Green Machine: A Card Game Introducing Students to Systems Thinking in Green Chemistry by Strategizing the Creation of a Recycling Plant

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S *Supporting Information*

ABSTRACT: Green Machine is a competitive strategy card game facilitating a systems thinking approach to learning recycling processes and green chemistry in accordance with the United Nations Sustainable Development Goals. Players compete to be the first to be able to launch their recycling plant by collecting a series of playing cards. Players must use interpersonal skills to consider the interconnected systems while showing an appreciation for commercial awareness and versatility, as dynamic problem solving (reflecting real-world scenarios) is required to play the game successfully. The card game was implemented with 19 U.K. graduate students and 29 U.S. second-year undergraduate students. Survey feedback showed that Green Machine was an innovative resource that was enjoyable to play and engaged students in learning recycling processes through systems thinking. On the basis of pre- and post-test questions to evaluate learning gain, Green Machine is a helpful resource to introduce students not only to green chemistry and sustainability but also to taking a systems thinking approach to learning.

KEYWORDS: *Second-Year Undergraduate, Graduate Education/Research, Chemical Engineering, Environmental Chemistry, Collaborative/Cooperative Learning, Humor/Puzzles/Games, Systems Thinking, Green Chemistry, Sustainability*
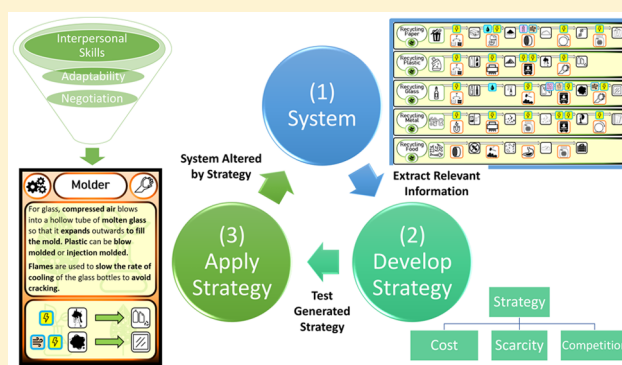
■ INTRODUCTION

Significant impetus for the inclusion of green and sustainable chemistry practices in educational environments across the globe has been facilitated via the creation of the United Nations (UN) Sustainable Development Goals (SDGs) in 2015.[1] These objectives seek to address global challenges relating to poverty, inequity, climate, environmental degradation, prosperity, and peace and justice. Because of the interconnected nature of the SDGs, meeting such objectives in an educational context can be achieved by integration of systems thinking approaches into the curriculum.[2] In view of the range of systems thinking definitions, an explicit definition is warranted. Here systems thinking is taken to be a set of synergistic analytic skills used to improve the capability to identify and understand systems, predict their behaviors, and devise modifications to them in order to produce desired effects. These skills work together as a system.[3] A system is hereby defined as groups or combinations of interrelated, interdependent, or interacting elements forming collective entities.[3]

By studying the interdependence of components in dynamic systems, students can transition from a fragmented and reductionist knowledge of subject matter to a more integrated and lateral understanding of concepts, resulting in deeper learning.[4] As a discipline, green chemistry is well-suited for instructors to adopt a systems thinking approach to education because applications of the principles of green chemistry, employment of life cycle analysis tools, and devising molecular design strategies all depend upon considering the reliance of reactions and processes on one another with local and global systems.[5] Through this, students can be challenged to solve real-world problems in the context of green chemistry with due consideration of ethics to deliver solutions that address the SDGs.

