RSC Sustainability

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ROYAL SOCIETY OF CHEMISTRY

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Sustainability Spotlight Statement

Producing sustainability-literate graduates is importance for addressing global environmental and industrial challenges. However, integrating sustainability into chemistry curricula remains difficult due to time and resource constraints. This work advances sustainable chemistry education by embedding systems thinking and sustainability analysis into an existing aspirin synthesis practical that can be implemented within a single three-hour laboratory session. By repurposing a widely taught experiment, the approach is resource-efficient, scalable across institutions, and suitable for diverse educational contexts. Students critically evaluate environmental, economic, and societal dimensions of chemical manufacturing, strengthening their capacity to address complex sustainability challenges. The role play activity embedded within the activity incorporates SDG 1 to SDG 17.

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ARTICLE

Sustainability and systems thinking in the chemistry of aspirin manufacture for first-year engineering students

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In response to the need to integrate sustainability in higher education, an activity incorporating green chemistry, life cycle inventories, and systems thinking was designed for first-year general chemistry. The activity is centred on the synthesis of aspirin, with students comparing three synthetic routes to salicylic acid. The pedagogical approach combined individual preparation, collaborative group tasks - including structured role play, and individual reflection. It was implemented in a large-enrolment engineering course within a three-hour laboratory session. Students considered trade-offs between renewable and non-renewable resources, waste generation, and energy use. To evaluate learning outcomes, random samples of individual and group submissions were analysed. The preparation exercise revealed that students were able to independently learn to apply green chemistry metrics and identify isolated environmental, economic, and societal implications of aspirin manufacture. Group activities, particularly the role-play component, supported deeper engagement and integration of these impacts. Group role-play summaries provided evidence of systems thinking and consideration of multiple Sustainable Development Goals. Subsequently, students demonstrated more holistic views of sustainability in the reflective exercise, recognising it as a shared collective and individual responsibility requiring contributions from multiple disciplines. Students valued the application of chemistry knowledge to a real-world context and the development of sustainability-related skills. With over 90% of students endorsing the activity's inclusion in the curriculum, this study offers a scalable model for meaningfully integrating sustainability and systems thinking within a single laboratory session.

Introduction

The inclusion of sustainability into higher education is not only an academic priority but also a societal need.[1] Science and engineering education play an important role in shaping students who can think critically about the environmental, societal, and economic challenges and develop innovative solutions that align with global sustainability agendas such as the United Nations Sustainable Development Goals (SDGs).

Engineers are responsible for designing and managing processes that produce essential products for society, from pharmaceuticals to materials and energy systems. However, traditional engineering practices often emphasized efficiency and profitability while neglecting sustainability considerations. This oversight has contributed to major global issues, such as climate change, environmental degradation, as well as social inequities and injustices.

The harmful impact of chemical production and use on the environment led to the development of environmental chemistry, which primarily focuses on measuring, detecting, and monitoring environmental pollutants.[2] Traditionally, environmental chemistry has concentrated on identifying and mitigating damage rather than preventing it.

A shift toward prevention occurred in the 1990s with the development of green chemistry. Green chemistry aims to minimize the environmental impact during the production and use of chemicals. The principles of green chemistry emphasize the use of safer solvents, renewable feedstocks, and energy efficiency, all of which are crucial in designing sustainable processes. As such, green chemistry represents the connection between innovation, efficiency, and environmental responsibility during synthesis and manufacturing. [3,4,5] For communities affected by industrial activities, these principles emphasize responsibilities such as minimizing waste, reducing carbon emissions, conserving resources, and ensuring social wellbeing. [6,7]

Researchers argue that chemistry education should include green chemistry and systems thinking to help students better understand how chemical processes affect society and the environment highlighted the importance of teaching green chemistry to promote ethical and responsible decision making.[8] Hurst[9] added that systems thinking, such as analysing life cycles and using green metrics, is essential for evaluating the sustainability of chemical processes. Mahaffy and colleagues[7] and the American Chemical Society[10] also recommended embedding systems thinking into the chemistry curriculum so that students can see how chemistry connects to environmental, economic, and societal factors. For first-year engineering students, this approach makes chemistry more relevant and prepares them to confront modern challenges responsibly. Mahaffy further showed this by using the Haber-Bosch process to illustrate how chemical technologies interact with society and the environment.

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Several studies use systems-oriented concept maps (SOCMEs), system maps, and conceptual modelling to help students visualise interactions across scales; these have been trialled effectively in first-year and later undergraduate courses.[11,12,13]

Despite broad advocacy, several barriers to embedding systems thinking across chemistry curricula are the tightly packed chemistry courses, instructors lack of training in systems thinking, and because traditional assessment methods do not readily capture systems thinking skills new assessment strategies need to be developed.[7,12] Efforts to assess systems thinking in chemistry are still evolving, and educators are uncertain how to measure progress reliably. [14,15]

Collectively, environmental chemistry, green chemistry, systems thinking led from environmental awareness to a recognition of the need to proactively include sustainability in chemistry education. For the purpose of chemistry education and manufacturing systems, sustainability is defined as an ongoing balance between environmental preservation, societal wellbeing, and economic viability. [16] This definition encourages the evaluation of chemical production processes not only in terms of efficiency and profit but also in terms of their implications for human health, environmental integrity, and social justice. The concept of sustainability is strongly aligned with the United Nations' 17 Sustainable Development Goals (SDGs), which include environmental advocacy, societal equity, and economic prosperity. [16]

This study responds to the education imperative for sustainability by implementing and evaluating a systems-based learning activity in chemistry. Centred on the synthesis of aspirin, the activity aims to promote systems thinking, encourage principled reflection, and develop students' ability to make informed decisions that balance environmental, societal, and economic considerations. By integrating guided reflection**,** green chemistry metrics**,** life cycle inventories, and collaborative problem-solving, the activity bridges theoretical knowledge with practical sustainability competencies.

