*[115] highlight that early intervention, providing students with an understanding of the benefits of active learning as well as the difference in perceived learning and actual learning, increases student motivation to engage with active learning techniques. Similarly, research has found that appropriate scaffolding of group work, alignment of learning objectives and associated tasks, and adequate student support are key to effective group learning activities.[123] As educators look to introduce novel learning activities such as described herein, we recommend early introduction of active learning and gamified learning to improve student motivation towards engagement. Increasing students' metacognitive abilities to assess their own learning in conjunction with active learning techniques has also been shown to lead to better student outcomes.[116] As we proceed to explore the benefits of active learning techniques in teaching green chemistry, we also look forward to developing additional tools to improve student metacognition (self-assessments). While data strongly suggests that active learning increases student understanding, we must continue to explore methods focused on best practices for its introduction. Through this we can lower instances of classroom silence and student loafing, providing clear evidence to students on the effectiveness of the learning platforms. Future work in this area will focus on integrating these strategies into undergraduate inorganic chemistry classrooms at the second, third, and fourth-year levels, gaining a better understanding of the benefits provided by gamified learning interventions and improved student metacognition.

Conclusions

In this work, we discuss several inquiry-based and gamified active learning tools and their implementation in conference and undergraduate classroom settings. These activities were designed to create opportunities for engagement between junior and senior researchers, using green chemistry as a shared framework to support interdisciplinary interaction. Applications drawn from sustainable green catalysis, including considerations of ligand design, metal selection, and reaction conditions, highlight the balance required when implementing green chemistry recommendations while maintaining chemical efficiency.

In addition to their utility in symposium settings, these tools integrate foundational concepts in coordination chemistry and provide an accessible avenue for inorganic chemistry educators to introduce green chemistry content without contributing to course crowding. Together with intentional facilitation and early classroom interventions that address student metacognition and the value of active learning, these approaches offer opportunities to support engagement with discipline-specific green chemistry applications while creating space for participation from diverse audiences.

Author contributions

Bannard, Daliaho, and Hong contributed equally to the development of the "*Peering into the Mist*: *the interdisciplinary Structure of Problem Solving in Industry and Government*" symposium hosted at CSC 2025 and the associated Activity 0. Bjornerud-Brown, Fitzgerald, Perry, Davy, and Durfy contributed equally to the conceptualization of symposium activities, development and implementation of activities, and methodology associated the development and facilitation of the symposium "*Exploring Green Catalysis-The Modes, The Methods, The Targets*" hosted at the 2025 CSC. Each activity lead summarized the content of their activity in the associated symposium workbook and SI; Bannard (Activity 0), Davy (Activity 1) Bjornerud-Brown, Durfy, Perry (Activity 2), Fitzgerald (Activity 3), and Davy (Activity 4). Bannard was responsible for editing the supporting information and final manuscript edits. Clapson, corresponding author, contributed to the original symposium proposal application, conceptualization of symposium activities, development and implementation of activities, formal analysis, investigation, methodology, funding acquisition, project administration, resources, supervision, validation, visualization, adaptation and implementation into the undergraduate inorganic II classroom, and writing and editing of the original manuscript draft and associated SI.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article has been included as part of the supplementary information (SI). Supplementary information: activity descriptions, print files, facilitation details, and guided worksheets. See DOI: https://doi.org/10.1039/d5su00967g.

