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Waving the green flag: incorporating sustainable and green chemistry practices into research and education

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Education and research in green chemistry has become an increasingly important topic in recent years. However, definitions and understanding of sustainability metrics and strategies remains unclear in many fields. Similarly, the link between sustainability in chemistry and chemistry's impact on society is often overlooked. Using methods like systems thinking, life cycle analysis, and green chemistry principles, researchers can begin to probe the sustainability of chemical systems. Developing a stronger understanding of the roles of various stakeholders in policy creation is likewise imperative in the integration of data driven policy towards the United Nations Sustainable Development Goals and chemistry for net-zero. Together, with a stronger background in sustainable development, researchers and policymakers can carve a path towards a more sustainable global future. Herein, we describe a series of inquiry-based and gamified active learning techniques applied during the "Waving the Green Flag" symposium hosted at the 2024 Canadian Chemistry Conference and Exhibition. Activities are focused on exploring the methods described above through a polymer chemistry approach, a hot topic in current sustainability research. The activities work to guide participants in the development and implementation of green chemistry initiatives into their own research and practice while providing an entry point to explore the bridge between academic research and policy. Recommendations for activity adaptations for classroom applications are provided.

Sustainability spotlight

The contents of the article are focused on sustainable development goals for quality education (4), 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 the role of researchers as stakeholders in policy generation. 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 clean water and sanitation (6), affordable and clean energy (7), responsible consumption and production (12), climate action (13), life below water (14), and life on land (15) are discussed.

Introduction

Advances in sustainable development, green chemistry and engineering, are critical in tackling global challenges such as climate change, plastic pollution, and downstream societal and environmental impacts caused by resource extraction and waste management.[1] The United Nations Sustainable Development Goals (SDGs) provide a framework of actionable targets in which researchers, educators, and policymakers can begin to implement green initiatives in the development of chemical processes, waste management procedures, quality education, and equity, diversity, inclusivity, accessibility, and reconciliation (EDI-AR).[2] The more recent Stockholm Declaration on Chemistry for the Future underpins the importance of a unified and rapid approach to implement circular and sustainable systems.[3] An understanding of the principles of green chemistry and their target fields is insufficient to accomplish these goals, therefore, we must deliver quantifiable results in green progress and utilize

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this data to develop practical sustainability policies. In training our future scientific leaders, it is imperative to incorporate methods such as systems thinking,[4,5] green metrical analysis,[6,7] and scientific communication to allow for a holistic understanding of the downstream effects of chemical processes. Here, systems thinking can be leveraged by scientists and policymakers to approach a sustainability problem from the top down, recognizing how different elements of chemistry and policy interact, influence each other, and contribute to overall patterns and behaviours. This approach is beneficial as is allows green chemistry contexts to move beyond linear, cause-and-effect thinking (*e.g.* water as a green solvent with a lower toxicity compared to organic solvents) to embrace circular and dynamic relationships within the system (*e.g.* where is the water sourced, how is the water treated/purified post reaction, what communities may be impacted by waste water entering communal water sources, *etc.*). Systems thinking similarly encourages safe space conversations in which individuals can share different knowledge and perspectives promoting an encompassing vision of key issues and how each stakeholder has an impact.[8]

Educational tools targeted at improving student understanding of green chemistry,[9–12] systems thinking,[13–18] and green data analysis[16,19] are becoming more popular. Institutions such as Beyond Benign,[20] supported by the American Chemistry Society Green Chemistry Institute, host community initiatives such as the Green Chemistry Commitment (GCC)[21] and The Green Chemistry Teaching and Learning Community (GCTLC)[22] geared at sharing green chemistry resources. Seminal work by Jessop *et al.* likewise provides researchers with an understanding on the preparation and utilization of life cycle analyses (LCAs) and the need for hotspot-driven research in furthering sustainable development.[23,24]

Despite the growing body of resources, researchers can often feel a disconnect between their own projects and sustainability initiatives – what is green research exactly, and how can green considerations be implemented into what might be considered "unrelated" research projects? At the professional level, green chemistry education similarly becomes underutilized, leaving a gap for early career and established researchers to gain additional experience in green implementation.[12] Here we outline a series of gamified and inquiry-based learning tools for utilization at research conferences, the professional's classroom, as well as in undergraduate classrooms. The activities are designed to act as an introduction to green principles, systems thinking, analysis of green metrics, and involvement in scientific policy. The aim is to spur conversations between researchers from a variety of disciplines and scientific levels on the breadth and intricacies of green chemistry and engineering implementation while developing interdisciplinary collaborations and actionable items for the integration of these principles into individuals' own research projects.

The activities were first demonstrated at the 2024 Canadian Chemistry Conference and Exhibitions hosted in Winnipeg, Manitoba during the "Waving the Green Flag: Emerging Methods in Sustainable Chemistry, Inorganic Catalysis, Measures of Sustainability, and Green Chemistry Education" symposium.[25] They represent the second iteration of interactive symposium integration within the national Canadian chemistry conference community.[26] The symposium was run as a half-day session, cross-listed with the inorganic, environmental, and chemistry education divisions. Discussions herein are focused on the experiences and feedback provided by the conference attendees with ongoing research focusing on the implementation of the activities in second and third-year undergraduate inorganic chemistry classrooms.