Design of the sustainability and systems thinking activity

Aspirin is a common pharmaceutical synthesized in many undergraduate labs. Its widespread use makes it a suitable topic for systems thinking activity. Aspirin is a nature-inspired drug, its immediate precursor, salicylic acid, is obtained from salicin from willow bark or methyl salicylate extracted from the oil of wintergreen, common natural products. [17,18] This offers an opportunity to explore syntheses from renewable sources, compared to the standard synthesis from petroleum-derived phenol.[19] The three sources correspond to three synthetic routes to synthesize salicylic acid (Figure 1). The routes may be examined using metrics to determine their relative sustainability.

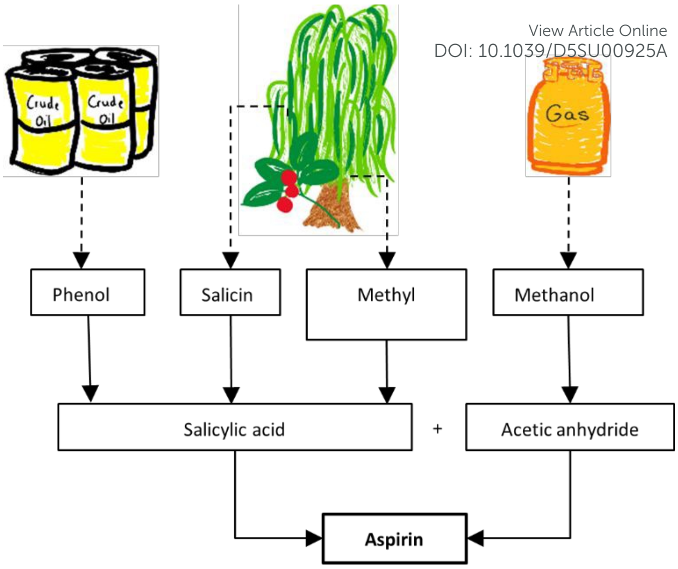

Figure 1: The flow diagram for the manufacture of aspirin from salicylic acid and acetic acid

The aspirin system

A system comprises interconnected components working toward a common goal.[20] The chemistry of aspirin synthesis via any of the three routes is positioned within a larger system involving environmental, economic, and societal considerations (Figure 2).

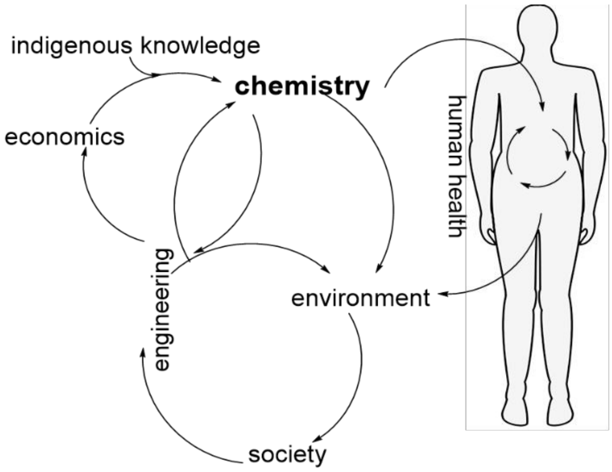

Figure 2: Broad systems associated with aspirin synthesis

Taking into account full production subsystems, such as the extraction of raw materials and each chemical reaction, the sustainability of the three routes will differ. Each route (Figure 1) has different environmental and economic implications. A systems perspective requires students to examine how choices of raw material sourcing, waste, and product disposal affect multiple outcomes to ensure that the present generation's needs are met without compromising the ability of future generations to meet their own economic, environmental, and societal needs.

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Green chemistry and metrics

Green chemistry metrics offer an accessible entry point for students to compare the sustainability of the three synthetic routes to salicylic acid. [21,22] The green metrics inform the sustainability and efficiency of different synthetic pathways.

The green chemistry metrics used are outlined below:

$$\%\,Atom\ economy\ = \frac{MM\ of\ the\ desired\ product}{MM\ of\ all\ the\ reactants} \times 100$$

$$\%\,Carbon\ efficiency = \frac{carbon\ atoms\ in\ the\ desired\ product}{total\ carbon\ atoms\ in\ all\ the\ reactants} \times 100$$

$$\%\,Mass\ efficiency = \frac{actual\ mass\ of\ the\ desired\ product}{total\ mass\ of\ all\ the\ reactants} \times 100$$

$$E\ factor = \frac{mass\ of\ the\ waste\ produced}{total\ mass\ of\ the\ product}$$

$$\%\,yield = \frac{actual\ mass\ of\ the\ desired\ product}{expected\ mass\ of\ the\ desired\ product} \times 100$$

For sustainable development and for economic reasons, it is important to use reactions with the highest possible value for atom economy, when most of the reactant atoms form the product. Carbon efficiency indicates how many carbon atoms end up in the desired product compared to how many carbon atoms were used to create the product. Atom economy and carbon efficiency can be calculated without the need for experimentation. This makes them useful metrics to evaluate alternative routes to a desired product at the conceptualization of a process.