To enhance the efficacy of adopting systems thinking approaches to teach green chemistry, incorporation of active learning strategies in the context of systems is likely to lead to
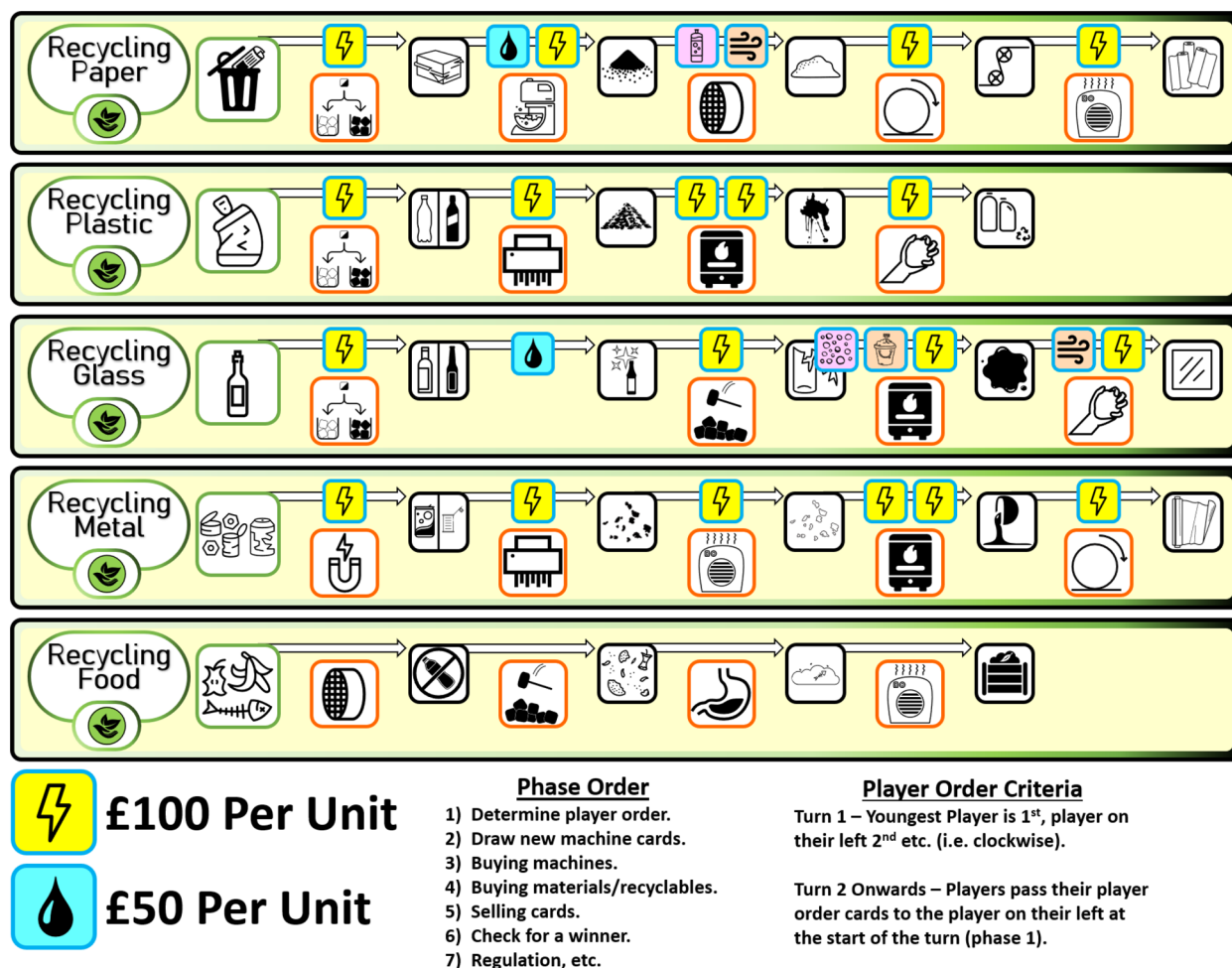
Figure 1. Front side of the reference sheet showing each recycling process.

increased student engagement and attainment.[6] One way to achieve this is for instructors to utilize resources to foster game-based learning, a type of game play that has defined learning outcomes. As learning and play are synonymous through balancing of subject matter with game play, such interventions can lead to cognitive and emotional student development within a social and cultural context.[7] Indeed, there are multiple examples in the chemistry education literature of the use of games to teach chemistry at a range of levels, with some of the most recent to include card games,[8−11] board games,[12−15] games requiring hands-on learning,[16−19] interactive computer games,[20−22] and mobile-application-based games.[23−26] Within green chemistry, game-based learning has been employed to construct an interactive computer game to motivate students at the undergraduate and advanced high school levels to consider green chemistry and sustainability issues as they design a hypothetical chemical product.[27] This game is free of charge and assists students to think like professional chemical engineers to develop a chemical product with respect to function and improved human and environmental health and, in doing so, to develop an appreciation of the Twelve Principles of Green Chemistry.[28] Hence, there are significant opportunities to develop further resources to facilitate game-based learning in green chemistry, especially by utilizing a systems thinking approach in conjunction with the activity.

■ IMPLEMENTATION OF GREEN MACHINE IN CHEMISTRY

Green Machine is a competitive strategy card game in which a number of players, from 2 to 6, represent recycling companies contracted by the government to recycle household waste. Players compete to be the first to launch their recycling plant. This is achieved through collecting a series of cards (as detailed on the reference sheet, Figure 1) and by having sufficient funds in the game at the end to make the plant operational. Associated learning objectives include the following:

1. **Apply** a systems thinking approach to waste valorization, considering the recycling processes of key household waste items.