Active learning and its role in quality education

Active learning, in which students engage with course content beyond passive lecturing, is a well-recognized practice to improve student understanding and problem solving,[27,28] while reducing barriers for minority students.[29–32] Pedagogical approaches such as problem-based learning,[33,34] inquiry-based learning,[35] and case-based learning[36,37] enable learners to engage with real-world green chemistry applications, leading to higher order thinking.[38,39] These approaches reinforce the value of green chemistry interventions, providing learners with an environment to validate their knowledge through critical reflections.[32,39]

Gamification of learning and gamified learning are examples of active learning in which students engage with course material through game-like experiences.[40,41] Gamified learning may include the creation of scientific games, challenging students to leverage course knowledge in order to complete the game. Alternatively, gamification of learning incorporates game components, such as leaderboards, into classroom activities.[42,43] The utilization of gamification and gamified learning techniques has been shown to increase student engagement, understanding, motivation, and enjoyment, while providing opportunities for peer-feedback and social learning.[44–47] Gamified activities, similarly, provide a low stakes entry to learning new content, allowing for broad audiences of learners to engage with the materials. The interdisciplinary nature of green chemistry requires innovative approaches for engaging broad audiences, making active learning and gamified learning of interest for exploring green chemistry in classrooms and conference settings.[26,39] We turn readers to the following references highlighting examples of green chemistry learning games.[48–51]

Guided networking as a tool to develop partnerships for the goals

Green chemistry is an interdisciplinary science requiring collaborative input from multiple stakeholders in order to develop practical methodologies to tackle global sustainability challenges.[11] Guided networking can be leveraged to develop interdisciplinary collaborations by providing researchers and other stakeholders with opportunities to connect and share ideas through structured interactions. To cultivate interdisciplinary relationships, clear and relatable goals must be defined,[52] identifying where disciplines are able to create impact. Structured interactions such as collaborative activities, targeted introductions in which participants can share their background, and discussion prompts should be integrated, enabling thought-provoking discussions where participants can explore common challenges.[52–54] Finally, effective networking fosters opportunities for feedback, resources sharing, and ongoing engagement, providing participants with methods to incorporate learnings into their own practice. The incorporation of activities focused on definitions of sustainability, green metrics, and policy into the "Waving the Green Flag" symposium alongside research presentations, take-home worksheets, and group discussions are reflective of the described best practices for guided networking and are utilized throughout.

In the facilitation of interactive, collaborative activities, it is imperative that a safe and welcoming environment be established,‡ recognizing the benefits of inclusive collaborations on creativity and scientific output,[55–61] essential for the development and progression of chemical sciences.[62]

Activity details

Activity one – sustainability web

Overview. Similar to previous interactive conference activities presented by Clapson *et al.* this activity builds upon participants' current definitions of sustainability as it relates to several aspects of research and learning.[26] In the previous iteration, participants were asked to utilize a systems thinking approach to define sustainability over three sectors including sustainability within generalized chemistry, within the field of base metal catalysis, and within society. We provided a Venn diagram to explore intersectionality of definitions. In this iteration, we moved away from the Venn diagram model and instead used a web model (analogous with a concept map used in chemical education[63] and other systems thinking activities).[8,13,14,17,18] We provided more sectors including scientific policy, graduate research, teaching (lecture), green principles, polymer chemistry, teaching (laboratories), inorganic chemistry, industrial chemistry, catalyst development, and society with "sustainability" at the centre. Participants were encouraged to leave their own definitions at any point and make and articulate connections to other definitions (where definitions were written on index cards and placed on the poster and connections were made using yarn wrapped around pushpins). In addition, participants were asked to agree or disagree with connections left by others by offering green check marks or red "X"s written on previously placed index cards. The sustainability web can be seen in Fig. 1.

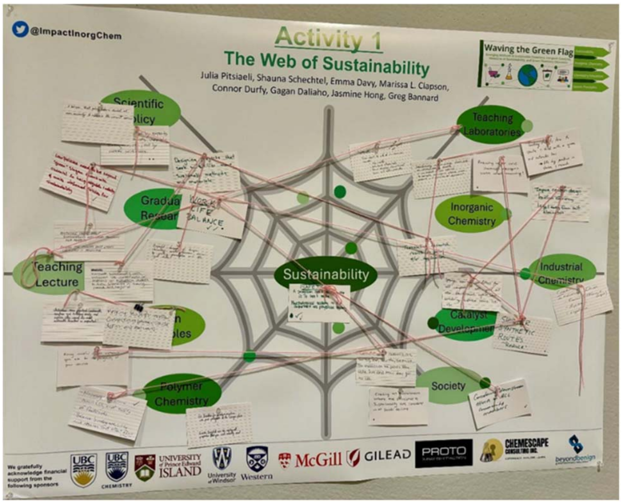

Fig. 1 The sustainability web with definitions and connections.

Learning objectives

- To evaluate/consider and contextualize/challenge one's prior knowledge about the notions of sustainability.
- To apply prior knowledge and ideas (*i.e.*, notions and definitions around sustainability) to new or known situations (*e.g.*, policy, inorganic chemistry, *etc.*).
- To create definitions around sustainability across some or all of the presented sub-disciplines.
- To create connections between definitions associated with sustainability across some or all the presented sub-disciplines.
- To evaluate, assess and compare/contrast existing definitions/connections associated with "sustainability" and the presented sub-disciplines.