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Notes and references

1 United Nations Sustainable Development Goals2015, https://sdgs.un.org/goals, (accessed 22 September 2022).
2 D. J. C. Constable, *iScience*, 2021, **24**, 103489.
3 P. T. Anastas, M. M. Kirchhoff and T. C. Williamson, *Appl. Catal., A*, 2001, **221**, 3–13.
4 J. V. Obligacion and K. H. Hopmann, *Organometallics*, 2022, **41**, 1739–1742.
5 J. C. Anastas and P. T. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, 1st edn, 1998, vol. 1.
6 12 Principles of Green Chemistry, https://www.acs.org/content/acs/en/greenchemistry/principles/12-principles-of-green-chemistry.html, (accessed 22 September 2022).
7 J. Hagen, *Industrial Catalysis*, Wiley, 3rd edn, 2015.
8 A. P. Dicks and A. Hent, *Green Chemistry Metrics A Guide to Determining and Evaluating Process Greenness*, Springer International Publishing, Cham, 2015.
9 A. Abera Tsedalu, *J. Chem.*, 2021, **2021**, 3590613.
10 M. Farhang, A. R. Akbarzadeh, M. Rabbani and A. M. Ghadiri, *Polyhedron*, 2022, **227**, 116124.
11 N. Miyaura and A. Suzuki, *Chem. Rev.*, 1995, **95**, 2457–2483.
12 C. S. G. Seo and R. H. Morris, *Organometallics*, 2019, **38**, 47–65.
13 K. S. Egorova and V. P. Ananikov, *Angew. Chem., Int. Ed.*, 2016, **55**, 12150–12162.
14 M. Bystrzanowska, P. Petkov and M. Tobiszewski, *ACS Sustain. Chem. Eng.*, 2019, **7**, 18434–18443.
15 P. Nuss and M. J. Eckelman, *PLoS One*, 2014, **9**, e101298.
16 J. Maes, E. A. Mitchell and B. U. W. Maes, *RSC Green Chem.*, 2016, 192–202.
17 P. J. Chirik, K. M. Engle, E. M. Simmons and S. R. Wisniewski, *Org. Process Res. Dev.*, 2023, **27**, 1160–1184.
18 M. L. Clapson, C. S. Durfy, D. Facchinato and M. W. Drover, *Cell Rep. Phys. Sci.*, 2023, **4**, 101548.
19 B. A. Baviskar, P. V. Ajmire, D. S. Chumbhale, M. S. Khan, V. G. Kuchake, M. Singupuram and P. R. Laddha, *Sustain. Chem. Pharm.*, 2023, **32**, 100953.
20 M. J. West and A. J. B. Watson, *Org. Biomol. Chem.*, 2019, **17**, 5055–5059.
21 L. C. Wilkins and R. L. Melen, *Coord. Chem. Rev.*, 2016, **324**, 123–139.
22 P. J. Chirik and K. Wieghardt, *Science*, 2010, **327**, 794–795.
23 Md. T. Islam, N. A. Bitu, B. M. Chaki, Md. J. Hossain, Md. A. Asraf, Md. F. Hossen, Md. Kudrat-E-Zahan and Md. A. Latif, *RSC Adv.*, 2024, **14**, 25256–25272.
24 J. W. Moir, N. K. Obhi, J. MacKellar, D. A. Laviska and A. S. Cannon, *J. Chem. Educ.*, 2025, **102**, 3387–3398.
25 N. K. Obhi, J. Moir, A. Oseolorun and A. S. Cannon, *Sustain. Chem. Pharm.*, 2025, **44**, 101944.
26 T. H. Swartz, A.-G. S. Palermo, S. K. Masur and J. A. Aberg, *J. Infect. Dis.*, 2019, **220**, 33–41.
27 B. K. AlShebli, T. Rahwan and W. L. Woon, *Nat. Commun.*, 2018, **9**, 5163.
28 Y. Yang, T. Y. Tian, T. K. Woodruff, B. F. Jones and B. Uzzi, *Proc. Natl. Acad. Sci. U. S. A.*, 2022, **119**, e2200841119.
29 L. G. Campbell, S. Mehtani, M. E. Dozier and J. Rinehart, *PLoS One*, 2013, **8**, e79147.
30 B. Hofstra, V. V. Kulkarni, S. Munoz-Najar Galvez, B. He, D. Jurafsky and D. A. McFarland, *Proc. Natl. Acad. Sci. U. S. A.*, 2020, **117**, 9284–9291.
31 P. J. Chirik, K. M. Engle, E. M. Simmons and S. R. Wisniewski, *Org. Process Res. Dev.*, 2023, **27**, 1160–1184.
32 M. L. Clapson, E. C. Davy, C. S. Durfy, S. Schechtel and S. S. Scott, *J. Chem. Educ.*, 2025, **102**, 1314–1322.
33 I. Ravn and S. Elsborg, *Int. J. Learn. Change*, 2011, **5**, 84.
34 L. Summerton, G. A. Hurst and J. H. Clark, *Curr. Opin. Green Sustainable Chem.*, 2018, **13**, 56–60.
35 M. L. Clapson, G. Bannard, G. Daliaho, J. Hong, E. Davy, J. Pitsiaeli, C. S. Durfy and S. Schechtel, *RSC Sustain.*, 2025, **3**, 4492–4503.
36 Program Overview - The Chemical Institute of Canada, https://www.cheminst.ca/conference/x2026/program/program-overview/, (accessed 26 December 2025).
37 Z. Zainuddin, S. K. W. Chu, M. Shujahat and C. J. Perera, *Educ. Res. Rev.*, 2020, **30**, 100326.
38 M. A. Martín-Lara and M. Calero, *J. Chem. Educ.*, 2020, **97**, 1375–1380.
39 J.-C. Tsai, S.-Y. Liu, C.-Y. Chang, S.-Y. Chen, C. Mader, T.-H. Meen, C. Tijus and J.-C. Tu, *Sustainability*, 2021, **13**, 4942.
40 T. Pippins, C. M. Anderson, E. F. Poindexter, S. W. Sultemeier and L. D. Schultz, *J. Chem. Educ.*, 2011, **88**, 1112–1115.
41 J. L. Miller, M. T. Wentzel, J. H. Clark and G. A. Hurst, *J. Chem. Educ.*, 2019, **96**, 3006–3013.
42 M. Enright, A. Sebuyira and J. Butler, *Green Chem.Teach.Learn. Community*, 2023, DOI: 10.59877/PHNR3014.
43 K. Trčková, R. Maršálek and Z. Václavíková, *J. Chem. Educ.*, 2023, **101**, 215–222.
44 A. R. Cash, J. R. Penick, C. F. Todd and M. C. So, *J. Chem. Educ.*, 2023, **100**, 4530–4535.