Reaction mass efficiency reflects both the stoichiometry and the experimentally obtained yield of the reaction. A higher reaction mass efficiency is ideal because it shows that the high amount of the reactant mass is reflected in the desired product implying less waste. The environmental factor (E-factor) quantifies all waste produced, defined as everything except the desired product, relative to the mass of the inputs. This metric is the inverse of reaction mass efficiency. Percent yield, pre-dating green metrics, is an important measure of reaction efficiency because many chemical reactions form by-products or remain unreacted. In the manufacturing of chemical products, a low percentage yield would indicate that the company is wasting reactants and money.

Although not possible to quantify by an easy metric, in the manufacture of consumable chemical products, like aspirin, energy consumption plays a prominent role when comparing feasible chemical routes. The energy consumed can be a costly input and, depending on the source, may generate waste in the form of carbon dioxide, contributing to global warming. The source and amount of energy used during the production cycle need to be included in environmental assessments of chemical processes. These metrics inform the sustainability and efficiency of different synthetic pathways. However, results depend on system boundaries, what is included in the assessment.

Life Cycle Assessment

Life Cycle Assessment (LCA) helps to identify environmental burdens beyond the laboratory or manufacturing process (e.g., raw material extraction, transport, disposal). LCA avoids burden shifting, so that the improvements in one stage do not worsen others. LCAs support green chemistry and sustainable process design by helping industries to align with regulations and sustainable development goals (SDGs). LCAs can guide investment in process upgrades (e.g., energy efficiency, waste minimization).

However, it is often difficult to study the entire lifecycle as outlined in Figure 3 and therefore system boundaries are preferred. In this study, a gate-to-gate boundary that considers the synthesis of salicylic acid from phenol, salicin and methyl salicylate and subsequent conversion to aspirin was chosen as the foreground system. This system boundary, which focused on specific chemistry process steps, was appropriate for the limited class time and unknown data beyond the gate-to-gate boundary. A detailed life cycle inventory (LCI) could be developed from the quantitative data provided of inputs (the mass of reactants) and outputs (mass of products and waste). Furthermore, the energy use could be qualitatively evaluated based on the given reaction procedures.

The gate-to-gate LCI used in the study compared two of the three routes for the synthesis of salicylic acid: from phenol (non-renewable, lower waste) and methyl salicylate (renewable, higher waste) synthesis routes for salicylic acid. The latter had the better green chemistry metrics of the two routes from renewable resources. The students calculated the mass efficiency, waste generated and the product yield to evaluate which route was more sustainable based on these inputs and outputs, demonstrating

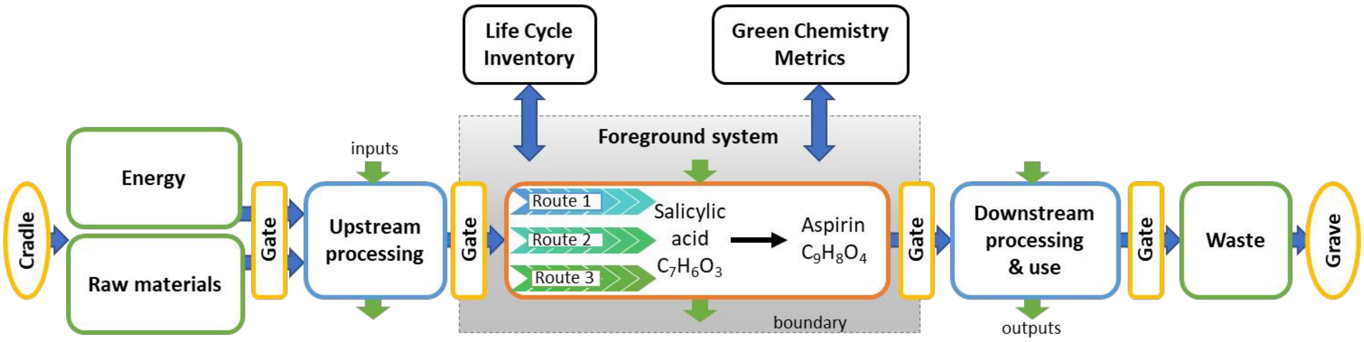

Figure 3: Life cycle assessment for chemical manufacturing processes.

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practical application of LCA principles in decision-making. For instance, Route 2 is not ideal because the depletion of starting material would demonstrate awareness of the environmental consequences of using large quantities of willow trees as a renewable yet finite resource. Furthermore, recognising that higher salicylic acid production for Routes 1 and 3 lead to high aspirin yield which translate to social benefits, such as improved public health, and to economic benefits for pharmaceutical manufacturers.

The benefits of integrating LCA into chemistry education are that it encourages systems thinking, promotes critical evaluation of chemical processes and bridges chemistry with real-world sustainability challenges. It prepares students for industry roles in sustainable design and process optimization. [7,23]

Implementation of the sustainability and systems thinking intervention

The activity was conducted as part of a General Chemistry 1 course for engineering students, with each cohort comprising 550 students. Up to 150 students could be accommodated in one practical (laboratory) session. Given that there were multiple sessions led by different instructors and teaching assistants with varying levels of knowledge of LCA and systems thinking, short instructional videos were pre-recorded for use in class. The activity was implemented in three stages, that is (i) individual preparation (before class), (ii) a group exercise (in-class) and (iii) an individual reflection (after class) (Figure 4) shortly after students learned reaction stoichiometry.