Comments. A brief keyword analysis of the definitions and responses provided on the sustainability web was summarized into five categories; material sourcing, synthetic practices, green education, sustainable workplaces, and community engagement. Twenty-six statements were provided in total. Twelve participants highlighted the importance of sustainable sourcing of materials, mentioning concepts such as mining practices, renewability of feedstocks, environmental impacts, as well as the impacts on local communities (41% of responses). Twenty-four participants mentioned concepts relating to green synthetic practices, many of which were focused on the classical green chemistry principles including reducing waste, atom economy, process safety, energy utilization,[64] and cost. Twenty-one percent (21%) of responses in this category underscored the importance of purposeful synthetic design driven by green chemistry metrics gathered from life cycle analysis data. All eight respondents in the green education category emphasized the importance of incorporating green chemistry perspectives and learning into all aspects of chemistry education rather than acting as a stand-alone course. Participants highlighted the need to create life-long sustainable practices in research and education by connecting modern chemistry and real-world applications to methods in sustainable design. In line with modern approaches to equity, diversity, inclusivity, accessibility, and reconciliation (EDI-AR),[8,62,65] and UN Sustainable Development Goals focused on gender equality (5), reduced inequalities (10), and partnerships for the goals (17), several individuals drew attention to the importance of safe working spaces for researchers, in terms of treatment and sense of belonging, as well as the need for work-life balance. Finally, thirteen participants mentioned sustainability considerations focused on community engagement in two forms, societal "buy-in" and green policy development. "Moving beyond the green slogan" to actionable items and policies was a recurring theme with participants zoning in on the importance of policy

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‡ We turn readers to the following references discussing methods to improve equity, diversity, and inclusivity in research and education as well as commentary on the benefits of diverse workspaces.[32,59,108–117]

development influenced by modern research. To progress in a sustainable manner, participants wanted to see greater collaborations between policy makers and scientists, suggesting that when firm, data-driven sustainability policies are put in place, public compliance and buy-in to sustainable practices will improve.

Activity two – puzzling out green metrics in polymer chemistry

Overview. Green metrics and life cycle assessments (LCAs) are key to determining if a new process is more sustainable or "greener" than a pre-existing process.[24] Various metric-based analysis frameworks, such as techno-economic analysis, material-flow analysis, LCA, and DOZN 2.0 (a green chemistry program developed by Merck to translate the 12 qualitative green chemistry principles into a quantitative score)[66,67] have been developed to identify feasibility and places of improvement of novel processes. Integration of these techniques can be beneficial in transitioning a process from bench-scale to commercial application, such as with plastic valorization.[68,69] These tools allow for informed research and development to identify hotspots in a given process, including chemical processes.[23] LCA is a multivariable assessment tool that quantifies environmental impact by calculating harm through the life cycle of a product across impact categories such as global warming potential (GWP), ionizing radiation (IR), and land use.[24,70] Compared to other green chemistry tools such as systems thinking and DOZN 2.0, LCA has been identified as the most effective tool to assess the greenness of a reaction.[16] With more focus being placed on incorporating metric-based analysis with research, it is key for future researchers to understand how to interpret this data.[71,72]

This activity was inspired by the green metrics puzzle activity previously reported in which life cycle analysis was leveraged to compare and analyse catalytic systems for reductive amination and hydroaminoalkylation.[26] In this iteration of the activity, the content was adapted to explore a more universally understood global challenge – plastics and polymers.[73–75] A focus was placed on the life cycle of polymers from cradle (resource extraction) to grave (material disposal). Utilizing plastics as a centre for systems thinking, the activity approaches LCA considerations such as polymer feedstocks, polymer derivatives, and depolymerization methods. The activities ask the participants to consider the impacts associated with different technologies, creating familiarity with reading green metrical data. Exploring plastics cradle to grave, considering the sourcing of polymer feedstocks, their manufacturing, and their end-of-life management, is key to gaining a better understanding of the impact that commodity polymers and plastics have on our environment.

The activity is formatted as a puzzle box-style escape room.[76] Forms of gamified learning, such as escape rooms, have been previously implemented to explore the relationship between material properties (polymers) and molecular functionality; for example, hydrophobic *versus* hydrophilic moieties.[77,78] These methods can create an engaging learning environment in which participants build stronger connections with the material, its design, synthesis, and implementation. This activity consists of three puzzles ranging from matching code puzzles to critically analysing LCA and green metrical data. These tasks guide the participants in reading tabulated LCA data over a variety of endpoint categories, with the goal of encouraging participants to think critically about polymers and their global impacts.

Learning objectives

- To evaluate and analyse concepts of sustainability as it relates to a cradle-to-cradle life cycle analysis.
- To evaluate sustainability through the lens of sustainable materials, resources, and reagents utilization and procurement.
- To explore and analyse concepts related to LCA in the contexts of polymer production and depolymerization.
- To understand preliminary concepts related to green catalysis and catalyst considerations in the context of depolymerization catalysts.

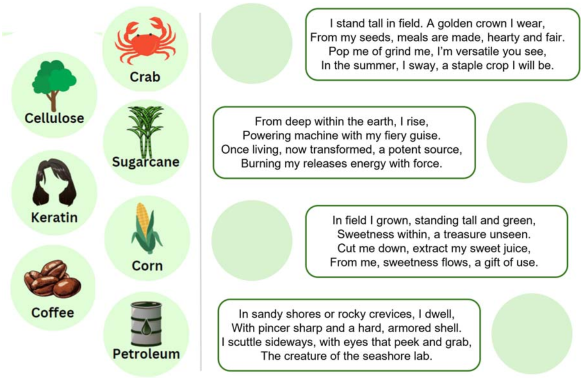
Puzzle details. The following section provides brief details on the puzzle contents and purpose in promoting green chemistry education. A more detailed overview of the activities can be found in the SI.