2. **Recognize** that recycling facilitates global sustainable development (as defined by the UN Sustainable Development Goals) and is an integral part of the life cycle of many products.

3. **Describe** the scientific principles, in a green chemistry context, that underpin recycling processes.

4. **Evaluate** relevant information from the system in order to independently formulate a robust strategy that uses the system advantageously.

5. **Analyze** system changes and **modify** a chosen strategic approach accordingly.
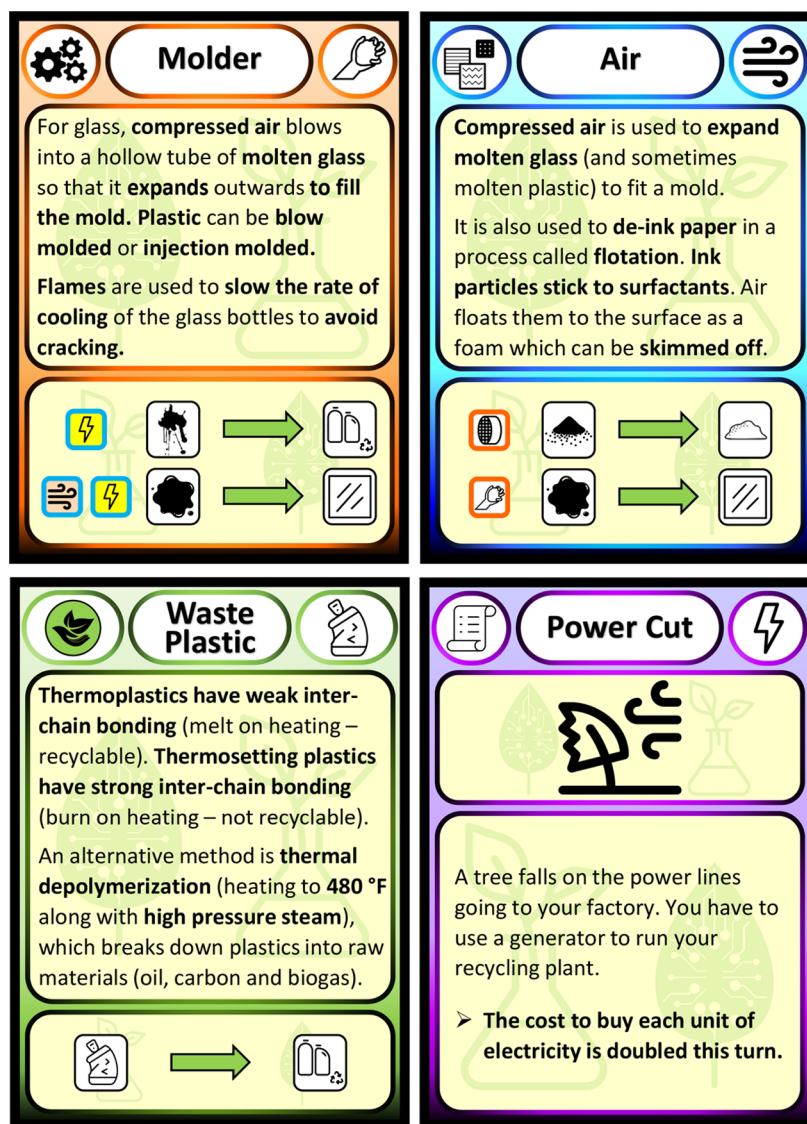
Figure 2. Representative game cards: machine card (orange), material card (blue), recyclable card (green), and government regulation card (purple).

Each player starts the game with no cards and 1000 currency units (e.g., pounds or dollars). In order to win, a player must have all of the machine cards (in orange) and material cards (in blue) and the recyclable card (in green) involved in their chosen process along with sufficient funds for the purchase of electricity and water (also in blue) required by the process. The recycling processes (and hence the cards needed to complete them) encompass food, glass, metal, paper, and plastic feedstocks, as shown in Figure 1. It is particularly noteworthy that the use, sorting, recovery, and recycling of plastic waste still remains largely unresolved, as many fundamental issues are often overlooked. For example, additives that are used to enhance polymer properties and prolong their life have the potential to contaminate soil, air, water, and food, where they can be released from plastics during the recycling and recovery processes. Therefore, sound recycling has to be performed in such a way as to ensure that the release of substances of high concern is avoided, ensuring environmental and human health protection (aligned with the UN SDGs) at all times.[29]