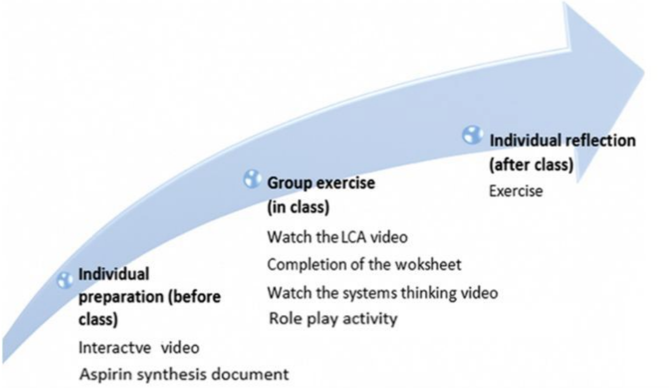

Figure 4: Stages of systems thinking introduction to students

(i) Individual preparation (before class)

As preparation, students watched an interactive video in which they were briefed about the Sustainable Development Goals and the UN General Assembly president's plea to integrate the SDGs in teaching and research at Higher Education institutions. [24,25]

Students engaged with video material on sustainability and reviewed a background document describing aspirin synthesis and green metrics. They evaluated three salicylic acid synthesis routes and calculated metrics such as atom economy and carbon efficiency to determine the least green route.

This individual exercise included questions on the anticipated impact of aspirin synthesis on the environment, economy, and society. Examples of potential impacts were provided to stimulate their thinking. In addition to preparing the students for optimum use of class time, it was used to establish the students' baseline application of systems thinking.

(ii) Group in class activities (3-hour session)

Students were introduced to the concept of a Life Cycle Inventory (LCI) through a short video and provided with a balance data sheet for the production of 1000 kg of salicylic acid for two routes, from phenol and methyl salicylate. Then, in groups of three, they calculated inputs, waste, mass efficiency, and % yield for synthesizing 1.5 tons of aspirin from 1.150 kg of salicylic acid. Students evaluated the environmental, economic, and societal impact of aspirin synthesis.

They were prompted to identify energy use in the synthetic procedure, e.g., in heating, and to consider the role of catalysts in reducing energy demands. To promote the application of systems thinking at increasing levels of granularity, students were asked to consider the impact of the foreground system on society, the economy and the environment.

After completing the worksheet, students watched a video explaining systems thinking. In the video, students were encouraged to think in terms of systems and to value partnerships in line with Sustainable Development Goal number 17. Groups had to consider the role of Chemistry in meeting the SDGs.

Finally, students participated in a role-play activity as: the Finance Director, the Environmental Manager and the industrial Chemist of an aspirin manufacturing plant. They debated upgrading a chemical plant to a more sustainable process, weighing the economic, environmental and societal impacts, capturing initial individual points of view and then the group consensus.

(iii) Individual reflection (after class)

After the practical session, students were given one week to complete an individual online reflection, which included a mix of multiple-choice and open-ended questions. This post exercise allowed students to express their perspectives and attitudes toward systems thinking and sustainability. Student responses were analysed both quantitatively and qualitatively, with open-ended answers coded to identify recurring themes and patterns. Students who completed the reflection were allocated a mark, providing an incentive for engagement.

Research methods

The study received ethical approval from the institutional ethics committee (Reference: NAS071/2022), and all participants provided informed consent for the use of their data.

The study was implemented in a service course for the Faculty of Engineering, Built Environment and Information Technology (EBIT) first-year students at the University of Pretoria. The group comprised

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of students enrolled for various engineering disciplines, such as civil, chemical, electrical, electronic, metallurgical and mining. At the time of the intervention, students had basic organic chemistry from high school and no had not received any university-level organic chemistry. The students were not yet been exposed to engineering-scale industrial processes. Consequently, their understanding of manufacturing systems and sustainability considerations was not developed yet.

The activity replaced one practical session and formed part of the formal assessment structure. The activity contributed 1.5% toward the final course mark.

A total of 552 first-year students completed individual preparatory exercises, and 92% consented to the use of their submissions for research purposes. For the in-class activities, 148 groups of three students completed the group worksheet, and participated in a structured role-play activity. Consent was obtained from 82% of the groups. Finally, 438 students completed an individual online reflection that probed their understanding of systems thinking and sustainability with 92% consenting to the use of their data.

For data analysis, 100 individual preparatory submissions, 75 group worksheets, and 100 individual reflections were randomly selected from consenting individuals and groups for detailed analysis.

Qualitative analysis was implemented as the mode of inquiry, complemented by quantitative results to indicate the relative frequency of emergent themes. The study examined and monitored students' insights into green chemistry, systems thinking, and sustainability through analysis of written responses collected before, during, and after the activity.

The qualitative approach adopted was informed and guided by the principles of thematic analysis described by various researchers.[26-29] Submissions were carefully reviewed to understand students' thinking, statements indicating conceptual shifts, systems-oriented reasoning, or sustainability awareness were highlighted, grouped and coded into themes.

It should be noted that a full formal qualitative coding framework was not implemented, the analysis focused on identifying recurring ideas and patterns rather than performing an extensive qualitative methodology.

This approach enabled identification of apparent shifts in students' systems thinking competencies and sustainability reasoning, providing interpretive insight into how the activity influenced their understanding of green chemistry and sustainability-oriented frameworks.

Research findings and discussions

(i) Individual preparation (before class)

From the preparation exercises, the two most important questions used to probe students' understanding and perceptions of sustainability were:

1. Use the green chemistry metrics to identify the least green aspirin synthetic route.
2. Explain the impact (environmental, societal and economic) of the inputs and outputs, including energy, of aspirin synthesis.

Using Green metrics to decide the least green route. Students calculated atom economy and carbon efficiency for the three possible synthetic routes to salicylic acid (Table 1) and were asked to identify the least sustainable route.