Puzzle 1 – exploring polymer feedstocks

Puzzle one is a riddle-based matching game geared at introducing participants to common polymer feedstocks, both petroleum and bio-derived (Fig. 2). Participants are required to match the appropriate feedstock tokens to the riddles provided, revealing a set of four numbers. These numbers are used to select the correct "clue" which reveals the location of the data folder required to complete the second puzzle.

Puzzle 2 – green metrics for common polymers

Puzzle 2 takes a deeper look at the overall sustainability of current polymer feedstocks and their corresponding commercial polymers. Leveraging the seminal work of Landis *et al.* as a guide,[79] participants explored their work on sustainability metrics, including life cycle analysis, associated with green polymer design. Participants are provided with a list of various petroleum, biological, and hybrid-base polymers, the associated life cycle assessment results for each of the polymers in TRACI



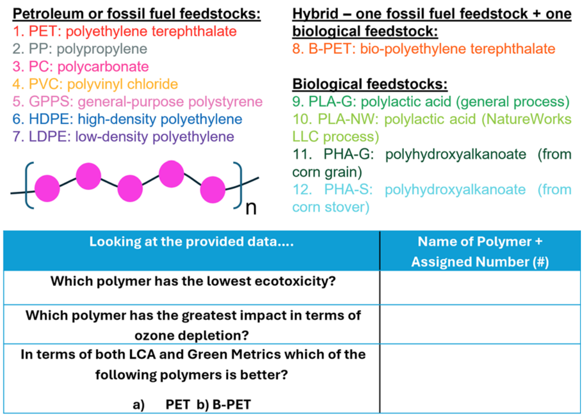
I stand tall in field. A golden crown I wear,
From my seeds, meals are made, hearty and fair.
Pop me of grind me, I'm versatile you see,
In the summer, I sway, a staple crop I will be.

From deep within the earth, I rise,
Powering machine with my fiery guise.
Once living, now transformed, a potent source,
Burning my releases energy with force.

In field I grown, standing tall and green,
Sweetness within, a treasure unseen.
Cut me down, extract my sweet juice,
From me, sweetness flows, a gift of use.

In sandy shores or rocky crevices, I dwell,
With pincer sharp and a hard, armored shell.
I scuttle sideways, with eyes that peek and grab,
The creature of the seashore lab.

Fig. 2 Image of key components of puzzle 1 – exploring polymer feedstocks.



Petroleum or fossil fuel feedstocks:
1. PET: polyethylene terephthalate
2. PP: polypropylene
3. PC: polycarbonate
4. PVC: polyvinyl chloride
5. GPPS: general-purpose polystyrene
6. HDPE: high-density polyethylene
7. LDPE: low-density polyethylene

Hybrid – one fossil fuel feedstock + one biological feedstock:
8. B-PET: bio-polyethylene terephthalate

Biological feedstocks:
9. PLA-G: polylactic acid (general process)
10. PLA-NW: polylactic acid (NatureWorks LLC process)
11. PHA-G: polyhydroxyalkanoate (from corn grain)
12. PHA-S: polyhydroxyalkanoate (from corn stover)

Looking at the provided data....	Name of Polymer + Assigned Number (#)
Which polymer has the lowest ecotoxicity?	
Which polymer has the greatest impact in terms of ozone depletion?	
In terms of both LCA and Green Metrics which of the following polymers is better? a) PET b) B-PET	

Fig. 3 Image of key components of puzzle 2 – green metrics for common polymer.

impact categories,[80,81] the green principles assessment for each of the polymer studies, and three prompts (Fig. 3). The prompts encouraged participants to review the green metrical data on a surface-level, becoming more familiar with the categories assessed.

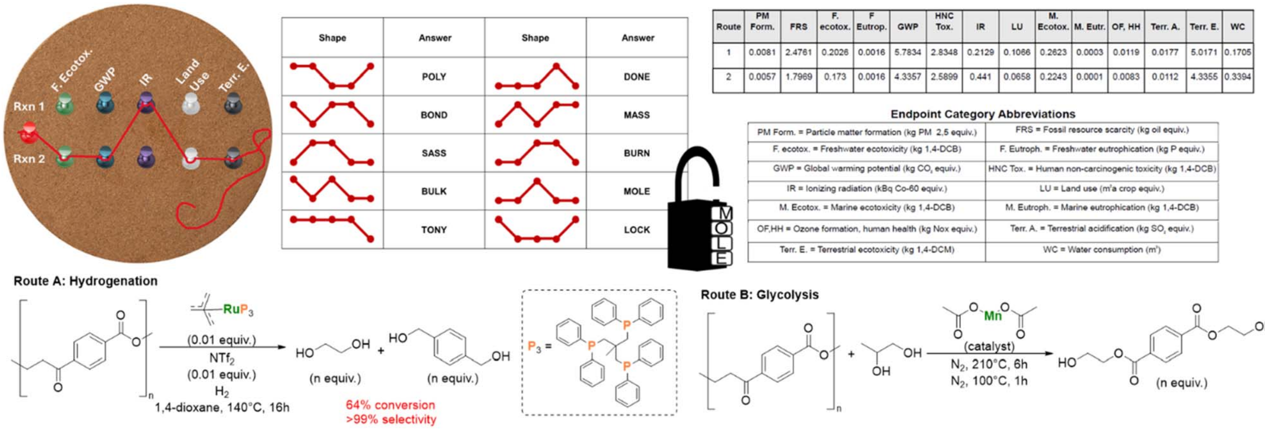
Puzzle 3 – green catalysts for depolymerization