Players start by making bids on machine cards (in orange). Here players must leverage their systems thinking skills in order to develop an effective strategy to collect the requisite cards. In doing so, players must weigh the relative ease of completing each recycling pathway alongside the actions of their competitors (who may also choose to bid for the same cards, aiming to complete the same pathway or another that also requires that card). In this way, players must also utilize their interpersonal skills, a key aspect of personal development, and decide who is bluffing, who is trying to overpay, and who is really serious about purchasing a given machine. Players are then tasked with purchasing materials and recyclables cards from a materials/recyclables market (for which no bidding occurs).

Players have to adapt their strategy quickly if they lose out on a bid for a machine card or if the cards in the materials/recyclables market do not fall their way. The mainstay of the game is the repeated and frequent use of systems thinking skills to continually reanalyze the system at large to adapt the employed strategy.

Table 1. Full List of Game Cards by Type

Machines		Materials		Recyclables		Government Regulation		Player Order	
Card Name	#	Card Name	#	Card Name	#	Card Name	#	Card Name	#
Sorter	6	Air	12	Waste Paper	4	Power Cut	1	First	1
Pulper	4	Surfactant	6	Waste Plastic	3	Catching Sun	1	Second	1
Roller	4	Sand	6	Waste Metal	4	Drought	1	Third	1
Heater	6	Carbonate	6	Waste Glass	4	Monsoon Season	1	Fourth	1
Filter	4			Waste Food	2	Monopoly Crackdown	1	Fifth	1
Shredder	3					Machine Subsidy	1	Sixth	1
Furnace	6					Machine Madness	1		
Molder	4					Material Shortage	1		
Electromagnet	3					Price Fixing	1		
Crusher	4					End of Trading	1		
Digester	2								

An opportunity then arises for players to sell any cards they no longer want back to their respective markets. Again, systems thinking is applied by successful players. Players may wish to reclaim funds for cards (if they change the pathway they are working to complete), but selling a card can give their competitors a chance to purchase it next time bids are made. Players must therefore consider the interconnected systems to see whether others need the card they plan to sell (or else they could be handing their opponents a clear advantage).

Under the umbrella of systems thinking skills comes commercial awareness: each decision must be weighed according to its cost. A missed opportunity (e.g., backing out of a bidding war) may prevent players from acquiring the necessary cards to win the game. However, a lack of funds that prevents them being able to afford the required utilities is just as problematic. Here systems thinking needs to be applied within a financial context.

A brief check is undertaken to see if a player has won. If no player has won, government regulation (in purple) is updated, and players receive a grant of 100 currency units. The government regulations also facilitate systems thinking. As in the real world, players must learn to adapt to but also to anticipate changes in government regulation, allowing them to solve problems in a dynamic fashion.[30] Players are able to see the regulation that is coming into effect on the next turn and can take steps to utilize or mitigate its impact before it comes into force, allowing players to plan ahead to an extent.

Play continues until such a time that one player meets the requirements to win the game; the first player to assemble their recycling plant and run the correct waste product through it is the winner. Representative cards are shown in Figure 2. To meet universal design principles, a key was designed for the four card types (machine, material, recyclable, and government regulation). A symbol indicating the card type is placed in the top left corner of each card (the symbol in the top right corner of each card is a unique identifier of the card). A full list of cards by type and quantity is shown in Table 1. Together with serving as prompts to inform players as to how the system will change (e.g., government regulation cards), many cards outline associated scientific principles, which players can be encouraged to read aloud to the group. All of the cards (except for the government regulation cards) contain background chemistry, including underpinning scientific principles, the chemicals, the physical processes involved, and information on the recycling processes themselves. Such principles include but are not limited to surface area to volume ratio (for easy melting and mixing), control of the cooling rate of materials

(to prevent damage), and the addition of lower-melting-point feedstock (to reduce energy use). These principles are linked to each process by way of the reference sheet (Figure 1), which facilitates matching of cards to their respective processes.

Systems and systems thinking are an integral part of Green Machine. In order to place the definitions provided earlier in the context of Green Machine, it is advisable to consider which elements of the game constitute the aforementioned systems and how systems thinking is inextricably linked to this.

The systems are the numerous mechanics of the game themselves, i.e., the bidding, buying, selling, government regulation, and recycling processes of the game. While Green Machine is framed within the context of the UN SDGs, these systems (i.e., potential impacts that each machine and individual process might have on the environment and health) are not modeled by the game.