45 C. Lathwesen and I. Eilks, *J. Chem. Educ.*, 2024, **101**, 3193–3201.
46 D. H. Cook, *J. Chem. Educ.*, 2014, **91**, 1580–1586.
47 The Safer Chemical Design Game - Gamification of green chemistry and safer chemical design concepts for students | Poorvu Center for Teaching and Learning, https://poorvucenter.yale.edu/SafeChemicalGameDesign, (accessed 27 March 2024).
48 M. Lees, M. T. Wentzel, J. H. Clark and G. A. Hurst, *J. Chem. Educ.*, 2020, **97**, 2014–2019.
49 A. Basak, S. Kumar, P. Upadhyay and S. Banerjee, *Int. J. Art Des. Educ.*, 2026, DOI: 10.1111/jade.12601.
50 Peering Into the Mist-What can you do with a chemistry degree?-YouTube, https://www.youtube.com/watch?v=TPd7dFgDr7M, (accessed 26 December 2025).
51 P. G. Jessop and A. R. MacDonald, *Green Chem.*, 2023, **25**, 9457–9462.
52 G. Osman, *Inquiry-Based Learning: A Powerful Approach to Facilitating Learning in Any Discipline*, 2009.
53 J. Kang, *Res. Sci. Educ.*, 2022, **52**, 339–355.
54 J. Campbell, K. Shaul, K. M. Slagle and D. Sovic, *Int. J. Sustain. High Educ.*, 2024, **25**, 1803–1819.
55 J. S. Parmar, S. K. Mistry, S. Micheal, T. Dune, D. Lim, S. Alford and A. Arora, *Educ. Sci.*, 2025, **15**, 602.
56 R. Ellwood and E. Abrams, *Cult. Stud. Sci. Educ.*, 2018, **13**, 395–427.
57 R. Chadwick, E. McLoughlin and O. E. Finlayson, *Ir. Educ. Stud.*, 2023, **42**, 315–337.
58 N. Muhamad Dah, M. S. A. Mat Noor, M. Z. Kamarudin and S. S. Syed Abdul Azziz, *Educ. Res. Rev.*, 2024, **43**, 100601.
59 J. Dobbelaere, J. B. Heidelberger and N. Borgermann, *J. Cell Sci.*, 2022, **135**(17), jcs259645.
60 T. Freese, N. Elzinga, M. Heinemann, M. M. Lerch and B. L. Feringa, *RSC Sustain.*, 2024, **2**, 1300–1336.
61 M. Farley, *Nat. Rev. Mol. Cell Biol.*, 2022, **23**, 517.
62 Accelerating Sustainability in Scientific Research | My Green Lab, https://mygreenlab.org/, (accessed 19 December 2025).
63 LEAF-Laboratory Efficiency Assessment Framework | Sustainable UCL-UCL-University College London, https://www.ucl.ac.uk/sustainable/take-action/staff-action/leaf-laboratory-efficiency-assessment-framework, (accessed 19 December 2025).
64 M. A. Urbina, A. J. R. Watts and E. E. Reardon, *Nature*, 2015, **528**, 479.
65 B. R. Schell and N. Bruns, *RSC Sustain.*, 2024, **2**, 3383–3396.
66 T. Freese, R. Kat, S. D. Lanooij, T. C. Böllersen, C. M. De Roo, N. Elzinga, M. Beatty, B. Setz, R. R. Weber, I. Malta, T. B. Gandek, A. Krikken, P. Fodran, R. Pollice, M. M. Lerch, Green Chemistry Teaching and Learning Community, *ChemRxiv*, 2024, DOI: 10.59877/FCXC3888.
67 N. Borgermann, A. Schmidt and J. Dobbelaere, *One Earth*, 2022, **5**, 18–21.
68 M. L. Clapson, *CHEMISTRY 3740: Inorganic Chemistry II Laboratory Manual*, University of Prince Edward Island, Charlottetown, PE, 2025.