The majority of students selected the preparation of salicylic acid from salicin (Route 2) as the least sustainable option (Figure 5). Some of the student's motivations for choosing Route 2 were:

> *Route 2, because less atoms are used to form the desired product and more atoms are lost (P001).*
>
> *Route 2, the least amount of salicylic acid is formed from the reactants (P002).*
>
> *Route 2, because its low % atom economy indicates a higher amount of waste and inefficiency in the reaction (P003).*
>
> *Route 2 requires lot of reactants in order to produce the desired product. (P004)*

Table 1: Atom economy and carbon efficiency percentage values

Route	% Atom economy	% Carbon efficiency
Route 1-SA from phenol	50	100
Route 2-SA from salicin	41	54
Route 3-SA from the oil of wintergreen	42	88

This indicates that the students understood that lower percentages of atom economy and carbon efficiency is an indication that fewer reactants are converted into the desired product, resulting in greater waste generation during manufacturing. This finding is in line with the study by Anastas[5].

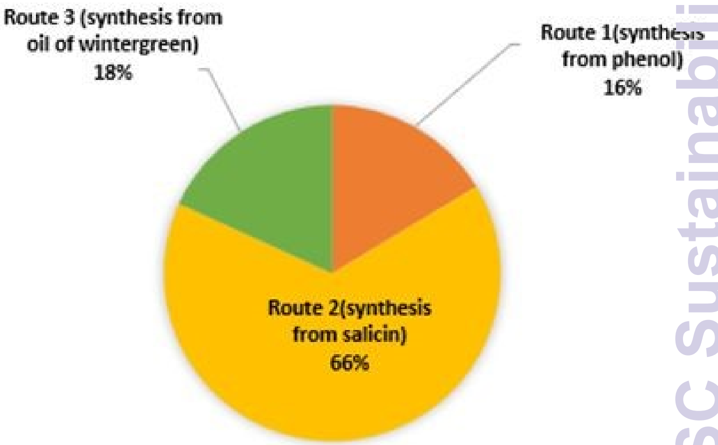

Figure 5: Students' response in choosing the least green route for making salicylic acid

At this stage, most students associated sustainability primarily with waste minimisation. While this indicates a partial success in applying green chemistry metrics, it also reflects a reductionist approach, with students missing an opportunity to connect the calculated values to the wider environmental, societal, and economic dimensions of sustainability. It is worth mentioning that only one student demonstrated a more holistic

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perspective by linking green chemistry metrics to resource implications. The student justified their choice of Route 2 by considering that willow trees are required as the natural feedstock for salicin:

> *Route 2, because it has the least % atomy economy and the reactants are sourced from willow trees, a large-scale project would take a very large amount of willow trees, which will affect the environment. (P005)*

Route 1 was chosen by a few students who considered that phenol is a non-renewable raw material. However, most students who chose routes 1 and 3 based their choice on incorrectly calculated values.

> *Route 1 because phenol is derived from fossil fuels which is not renewable whereas the other two routes are derived from plants which are renewable. (P006)*

The impact (environmental, societal and economical) of inputs and outputs for the synthesis of Aspirin. Students' responses regarding the potential environmental, societal, and economic impacts of the inputs and outputs involved in the conversion of salicylic acid to aspirin are summarised in Table 2.

Table 2: The impacts of the inputs and outputs during aspirin synthesis

	Chemical	Impact assessment
Inputs	Sulfuric acid	is highly corrosive and can cause skin burn (societal impact). widely used in industries and contribute to acid rain (environmental impact).
	Salicylic acid	used in skincare products (societal impact).
	Acetic anhydride	is corrosive and can cause skin and eye irritation (societal impact).
	Energy	is associated with fossil fuel combustion and gas emissions (environmental impact).
Outputs	Water	is necessary for agriculture (environmental) and food production (societal).
	Aspirin	used to relieve pain and prevent strokes (societal impact). used to increase crop yields (environmental impact). sold at a profit by manufacturers (economic impact).
	Acetic acid	is corrosive in high concentrations and harmful to aquatic life (environmental impact)

Overall, students were able to identify some immediate impacts associated with individual chemicals, however, these assessments were largely superficial and predominantly influenced by information drawn from Material Safety Data Sheets (MSDSs). MSDSs document the hazards, safe handling, and emergency procedures of chemical substances. Recording the potential danger of all chemicals that they would be using or producing in their practical sessions had been a requirement for entry to the preceding laboratory sessions for the course.

The dominance of MSDS inspired responses indicates that students may be associating sustainability with chemical safety rather than understanding it as an interconnected system consisting of environmental integrity, societal wellbeing, and economic viability. For example, sulfuric acid was almost exclusively discussed in terms of its corrosive nature and potential to cause skin burns, with minimal consideration of downstream consequences such as water pollution resulting from improper disposal, occupational injuries affecting productivity, or the economic implications of workplace accidents and regulatory compliance. Similarly, while students noted the corrosivity of acetic anhydride and acetic acid, they did not extend this reasoning to consider that the usage of anti-corrosive equipment and protective clothing could increase manufacturing costs and, consequently, the market price of aspirin.

An interesting finding was students' perception of water as an output. Water was mentioned as beneficial due to its role in agriculture and food production, demonstrating a failure to recognise that water generated during chemical manufacturing is often contaminated and may pose environmental risks if used untreated. The lack of any reference to wastewater purification or its associated economic and environmental costs highlights a significant gap in students' systems thinking and life cycle awareness.

These findings suggest that an emphasis on chemical safety alone may unintentionally promote a reductionist approach, in which students focus on immediate hazards rather than adopting a perspective that integrates environmental, societal, and economic dimensions of sustainability.