With regard to the systems thinking skills themselves, the definition states that analytical skills underpin systems thinking. Such analytical skills include but are not limited to logical thinking, selecting and analyzing information, developing and evaluating solutions to problems, and constructing plans.[3] These systems thinking skills (i.e., a broad collection of analytical skills) are then applied to Green Machine. As outlined above, the systems thinking skills are leveraged and applied to all of the systems contained within the game.

A reflection on how the card game evaluation sessions meet the learning objectives is merited. Objectives 2 and 3 are achieved through the background information provided in the game rules and on the game cards themselves. Objectives 4 and 5 are facilitated through gameplay, i.e., players rely on achieving these objectives in order to play the game. Objective 1 is met through a combination of both background information and gameplay.

Two separate sessions were run where Green Machine was implemented, one in the U.K. and the other in the U.S. The session in the U.K. lasted 90 minutes and involved 19 graduate-level students enrolled in the MSc in Green Chemistry and Sustainable Industrial Technology course established by Professor James Clark and colleagues at the University of York in 2001.[31−33] The session in the U.S. also lasted 90 minutes and involved 29 second-year undergraduate students enrolled in an Organic Chemistry 2 Laboratory course with varying declared majors in science (predominantly biology and chemistry) at Augsburg University.

Both sessions were run in the same way, with coordination and agreement between the instructors as to how they should be conducted to ensure a consistent approach. The students

were divided into groups of four (where numbers allowed), and each group was given a set of Green Machine cards and an instruction manual. Each student was provided with a reference sheet. A PowerPoint presentation was used to introduce the session, the topic of systems thinking, and the game's concept. The presentation was adjourned after slide 5, and a set of pretest questions was used to obtain a baseline of the students' knowledge of recycling principles and using systems thinking skills. Slides 6 to 19 were used to explain the rules to students, with the session being stopped periodically for each group to play a part of the game as it was explained. The students were then left to continue playing the game until a winner in each group was found. After each group finished, that group was given a feedback survey to complete. Once all groups had completed the feedback survey, a set of post-test questions were completed by each student. The material of the post-test was identical to that of the pretest. The presentation slides, rules, full reference sheet, playing cards, market board, pre/post-test questions, and feedback survey are available in the Supporting Information.

■ STUDENT PERCEPTIONS OF GREEN MACHINE

After permission was obtained from the Institutional Review Board where relevant, sessions were conducted in the U.K. and U.S. Survey feedback was collected anonymously. For the U.K. session, 18 of 19 graduate students (95%) completed the survey (one student had to leave early). Because all but one of the students completed the survey, the results for the U.K. session are representative. The same is true for the U.S. session, where 29 of 29 undergraduate students (100%) completed the survey.

The survey questions were as follows:

1. I enjoyed playing Green Machine.
2. Playing Green Machine helped me better understand recycling processes.
3. Playing Green Machine improved my systems thinking skills.
4. Green Machine is an innovative resource to assist students in improving their systems thinking skills and learning about recycling processes.
5. I feel more engaged by systems thinking and recycling processes through playing Green Machine relative to the start of the session.
6. Playing Green Machine challenged me to use systems thinking skills.
7. Green Machine helped me to appreciate how systems thinking skills can be applied to real world problems.
8. [U.S. only] What was your major?
9. How can Green Machine be improved?
10. Other comments on Green Machine?

A Likert-style response scale was used to evaluate the student responses to questions 1−7, with 5 being assigned to "Strongly Agree" and 1 being assigned to "Strongly Disagree", and the responses to each question were averaged. Figure 3 shows the average scores for survey questions 1−7 as given by both the U.K. and U.S. students. The range of the averages for the U.K. students was from 4.17/5.00 (question 1) to 3.47/5.00 (question 3); for the U.S. students the range of the averages was from 4.14/5.00 (question 1) to 3.45/5.00 (question 2). The overall average response (i.e., the average of the averages) was 3.78/5.00 for the U.K. students and 3.87/
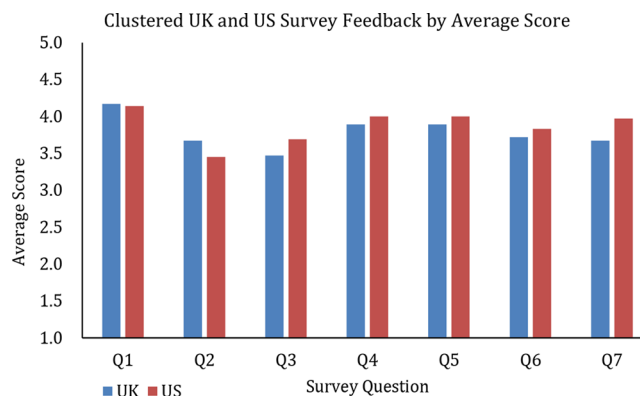

Figure 3. Clustered average scores of survey feedback by question number for U.K. ($n = 18$) and U.S. ($n = 29$) students.