69 Beyond Benign Greener Solvent Guide | Green Chemistry Teaching and Learning Community (GCTLC), https://gctlc.org/beyond-benign-greener-solvent-guide, (accessed 19 December 2025).
70 C. Capello, U. Fischer and K. Hungerbühler, *Green Chem.*, 2007, **9**, 927–934.
71 Could accessible labs spark new era of chemistry discovery?, https://www.rsc.org/news/disability-inclusive-laboratories-in-the-chemical-sciences-launch, (accessed 17 December 2025).
72 M. A. Sukhai, C. E. Mohler, T. Doyle, E. Carson, C. Nieder, D. Levy-Pinto, E. Duffett and F. Smith, *Creating an Accessible Science Laboratory Environment for Students with Disabilities*, 2014.
73 O. Egambaram, K. Hilton, J. Leigh, R. Richardson, J. Sarju, A. Slater and B. Turner, *J. Chem. Educ.*, 2022, **99**, 3814–3821.
74 S. M. Mercer, J. Andraos and P. G. Jessop, *J. Chem. Educ.*, 2012, **89**, 215–220.
75 A. Milo, L. Chen, K. A. Grice and D. A. Vosburg, *J. Chem. Educ.*, 2025, **102**, 2261–2267.
76 L. B. Armstrong, M. C. Rivas, Z. Zhou, L. M. Irie, G. A. Kerstiens, M. T. Robak, M. C. Douskey and A. M. Baranger, *J. Chem. Educ.*, 2019, **96**, 2410–2419.
77 M. L. Clapson, S. Schechtel, E. Davy and C. S. Durfy, *Educ. Sci.*, 2024, **14**, 1273.
78 A. Veldkamp, L. van de Grint, M. C. P. J. Knippels and W. R. van Joolingen, *Educ. Res. Rev.*, 2020, **31**, 100364.
79 D. J. Nelson, A. Collado, S. Manzini, S. Meiries, A. M. Z. Slawin, D. B. Cordes and S. P. Nolan, *Organometallics*, 2014, **33**, 2048–2058.
80 R. J. Lundgren and M. Stradiotto, in *Ligand Design in Metal Chemistry*, John Wiley & Sons, Ltd, Chichester, UK, 2016, pp. 1–14.
81 R. H. Crabtree, *The Organometallic Chemistry of the Transition Metals*: 6th edn, 2014, pp. 1–504, DOI: 10.1002/9781118788301.
82 M. Farhang, A. R. Akbarzadeh, M. Rabbani and A. M. Ghadiri, *Polyhedron*, 2022, **227**, 116124.
83 M. Beller, A. Varela-Fernandez, J. G. Vries, S. Man Wong, C. Ming So and F. Y. Kwong, *Applied Homogeneous Catalysis with Organometallic Compounds*, 2017, 411–464.
84 R. Franzén and Y. Xu, *Can. J. Chem.*, 2005, **83**, 266–272.
85 V. P. Ananikov, *ACS Catal.*, 2015, **5**, 1964–1971.
86 E. Negishi, *Acc. Chem. Res.*, 1982, **15**, 340–348.
87 F.-S. Han, *Chem. Soc. Rev.*, 2013, **42**, 5270.
88 S. Enthaler, K. Junge, M. Beller, S. Enthaler, K. Junge and M. Beller, *Angew. Chem., Int. Ed.*, 2008, **47**, 3317–3321.
89 A. Fürstner, A. Leitner, M. Méndez and H. Krause, *J. Am. Chem. Soc.*, 2002, **124**, 13856–13863.
90 A. Piontek, E. Bisz and M. Szostak, *Angew. Chem., Int. Ed.*, 2018, **57**, 11116–11128.
91 M. L. Neidig, S. H. Carpenter, D. J. Curran, J. C. Demuth, V. E. Fleischauer, T. E. Iannuzzi, P. G. N. Neate, J. D. Sears and N. J. Wolford, *Acc. Chem. Res.*, 2018, **52**, 140.
92 B. D. Sherry and A. Fürstner, *Acc. Chem. Res.*, 2008, **41**, 1500–1511.