Conversations on recycling practices are most common when we consider plastics at their end of life. It is a practice many of us are familiar with from our day-to-day life. However, there are downfalls to current recycling practices including plastic compatibility, material degradation, and overall cost.[82] An emerging method in polymer chemistry is depolymerization, wherein, a catalyst is used to degrade the polymer back to reusable monomer feedstocks.[83] With net-zero goals in mind, the monomers produced could then be used to synthesize virgin plastic or alternative value-added products.[84] Puzzle 3 explores the green metrics of two catalytic processes used for the depolymerization of polyethylene terephthalate (PET) a common industrial polymer. Participants are provided with the reaction schemes for each of the catalytic processes; (A) PET hydrogenation utilizing a ruthenium catalyst to yield glycol and 1,4-benzenedimethanol,[85] and (B) glycolysis, catalysed by a manganese acetate complex in the presence of 1,2-propanediol to form bis(2-hydroxyethyl) terephthalate.[86] The green metrics associated with the two processes were reported by Lizundia *et al.*[87]

Utilizing their green analysis of a series of endpoint categories, participant must determine that the metrics need to be plotted on the provided cork trivet (Fig. 4) to determine the associated plot shape and corresponding letter code for a final lock (inspired by Ang *et al.*).[88] Puzzle 3, while similar in nature to puzzle 2, showcases that green metrics can be utilized to assess chemical processes alongside products, underscoring the prioritization of differing metrics is a key component to determining which process is superior for a specific application.

The final lock opened an envelope containing an exit survey alongside the instructions to complete a polymer synthesis activity. In the activity, participants synthesize a glue-based slime, substituting borax for contact solution as a greener alternative, and added different additives to the polymer mixture.[89] They were encouraged to assess the effects of the additives on the polymer properties, considering the environmental impacts of additive use and how additives may affect recycling or depolymerization processes.[90] The questionnaire prompted participants to consider what polymer feedstocks they considered optimal and what factors influenced their choice as well as which criteria, when assessing the sustainability of the depolymerization catalysts, they found most significant. There were ten respondents in total. While there was little consensus on which polymer feedstock was the optimal choice, however, 60% of respondents indicated that secondary (agricultural residue, oil-refining byproducts, fishery waste) or tertiary (municipal waste, used cooking oils) waste feedstocks are a better choice compared to primary sources (crops, timber, fossil fuels).[91]

When considering the various criteria for comparing the depolymerization processes, number of reaction steps (including purification), catalyst metal abundance, and catalytic efficiency (turnover frequency) were rated as the top three most significant criteria. This highlights a common narrative in green chemistry communities where "greenness" must be balanced with efficiency and cost.[92,93]



Route	PM Form.	FRS	F. ecotox.	F Eutrop.	GWP	HNC Tox.	IR	LU	M. Ecotox.	M. Eutr.	OF, HH	Terr. A.	Terr. E.	WC
1	0.0081	2.4761	0.2026	0.0016	5.7834	2.8348	0.2129	0.1066	0.2623	0.0003	0.0119	0.0177	5.0171	0.1705
2	0.0057	1.7969	0.173	0.0016	4.3357	2.5899	0.441	0.0658	0.2243	0.0001	0.0083	0.0112	4.3355	0.3394

Endpoint Category Abbreviations

PM Form. = Particle matter formation (kg PM 2,5 equiv.)
FRS = Fossil resource scarcity (kg oil equiv.)
F. ecotox. = Freshwater ecotoxicity (kg 1,4-DCB)
F. Eutroph. = Freshwater eutrophication (kg P equiv.)
GWP = Global warming potential (kg CO_2 equiv.)
HNC Tox. = Human non-carcinogenic toxicity (kg 1,4-DCB)
IR = Ionizing radiation (kBq Co-60 equiv.)
LU = Land use (m^2a crop equiv.)
M. Ecotox. = Marine ecotoxicity (kg 1,4-DCB)
M. Eutroph. = Marine eutrophication (kg 1,4-DCB)
OF,HH = Ozone formation, human health (kg Nox equiv.)
Terr. A. = Terrestrial acidification (kg SO_2 equiv.)
Terr. E. = Terrestrial ecotoxicity (kg 1,4-DCM)
WC = Water consumption (m^3)

Fig. 4 Image of key components of puzzle 3 – green catalysts for depolymerization. Image adapted from ref. 76.

Activity three – Poli-zzies tower

Overview. While the need for scientific consultation in sustainable policy development is clear, how researchers, especially early career researchers, can become involved with policy creation is not well defined.[94] Building dynamic, effective, and lasting policy requires the continued participation of all stakeholders, including junior scientists.[95–98] Junior researchers are readily exposed to emerging scientific trends in green chemistry during their training. Similarly, compared to their more established counterparts, they are often less biased by professional obligations and interests, allowing them to contribute strongly evidence-based information to policy-makers. While mechanisms for researcher training in policy are available,[94,95,97–100] scientists need an entry point to better understand their role as stakeholders.