5.00 for the U.S. students, roughly corresponding to an average agree response to all questions in both cases.

Comparing the U.K. data to the U.S. data yields interesting results. On average, the U.S. students provided more positive responses to the survey questions (true for all but questions 1 and 2). The largest differences were for question 7 (0.30 higher for the U.S.) and question 2 (0.22 lower for the U.S.), i.e., the two student groups shared broad agreement. It is noteworthy that both rated question 1 the most positively and questions 2 and 3 poorly.

Figure 4 shows the percentage of each type of response for each of the survey questions as given by both the U.K. and U.S. students.
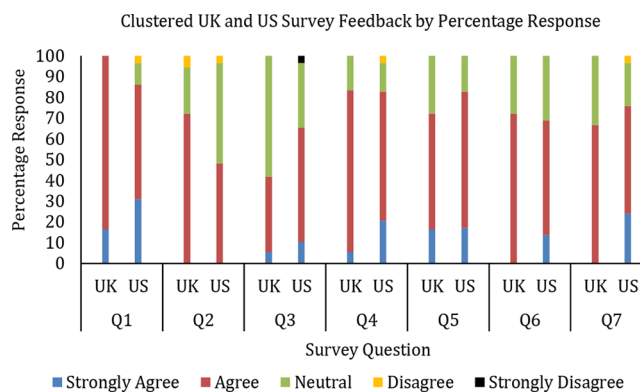

Figure 4. Clustered responses of survey feedback by question number for U.K. ($n = 18$) and U.S. ($n = 29$) students.

For the U.K. students, question 1 had the best response, with 100% agreeing or strongly agreeing with the statement "I enjoyed playing Green Machine". Question 2 was the most polarizing, with one student disagreeing with the statement "Playing Green Machine helped me better understand recycling processes." Question 3 had the worst response, with just 42% agreeing or strongly agreeing with the statement "Playing Green Machine improved my systems thinking skills."

For the U.S. students, question 1 had the best response, with 86% agreeing or strongly agreeing with the statement "I enjoyed playing Green Machine." Question 2 had the worst response, with just 48% agreeing with the statement "Playing Green Machine helped me better understand recycling processes."

While the U.S. responses were on average more positive, their responses were more polarized. There were far more "strongly agree", "disagree", and "strongly disagree" responses from the U.S. cohort than from the U.K. cohort.

Representative free text comments regarding playing Green Machine include the following:

- "Definitely engaging, I got a very good sense of a commercial recycling plant/economy."
- "Was very fun and well thought out."
- "It was fun once I got the hang of it!"
- "It was a lot of fun! I felt like it was a great bonding exercise."

LEARNING GAIN FROM GREEN MACHINE

Figure 5 shows the marks obtained by the U.K. students for both the pre- and post-test questions. Questions 1−6 relate to
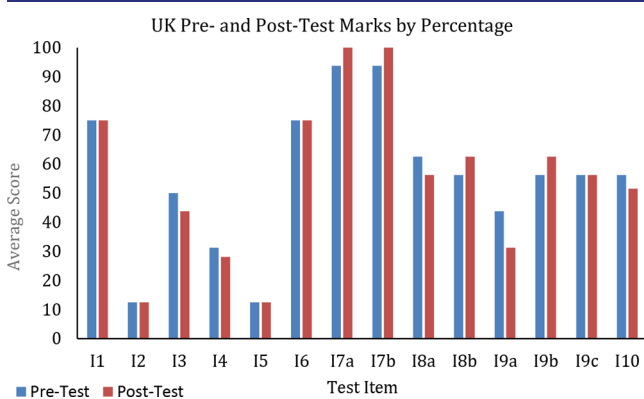

Figure 5. Clustered average marks of U.K. students ($n = 16$) on the pre- and post-test questions.

the recycling processes, and questions 7−10 relate to utilizing systems thinking. Upon first examination, there is no clear improvement in either of the two sections. The average percentage score decreased from 52.2% to 50.7% between the pre- and post-test. For the recycling questions, the scores fell from 42.7% to 41.1%, and for the systems thinking questions, the scores fell from 60.3% to 58.9%. A possible explanation of the lower marks could be that students may have rushed to complete the questions at the end of the workshop and not given full care and attention to them.