93 D. S. Reay, E. A. Davidson, K. A. Smith, P. Smith, J. M. Melillo, F. Dentener and P. J. Crutzen, *Nat. Clim. Change*, 2012, **2**, 410–416.

94 L. E. Doyle, W. E. Piers and J. Borau-Garcia, *J. Am. Chem. Soc.*, 2015, **137**, 2187–2190.

95 J. D. Smith, E. Chih, W. E. Piers and D. M. Spasyuk, *Polyhedron*, 2018, **155**, 281–290.

96 J. D. Smith, J. Borau-Garcia, W. E. Piers and D. Spasyuk, *Can. J. Chem.*, 2016, **94**, 293–296.

97 J. D. Smith, J. R. Logan, L. E. Doyle, R. J. Burford, S. Sugawara, C. Ohnita, Y. Yamamoto, W. E. Piers, D. M. Spasyuk and J. Borau-Garcia, *Dalton Trans.*, 2016, **45**, 12669–12679.

98 D. V. Gutsulyak, W. E. Piers, J. Borau-Garcia and M. Parvez, *J. Am. Chem. Soc.*, 2013, **135**, 11776–11779.

99 E. A. LaPierre, W. E. Piers and C. Gendy, *Organometallics*, 2018, **37**, 3394–3398.

100 M. L. Clapson, J. K. Kirkland, W. E. Piers, D. H. Ess, B. Gelfand and J.-B. Lin, *Organometallics*, 2022, **41**, 235–245.