The game of Poli-zzies was developed to enable participants to question and engage with chemical policy, the various stakeholders who develop policy, and what role each participant has as a stakeholder. Poli-zzies is based on the game Fuzzies by CMYK,[101] a competitive tower building game, which allows the activity to be an "out-of-the-box" experience incorporating tactile learning. Each game accommodates 2–4 players. The original game was modified in several ways: the competitive ruleset was replaced with a collaborative ruleset, the challenge cards became key gameplay elements rather than punitive elements, and the game pieces were assigned by colour to specific categories of stakeholders (Fig. 5). To align with a focus on chemical policy, the stakeholders were chosen to be non-governmental organizations (NGO), industrial (R&D), industrial (production), government, and academia.

The game itself is a strong visual representation of how policy is shaped by the efforts of many stakeholders as the policy tower is composed literally of the stakeholders. To incentivise gameplay, there are two win-conditions: first, to finish all six game cards without knocking over the tower; second, to build the tallest tower. The second win condition is meant to enable friendly competition between groups of Poli-zzies players while maintaining a collaborative attitude within each group.

The six cards, which determine the length of the game, were developed to be relevant to a scientifically literate general audience – there is no specialised knowledge required. The six themes explored in the game cards are: barriers to implementing sustainable policies, advantages and disadvantages of organizational codes of conduct, relative strengths and impact of various stakeholders during a catastrophic event, the various metrics for green chemistry, rigid *versus* flexible targets when developing sustainability goals, and the influence each player can have as a stakeholder (Fig. S7a–f). As policy and current events are in constant flux, the cards are intended to be able to be substituted or modified as needed; guidance on developing new cards is given in the SI. Six cards typically result in play times of 45–60 minutes depending on participant engagement, and shorter games can be achieved by simply lowering the number of cards.

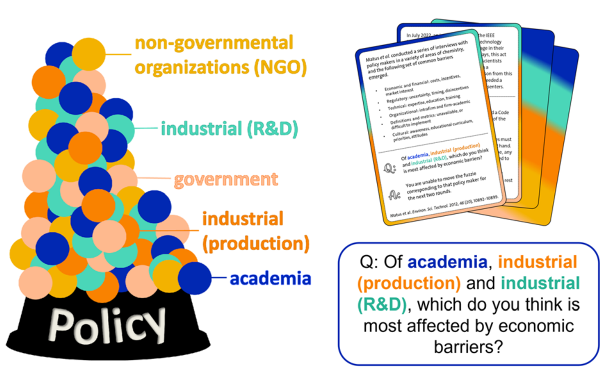


Fig. 5 Example game tower with colour coded stakeholders (left). Example cards and questions utilized during the game (right).

Learning objectives

- To apply prior knowledge in the determination of existing policy within laboratory groups, universities, industry, municipalities, provincial, federal, *etc.* and analyse how those policies are created/implemented.
- To challenge concepts related to "who should decide" policy and how singular researchers may affect policy.
- To evaluate the importance of scientific communication and education in the creation of meaningful policy and societal comprehension.
- To evaluate the relationship between policy, safety, and rising global concerns.

Comments. Out of six groups (one with 2 participants, one with 3, and four with 4), only two completed the full game. Most groups either ran out of time—largely due to the conference schedule—or knocked over their tower. For use in similar settings, we recommend using fewer than six cards to better fit within tight timeframes.

While players were actively engaged with moving the pieces, much of the gameplay was driven by the discussions that emerged from the prompts. That said, the gameplay mechanics were well-matched to the participants' level and didn't present any barriers. Once the rules were introduced, facilitation was straightforward. Groups—particularly those with 3 to 4 members—tended to manage themselves without much need for facilitator input. Participants remained engaged throughout and responded positively to the prompts. Verbal feedback suggested that the variety of questions kept the experience interesting and relevant. Overall, the activity was effective in promoting meaningful conversation and reflection, especially in small-group formats.

Flash talks and worksheets

Overview. For this final activity, we invited speakers to give 5-minute flash talks in two blocks; each block was followed by 25 minutes of questions from the audience. These speakers were selected across a variety of sectors including academia, industry, safety, chemical education, and inorganic/materials chemistry. Speakers included: Joe Gilroy (Western University; polymer science and catalysis; academia); Johanna Blacquiere (Western University; inorganic chemistry and catalysis;

academia); Dylan Webb (Mount Royal University; inorganic chemistry; academia); Amanda Bongers (Queen's University; chemical education research; academia); John De Backere (University of Toronto; chemical education; academia); Brenna Brown (National Laboratory Services Manage; Brenntag Canada; industry). All speakers were invited based on their diversity of experience and our existing networks. Speakers were provided guidelines for their flash talks and details about the symposium in their invitation letters (a copy of this invitation letter can be found in the SI).

Following the flash talks, we provided the opportunity for participants to have round-table discussions with each other. To provide structure to these discussions, we provided worksheets across four themes: policy, chemistry education, inorganic chemistry, and materials chemistry. These worksheets, provided as guidance, were tuned to the specific theme they were to address but generally explored:

(i) Positionality: in what space participants work themselves and work with others.
(ii) Goals: what participants wanted to achieve.
(iii) Challenges and opportunities: what barriers are present, what barriers can be overcome, what opportunities are present in their circumstances.
(iv) Resources for continued learning: where can participants learn more about certain topics brought up in the discussion or in completing the worksheet.