Three outliers were removed from the experiment. The first removal was the student who left the workshop early (and thus did not complete either the survey or the post-test). The second was a student who scored very poorly in the post-test as a result of choosing to select multiple answers for each multiple choice question (whereas this was stipulated only for question 4). Finally, one student arrived late and thus did not have sufficient time to complete the pretest questions.

Figure 6 shows the marks obtained by the U.S. students for both the pre- and post-test questions; the questions were identical to those given to the U.K. cohort. In contrast to the U.K. students, the U.S. students showed an improvement between the pre- and post-test questions: the average pretest score was 47.6%, and the average post-test score was 53.0%. The U.S. students also improved within each of the two question groupings: the average score rose from 43.4% to 50.0% for the recycling questions and from 51.2% to 55.7% for the systems thinking questions.
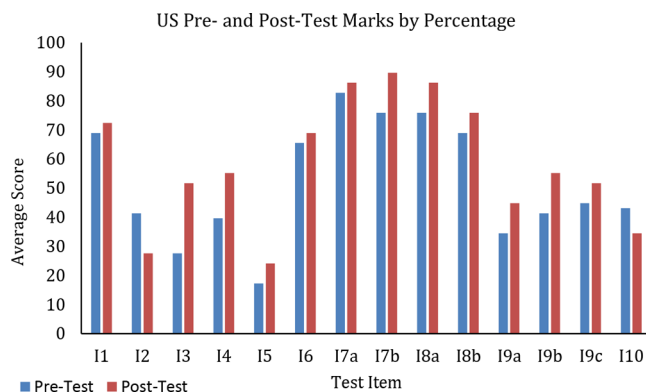

Figure 6. Clustered average marks of U.S. students ($n = 29$) on the pre- and post-test questions.

Figure 7 shows a comparison of the U.K. and U.S. marks for the recycling questions on both the pre- and post-test. On the
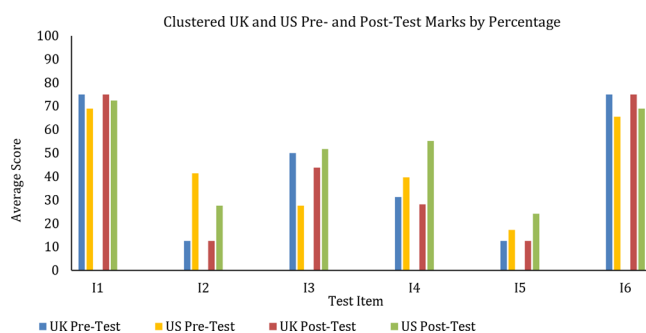

Figure 7. Clustered average marks of U.S. ($n = 29$) and U.K. ($n = 16$) students on the pre- and post-test recycling questions.

pretest questions, on average the U.K. and U.S. students did comparably (42.7% compared to 43.4%). On the post-test, however, the U.S. students improved while the U.K. students regressed slightly (41.1% U.K., 50.0% U.S.). The U.S. students improved between the pre- and post-test in all but question 2.

Figure 8 shows a comparison of the U.K. and U.S. marks for the systems thinking questions on both the pre- and post-test.
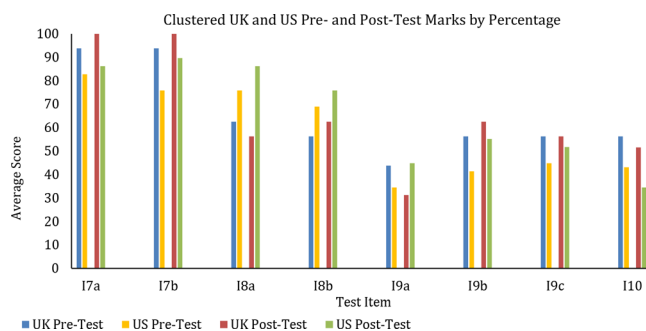

Figure 8. Clustered average marks of U.S. ($n = 29$) and U.K. ($n = 16$) students on the pre- and post-test systems thinking questions.

The U.K. students performed better on both the pretest (60.3% compared to 51.2%) and the post-test (58.9% compared to 55.7%). Again, the U.S. students improved between the two while the U.K. students regressed slightly. The U.S. students improved between the pre- and post-test in all but question 10.