101 S. Sung, Q. Wang, T. Kraemer, R. D. Young, T. Krämer, R. D. Young, T. Kraemer and R. D. Young, *Chem. Sci.*, 2018, **9**, 8234–8241.

102 Q. Wang, R. A. Manzano, H. Tinnermann, S. Sung, B. Leforestier, T. Krämer and R. D. Young, *Angew. Chem.*, 2021, **133**, 18316–18325.

103 M. R. Hoffbauer and V. M. Iluc, *J. Am. Chem. Soc.*, 2021, **143**, 5592–5597.

104 C. Diemand-Yauman, D. M. Oppenheimer and E. B. Vaughan, *Cognition*, 2011, **118**, 111–115.

105 M. Lancaster, *Green Chemistry: an Introductory Text*, The Royal Society of Chemistry, 2016, pp. 95–146.

106 M. Lancaster, in *Green Chemistry: an Introductory Text*, The Royal Society of Chemistry, 2016, pp. 24–66.

107 D. H. Meadows, *Thinking in Systems*, Earthscan, London, U.K., 2009.

108 K. B. Aubrecht, M. Bourgeois, E. J. Brush, J. MacKellar and J. E. Wissinger, *J. Chem. Educ.*, 2019, **96**, 2872–2880.

109 C. Smith, S. Diver and R. Reed, *Environ. Plann. F*, 2023, **2**, 121–143.

110 S. M. Mercer, J. Andraos and P. G. Jessop, *J. Chem. Educ.*, 2012, **89**, 215–220.

111 B. C. T. Gilbert, M. L. Clapson and A. Musgrove, *J. Chem. Educ.*, 2020, **97**, 4055–4062.

112 M. L. Clapson, S. Schechtel, B. Gilbert and V. J. Mozol, *J. Chem. Educ.*, 2023, **100**, 415–422.

113 M. L. Clapson, B. Gilbert, V. J. Mozol, S. Schechtel, J. Tran and S. White, *J. Chem. Educ.*, 2020, **97**, 125–131.

114 S. Schechtel, V. Mozol, M. Clapson, B. Gilbert, J. Tran and S. White, *Papers on PostsecondaryLearn. Teach.*, 2020, **4**, 17–24.

115 L. Deslauriers, L. S. McCarty, K. Miller, K. Callaghan and G. Kestin, *Proc. Natl. Acad. Sci. U. S. A.*, 2019, **116**, 19251–19257.

116 J. M. Mutambuki, M. Mwavita, C. Z. Muteti, B. I. Jacob and S. Mohanty, *J. Chem. Educ.*, 2020, **97**, 1832–1840.

117 S. Freeman, S. L. Eddy, M. McDonough, M. K. Smith, N. Okoroafor, H. Jordt and M. P. Wenderoth, *Proc. Natl. Acad. Sci. U. S. A.*, 2014, **111**, 8410–8415.

118 M. M. Wilson, F. Zafar and C. Nichol, *Educ. Sci.*, 2025, **15**, 421.

119 S. Li, H. Zhou and Y. Zheng, *Front. Psychol.*, 2025, **16**, 1682073.

120 Z. Luo, E. Marnburg, T. Øgaard and F. Okumus, *J. Hosp. Leis. Sport Tour. Educ.*, 2021, **28**, 100314.

121 O. Juma, M. Husiyin, A. Akhat and I. Habibulla, *Front. Psychol.*, 2022, **12**, 819821.

122 Z. Donghai, *Educ.Dev.Res.*, 2019, **39**, 40–46.

123 M. de Hei, J. W. Strijbos, E. Sjoer and W. Admiraal, *Educ. Res. Rev.*, 2016, **18**, 33–45.