These worksheets can be found in full in the SI. The goal of the worksheets was to provide a guided space for collaboration amongst participants and to engage in active learning. Additionally, we wanted participants to have something to take back to their institution after the symposium to consider how green chemistry and sustainability can intersect with their own research, teaching, and service. The takeaways were their answers from the discussion on how to implement green chemistry as well as the compiled resource list for continued learning post-conference. All worksheets were made available to participants following the symposium.

Learning objectives

- To organize one's own ideas about sustainability and green chemistry as it intersects with their own field of work.
- To design classroom- or research-based activities about sustainability and green chemistry for one's teaching or research group.
- To define one's own circumstances and values in sustainability and green chemistry in their work.

Discussion

The field of green chemistry is highly interdisciplinary in nature, with green chemistry principles being able to be implemented in all chemistry disciplines. To engage a broad conference audience, and encourage attendance from both researchers and educators, we chose to implement activities incorporating concepts of inquiry-based learning (flash talks and worksheets), gamified learning (activity one), and gamification (activities two and three). Gamification and gamified learning, as mentioned previously, can work to create an inclusive learning environment with low-stake opportunities to engage with the material. The sustainability web was chosen as the first activity to open the symposium, providing participants with an opportunity to introduce themselves, share their viewpoints on sustainability, and begin to engage in conversations on the role of sustainability as it relates to different subdisciplines. Similar to previous iterations,[26] the activity encourages participants to utilize a systems thinking approach in assessing the different definitions of sustainability and their relationship to various stakeholders and communities of practice, working to prompt discussion, framing the context for later learning. The development of the web of connections is similar to other systems thinking activities previously described.[13]

During the facilitation of the "Waving the Green Flag" symposium there was an eagerness in the room emanating from participants and facilitators alike. Individuals were excited to engage with a new symposium format, interactive and gamified, as well as the green chemistry content contained therein. Near the end of the symposium, when prompted with the question "What inspired you today?", 11 attendees responded, noting their enjoyment connecting with other passionate individuals on green chemistry, the open communication and positive feedback from participants, discovering new methods to make changes to their own sustainability practices, the connections between safety and sustainability, and the key role that policy at all levels plays to implement and sustain green chemistry initiatives.

The symposium was run over several hours, 8:00 am–12:30 pm, with an intermission for participants to attend the plenary lecture (9:40 am–10:50 am). Flash talks and panel discussions were hosted both before and after the plenary lecture on a designated schedule with the activities and networking filling the free time. The session was ended following time for guided discussions. Activities one through three can be completed in any order, however, participants were encouraged to complete them in order as the educational contents are scaffolded. Each flash talk session consisted of three 5-minute presentations followed by a 20-minute discussion panel with the speakers. The closing guided discussions (30 minutes) were facilitated in an open format with the provided worksheets acting as a conversational prompt. Facilitators noted a drop in attendance numbers following the break for the plenary lecture. In the future we recommend attempting to schedule the sessions with a smaller break to reduce attrition.

To explore modern methods in green chemistry applications, we chose to develop activity two, focusing on the life cycle of polymers and plastics, a field in which most individuals have some familiarity due to the plastic pollution crisis.[73–75] The puzzles therein explored the green metrical data associated with various feedstocks (biomass and petroleum sources), the resulting polymer products, and depolymerization, an emerging methods in plastic recycling, giving participants a stronger understanding on how LCA data may be utilized to inform practice. Flash presentations and panel discussions with current green chemistry leaders in research, education, industry, and safety were likewise included to expand the conversation to other fields. Together, activities one and two provided participants with the background knowledge and lines of thinking to examine the presented research through a green lens, searching for the connections between the research performed and the final impacts on sustainability. The following discussions during the panel were reflective of these insights, focusing more on the implications of green chemistry, how the presented methods may be incorporated into individuals' own research, and the downstream effect on future research and policy.

In response to the growing conversations on the importance of developing scientifically data-driven policy for furthering sustainable development goals, we chose to create an activity focused on showcasing the roles of different stakeholders in policy development. An important feature of the game was to showcase that there are no right or wrong answers, but that all decisions have downstream consequences that can affect later policy development and industrial implementation. Tensions between the need for scientific rigor and the requirement for timely political action are reflected in how the tower is built, and what heights can be achieved. This activity was the most popular, with participants engaging in lively discussions on both the concepts approached in game, focused on recent events associated with the 17 Sustainable Development Goals, as well as their own experiences. It showcases a desire to engage more deeply in conversations on the best paths forward in sustainable development, moving away from the "vision" to the actual application.

To support this translation, we incorporated the take-away worksheets to be utilized during the guided discussions. The worksheets not only acted as discussion prompts but gave researchers a guided framework in which to explore their own chemistry, identifying resources available to them (materials, funding, support networks) and which best practices in green chemistry can be implemented to augment their research. As the symposium was cross-listed with the inorganic, environmental, and education divisions, we limited the worksheets to:

- Inorganic chemistry, in relationship to the development of catalysts as seen in the depolymerization puzzle,
- Materials chemistry, as it relates to the design of materials such as polymers and plastics, explored in activity two,
- Green chemistry education, relating to the development of green chemistry interventions and the creation of active learning tools such as those leveraged during the symposium, and
- Policy, focused on how individuals may become more involved in policy, what resources are available to them, and how to frame their own research in terms of policy development.