Questions 1 and 6 were answered comparatively well by both cohorts, particularly compared with questions 2−5. This is likely a result of the fact that it was possible to answer questions 1 and 6 without specific recycling knowledge. Answers to these questions are also provided on the game cards, but the ability to draw on previous/general knowledge explains why students performed well.

There are clear differences in student performance when questions 7/8 and questions 9/10 are compared. Students found questions 9 and 10 to be more challenging by design. In questions 7 and 8, students had to identify the impact of a single variable (e.g., time spent refluxing) on the yield of a reaction. In contrast, for question 9, students had to make a comparison between two reaction variables (temperature and pH) and their effects on the yield. Question 10 was altogether different, asking students to suggest a suitable acid for the reaction and a determination of and rationale for the ease of developing a green alternative to the reaction. Since questions 9 and 10 required higher levels of thinking than questions 7 and 8, it is not surprising that students on average performed worse on those questions.

The difference in performance between the U.K. and U.S. students, particularly for the systems thinking questions (7−10), is likely due to the fact that the students were at different stages. The U.K. students were graduates undertaking a postgraduate qualification in Green Chemistry and Sustainable Industrial Technology, where systems thinking is included in the degree program.[34] Students also learn about the use of greener chemical products,[35,36] develop an awareness of green chemistry principles and reducing environmental impact as well as investigating the impact of solvents in reactions with an aim to find greener alternatives.[37] This specialist knowledge coupled with the systems thinking skills developed as part of their degree program was expected to lead to a positive performance enhancement relative to the U.S. cohort. While this held true for the systems thinking questions (7−10), it was not the case for the recycling questions (1−6) according to Figures 7 and 8.

In contrast, the U.S. students were second-year undergraduate students who had a comparably lesser subject knowledge within green chemistry and sustainability and were less adept at utilizing systems thinking approaches. However, green chemistry was not absent from the curriculum. U.S. students undertook a laboratory component to their course that contained elements of green chemistry and sustainability. Such work was carried out in the fields of sustainable polymers (hydrogels, dental polymers, and block copolymerization) and the creation of simple target molecules from given starting materials. While not providing the same level of specialist knowledge as for the U.K. students, the U.S. cohort was still provided with useful background and an introduction to green chemistry and sustainability.

One possible explanation for the lack of a performance enhancement for the recycling questions could be U.K. students' overfamiliarity with green chemistry. It is possible that the U.K. cohort falsely believed that they already possessed all of the information (both in terms of recycling and systems thinking) provided by the game and thus perhaps did not engage with it fully. Alternatively, it could be the case that while the U.K. students had greater specialist knowledge, this was not directly applicable to the recycling questions of Green Machine, allowing a similar level of performance to be obtained by the U.S. students with just a broad background of knowledge in green chemistry.

With regard to the systems thinking questions, the U.K. students did outperform their U.S. counterparts. Systems thinking components of the U.K. degree program[33] that are not present for the U.S. degree programs were most likely the largest contributing factor to this difference. The improvement made by the U.S. cohort from playing Green Machine (as revealed in the pre- and post-test questions) suggests that Green Machine can be used to improve systems thinking skills, particularly for those who are unfamiliar with systems thinking.

Taken together, the results indicate that this resource is likely to be better suited as an introduction to green chemistry and associated systems thinking for students at the undergraduate level as opposed to more highly trained postgraduate students.

CONCLUSIONS

Green Machine is an enjoyable game designed to foster the adoption of a systems thinking approach to green chemistry and sustainability issues aligned with the UN SDGs. Generally, students perceived Green Machine to be an innovative resource that encouraged them to learn about recycling processes through a systems approach. Learning gain was evaluated for postgraduate (U.K.) and undergraduate (U.S.) cohorts, and the results indicated that Green Machine is best-suited to be utilized at the undergraduate level as an introduction to green chemistry/sustainability by considering recycling processes and to initiate students into taking a systems thinking approach to learning. It is envisaged that following implementation of the game, instructors can facilitate subsequent teaching from a discipline-specific perspective and/or via a systems thinking approach.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00278.

> Session slides for presentation to a cohort of students (PDF)
> Game rules (PDF)
> Materials market board (PDF, DOCX)
> Process reference sheet (PDF)
> Playing cards (PDF, DOCX)
> Questions to measure learning gain (PDF, DOCX)
> Feedback form (PDF, DOCX)

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Notes

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