The preparation exercise demonstrated that students were able to use self-taught green chemistry metrics to identify less sustainable synthetic routes. However, the impact assessment revealed a lack of deeper, interconnected sustainability thinking. This highlights the need for more explicit instructional support to help students move beyond hazard identification towards holistic sustainability analysis.

(ii) In class group exercise

In class, groups of 3 or 4 students completed the mass balance table for the synthesis of 1150 kg of salicylic acid needed for the synthesis of 1500 kg aspirin from the two more sustainable routes. They also calculated the mass efficiency, percentage yield and the E factor (Table 3).

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Table 3: Comparison of average metric values for different routes

Green metrics	Route 1	Route 3
Atom economy (%)	65.22	54.88
Reaction mass efficiency (%)	41.42	27.86
Yield (%)	84.44	87.96
E-factor	1306.51	3471.50

Choosing between Route 1 and Route 3. The students were required to choose the more sustainable route for synthesising salicylic acid, from either phenol (Route 1) or from oil of wintergreen (Route 3), for their "company."

The majority of groups (81%) selected Route 1, the synthesis of SA from phenol, because it demonstrated higher atom economy and reaction mass efficiency values, as well as a lower E-factor, implying less waste generation. They also reasoned that the comparable yield still allows for reasonable economic viability. The reasoning is shown by the two group quotes below:

> *Route 1, although the % yield is lower, % atom economy, % reaction mass efficiency is higher and the waste produced is lower. (G01).*
>
> *Route 1, because it produces less waste than route 3 and there is better utilization of reactants as shown by high % atom economy (G02)*

This indicates that most students recognised the environmental advantage of this route, which aligns with the principles of green chemistry.[3,30] It also reveals a developing, but still limited, systems thinking approach, where sustainability is understood as balancing profitability with environmental responsibility.[31]

However, 19% of the groups chose Route 3, the synthesis from oil of wintergreen. Many based their choice on incorrectly calculated metrics using the same reasoning as other groups provide for route 1. Groups who had calculated the metrics correctly motivated their choice based on (1) the raw material's renewable origin and (2) the slightly higher percentage yield. Some students equated high yield with profit, demonstrating a profit-driven perspective that overlooks the environmental costs associated with higher waste production. Some of the students' motivations for choosing Route 3 were:

> *Route 3, because it uses oil of wintergreen from trees which can be replanted unlike route 1 which uses crude oil which depletes. (G04).*
>
> *Route 3, has high % yield and it therefore more economical (G05).*

The preference for Route 3 based on its renewable feedstock also highlights a shallow interpretation of sustainability. While renewable resources are indeed a key component of sustainable chemistry, they do not automatically make a process sustainable if the reaction still generates substantial waste or consumes significant energy.[32] A truly sustainable decision requires balancing multiple dimensions, environmental, economic, and societal, rather than focusing on a single attribute.[33,34,35] The choice of Route 3 based on an economic association with a higher % yield suggests a "profit over planet" mindset and indicates a partial or reductionist understanding of sustainability, where economic performance was prioritised over environmental impact.[36]

Students' suggestions to manage the manufacturing impact. When students were asked how the impact of the inputs and outputs could be minimized or managed to make the process sustainable, they provided the following responses:

> *Effective waste management can be implemented to recycle any unused waste. This will lessen the amounts of inputs that need for the reaction (G04).*
>
> *By recycling the byproducts, therefore creating jobs in other sectors This will reduce environmental impact, creating jobs (societal impact and making money for other small companies (G05).*
>
> *Reuse waste for other processes, and ensuring that the disposal of waste is not near populated areas as that will decrease the quality of life in the area. Reuse of waste can decrease expenditure of raw materials for other processes (G06).*
>
> *Replace toxic reagent with products with environmentally friendly products (G07).*
>
> *The impact can be minimized by shortening the synthesis process by eliminating unnecessary steps, this will minimize waste and increase production. Start by using renewable resources, including renewable energy. Encourage reforestations for job creation (G08).*

Proper waste handling and management were the most common responses. When recycling was mentioned, it was frequently coupled to job creation indicating that students linked recycling not only to waste reduction but also to societal and economic benefits such as job opportunities and community development.

Increasing yield or *producing more product with less input (G09)* was reflected as resulting in higher efficiency, reduced waste, lower production costs and potentially greater profit margins.

These reflections demonstrate a shift towards considering waste minimization, resource efficiency, process redesign, and socio-economic dimensions of sustainability.

Anticipated cost of aspirin synthesis. Students were also asked to anticipate cost implications for aspirin manufacture beyond the cost of raw materials and energy. They showed awareness that pharmaceutical production involves more than environmental effects and includes significant economic and societal costs**.** Their responses listed multiple financial burdens related to aspirin production, especially in areas such as human resources**,** capital investment**,** infrastructure, energy and logistics. Smaller but still important cost factors mentioned by students included regulatory compliance, such as taxation, personal protective equipment (PPE), and waste disposal requirements, which are consistent with broader financial considerations for meeting environmental and safety regulations.