Conferences targeted at exploring research progress in sustainable chemistry and engineering are becoming more popular. The American Chemical Society Green Chemistry Institute (ACS-GCI) Annual Green Chemistry & Engineering Conference is well established,[102] while conferences such as the Commonwealth Chemistry Congress,[103] focusing on the 17 UN Sustainability Goals, and the International Conference on Sustainable Chemistry for Net-Zero are newly emerging.[104] While green chemistry specific conferences play an important role in sharing modern methods across disciplines in sustainable development, we argue that mixed conferences, such as the Canadian Chemistry Conference and Exhibition (CSC) strongly benefit from the incorporation of green chemistry symposia. Interactive symposia such as this can have added benefit in that they are accessible to a wide range of audiences and can help improve sustainability "buy-in" amongst researchers who may not consider their work to be within the field of green chemistry. These symposia reduced barriers within the community, highlighting applicable paths forward for all chemists. We hope that this article acts as inspiration for further development in this area.

The activities described herein can be readily adapted to undergraduate classrooms following an introduction on the 12 Green Chemistry Principles and the purpose and scope of green chemistry metrics. While an understanding of inorganic chemistry, catalysis and polymer design, is not required to complete the activities, it can be an asset in probing deeper questions on green chemistry applications within those fields. For example, educators may choose to discuss the utilization of base metals in place of precious metals as a green alternative in catalyst design.[105] Similarly, educators may wish to discuss the importance of balancing green chemistry principles with material and catalyst function. With a desire to deepen learning on green chemistry applications in inorganic and materials chemistry, we recommend introducing this activity in second or third-year inorganic chemistry classrooms following an introduction on catalyst design and polymer structure–property relationships. Graduate student supervisors may also find it beneficial to utilize the guided worksheets as a discussion prompt during research or group meetings. This can help students to ground their work in sustainable design and prompt a stronger understanding of the down-stream impacts of their research on both the chemistry community and society – a benefit when engaging in manuscript and grant writing.[106,107]

Future directions

Following the success of the Waving the Green Flag symposium at the 2024 CSC, we hope to continue to develop interactive symposia for future chemistry and engineering conferences. We plan to utilize the 17 UN Sustainable Development goals as a guide in selecting future green chemistry topics. For example, delving deeper into the inorganic and materials chemistry and engineering approaches to water purification, SDGs 6 (Clean Water and Sanitation) and 14 (Life Below Water). We plan to engage with outside communities, such as Canadian First Nations communities, to gain a stronger insight into how chemistry directives and policy development can be leveraged to further green chemistry and engineering while incorporating traditional ways of knowing and doing. Here, the goal is to develop reciprocal relationships in which scientific communities can engage with the public representatives to develop meaningful paths forward in sustainable development. Through this work, we aim to establish communities of practice both within the academic and industrial chemistry community, but also with external stakeholders. EDI-AR will rest as our core principle as we reduce barriers to access sustainable developmental tools and sustainable communities of practice.

Additional to developing new curricula for implementation in interactive symposia or classrooms, we also aim to develop a series of assessment tools to better reflect participants' understanding of the content and the ability of the activities to achieve their desired learning objectives. Here, we will implement a series of self-reflections in which participants rate their understanding of green chemistry principles both before and after the activities. The self-reflections will include a series of exam-style questions reflective of the course (or symposium) learning outcomes. By comparing participants reflections and answers both before and after the activities, we can assess the effectiveness of the activities on learning in green chemistry. Future participants will also be asked to complete a post-symposium feedback survey focused on the utility of each activity and the perceived effects on learning. With this data, we hope to better design interactive activities and gain a deeper understanding of the benefits of these tools in professional and classroom learning.

Conclusions

The "Waving the Green Flag" symposium, hosted at the 2024 Canadian Chemistry Conference and Exhibition represents the second iteration of inquiry-based, gamified active learning techniques to be applied in a conference learning space – the professional's classroom. Interventions such as this represent a novel path forward in the training of our future sustainability leaders, providing learning in systems thinking, green metrical analysis, and methods in green chemistry that can be readily applied to individual research projects. The activities are geared to engage broad research audiences, leveraging well known global challenges, such as plastic pollution, to frame discussions. This helps to create an inclusive atmosphere where participants can engage with the material and gain a sense of belonging within the green chemistry community – a vital component in developing partnerships for the goals.

Continued support from the conference program chairs as well as resoundingly positive feedback from attendees and those within the green chemistry community following the conference highlights the utility of interactive symposia, providing a fresh perspective on conference learning. There is a desire in the chemistry community to engage more deeply with research, and with one another, to solve our global challenges. Individuals are eager to not only share their research, but to share their opinions and insights in a collaborative environment where interdisciplinary initiatives can be slow to progress. Green and sustainable chemistry is an ever-changing field of research, responding to our global challenges, policies, and societal feedback. Our best path forward as scientific representatives is to approach learning and implementation of green chemistry through a dynamic lens – reflected in the organization of symposia and activities such as this. We continue to develop methods to foster open, research driven, community spaces within green chemistry and hope others will take inspiration from this work to continue the same.

Author contributions

Bannard, Daliaho, Hong, Davy, Pitsiaeli, and Durfy contributed equally to the conceptualization of symposium activities, development and implementation of activities, methodology, visualization, and review and editing of the final manuscript and associated SI. Schechtel contributed to the conceptualization of symposium activities, development of the worksheets, methodology, visualization, and review and editing of the final manuscript and associated Supporting Information. 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, 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 have been included as part of the SI. Activity descriptions, print files, and facilitation details, guided worksheets, and presenter invitations. See DOI: **https://doi.org/10.1039/d5su00554j**.

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