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Some aspirin cost implications responses were:

> *The cost of disposing waste materials, and buying and maintaining the equipment's used, including solar panels (G05).*
>
> *The cost of labour, equipment's maintenance, and waste disposal (G07)*
>
> *Cost of energy, protective equipment, training personnel to follow procedures when dealing with hazardous chemicals (G10)*
>
> *Cost of employee's salaries and taxes, and the transportation, distribution and packing (G11)*
>
> *Cost of extraction of raw materials, either from crude oil or tree harvesting (G12)*
>
> *Cost of educating workers on safety practices, managing disasters or injuries that might occur at work. Cost of personnel educational development. (G13)*

Interestingly, some students also recognized innovation as a cost factor, implying awareness that research and development activities and process optimization require financial investment but are essential for long-term sustainability and competitiveness. Others mentioned the need to budget for proper waste management that will ensure that there are no violations of the planet, animals and people. They noted "it is important that not only companies will benefit from manufacturing process but employees are fairly compensated and tax is paid to the government." These responses suggest that students perceive the aspirin manufacturing process as economically demanding, requiring investment in technology, compliance, and human capital. Their comments also reflect a growing awareness of the interconnectedness between financial, environmental, and societal dimensions of sustainable chemical production. [3, 33,34,37]

Energy minimisation measures in aspirin synthesis. Figure 6 is in response to the instruction to identify measures that can be implemented to minimize the impact of energy on aspirin synthesis.

55% of student groups proposed replacing fossil fuels with cost effective renewable energy sources such as solar, wind, and hydro power, this measure may not directly reduce the company's total energy consumption, however, it creates an opportunity for redirecting energy from the grid to other consumers. This will eventually reduce loadshedding which is caused by high electricity demand in South Africa.

In addition to the adoption of renewable energy sources, students proposed a range of process-oriented strategies to minimise energy consumption during aspirin synthesis. This included reaction optimisation to increase efficiency, the use of catalysts to lower activation energy, and the implementation of smart or automated machinery to improve operational precision and reduce energy waste. A few groups also suggested scheduling plant operations during off-peak electricity periods to take advantage of lower grid demand. Collectively, these proposals demonstrate elements of systems-oriented reasoning, as students considered the environment, the society and the cost saving measures for the manufacturing company.

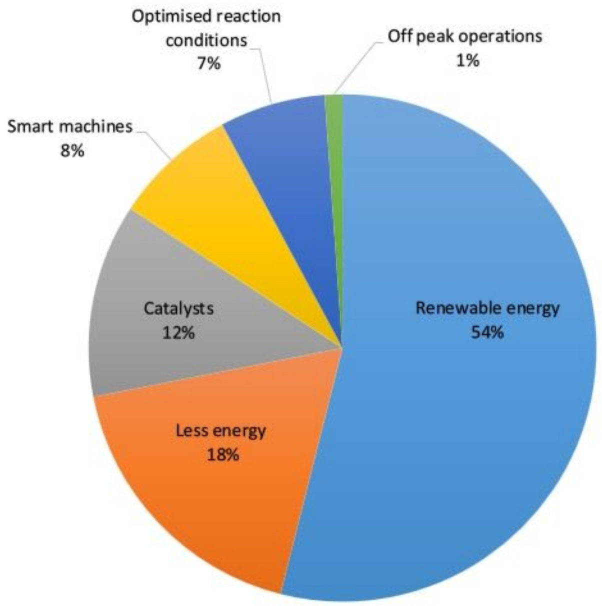

Figure 6: Themes emerging from an analysis of student's suggestions to minimize the impact of energy in aspirin synthesis

Role play activity, systems thinking and SDGs. To deepen students' understanding of sustainability in manufacturing, a role-play activity based on systems thinking principles was rolled out. Students worked in groups and assumed three key stakeholder roles within a manufacturing context: a finance manager, a community representative, and an environmental officer. Each role was tasked with proposing measures to ensure the successful operation of a manufacturing plant.

Figure 7 reflects the outcomes of the students' role-play activity responses generated during group discussions. Students' statements were systematically coded and organised into recurring themes and categories to identify patterns in their perceptions and attitudes. Responses that appeared five or more times across the different groups were classified as themes, indicating commonly shared perspectives among the participants. This was applied to ensure that the themes represented recurring viewpoints across multiple student groups rather than isolated responses**,** thereby affirming reliability of the emerging themes.

As illustrated in Figure 7, each role reflected the self-interest motivated by the assigned perspectives. Finance managers focused primarily on productivity and cost reduction. Community representatives, on the other hand, focused on social equity and inclusion**,** proposing actions that would enhance community well-being and reduce inequalities. Environmental officers emphasized environmental protection and compliance with green practices.

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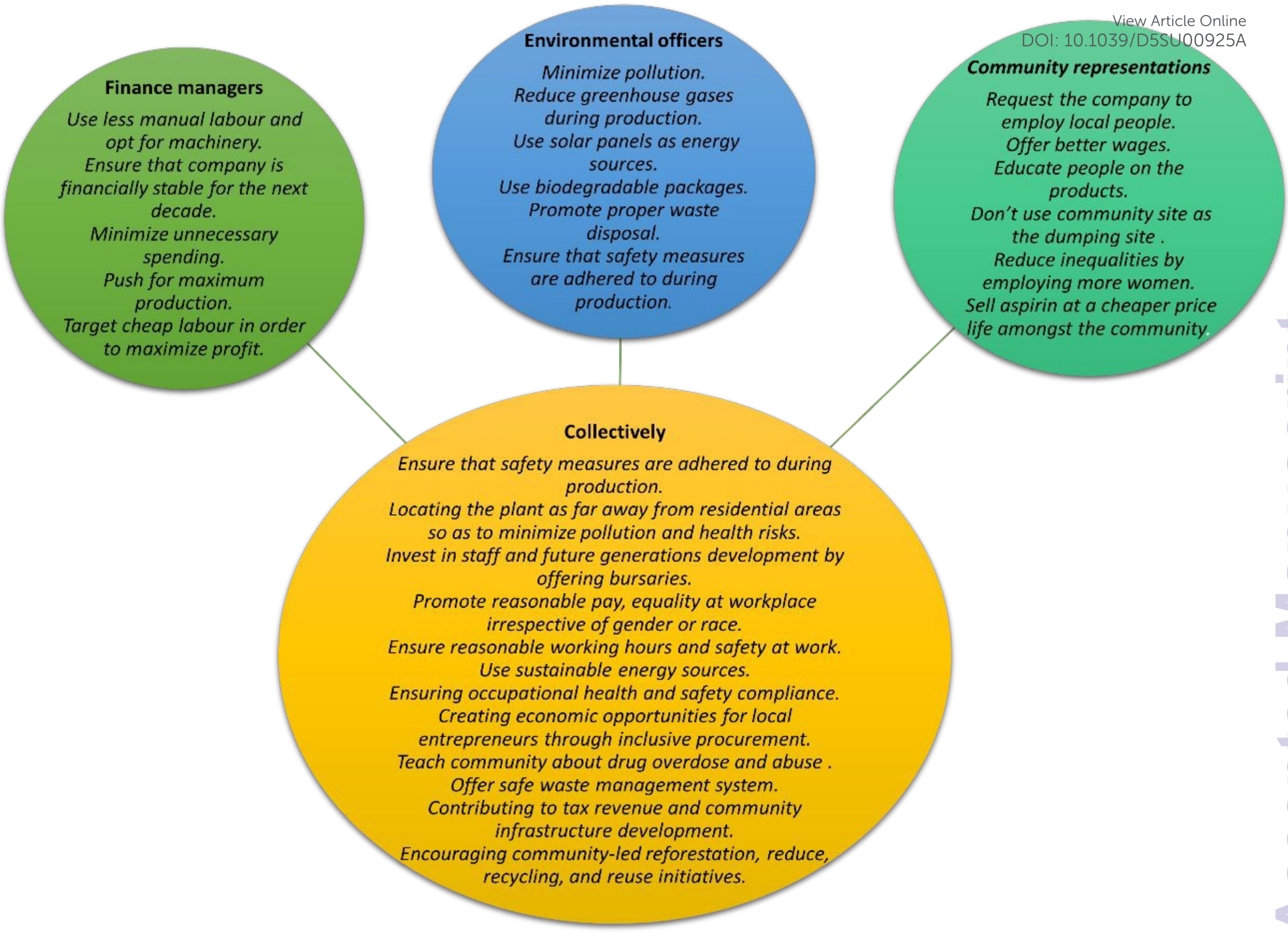

Finance managers

Use less manual labour and opt for machinery.
Ensure that company is financially stable for the next decade.
Minimize unnecessary spending.
Push for maximum production.
Target cheap labour in order to maximize profit.

Environmental officers

Minimize pollution.
Reduce greenhouse gases during production.
Use solar panels as energy sources.
Use biodegradable packages.
Promote proper waste disposal.
Ensure that safety measures are adhered to during production.

Community representations

Request the company to employ local people.
Offer better wages.
Educate people on the products.
Don't use community site as the dumping site .
Reduce inequalities by employing more women.
Sell aspirin at a cheaper price life amongst the community.

Collectively

Ensure that safety measures are adhered to during production.
Locating the plant as far away from residential areas so as to minimize pollution and health risks.
Invest in staff and future generations development by offering bursaries.
Promote reasonable pay, equality at workplace irrespective of gender or race.
Ensure reasonable working hours and safety at work.
Use sustainable energy sources.
Ensuring occupational health and safety compliance.
Creating economic opportunities for local entrepreneurs through inclusive procurement.
Teach community about drug overdose and abuse .
Offer safe waste management system.
Contributing to tax revenue and community infrastructure development.
Encouraging community-led reforestation, reduce, recycling, and reuse initiatives.

Figure 7: An aggregated view of the role play activity capturing the individual stakeholder and the collective reflection on the plant upgrade

In the second phase of the role play, students were required to collaborate, negotiate across roles and develop a joint sustainability plan for the upgrading of the manufacturing plant. This phase encouraged students to engage in systems thinking by recognising the interconnections and trade-offs between economic, societal, and environmental subsystems. The integrated proposals that emerged demonstrated a shift from isolated priorities to holistic sustainability planning, balancing environmental protection, societal welfare, and economic growth. The collectively agreed-upon measures are summarized in Figure 7.

Meadows defined systems thinking as the skill to recognise interconnections among economic, societal, and environmental subsystems; recognise trade-offs; integrate multiple stakeholder perspectives; and develop holistic sustainability strategies. [20]

In this study, systems thinking was noticeably elicited through the role-play design as outlined in Table 4. The shift from role-specific to collaborative, holistic sustainability planning suggests the development of systems-oriented reasoning. This progression reflects a movement from subsystem isolation to systems integration. Students were able to merge tensions among productivity, societal equity, and environmental integrity. Such reconciliation aligns with Meadows *Thinking in Systems* perspective, clearly indicating that positive change requires re-evaluating system goals and the consideration and integration of multiple perspectives. [20]

Meadows views systems as interrelated structures governed by feedback and a shift in paradigms.[20] The role-play activity assisted in the acknowledgment of interdependencies among economic, societal, and environmental subsystems. Students demonstrated awareness of feedback dynamics, such as the impact of pollution on public health and agricultural products.

Table 4: Observable evidence of systems thinking skills in relation to this study

Systems thinking skills	Evidence
Recognition of interconnections	Linking industrial pollution to health, agriculture, water quality
Trade-off reasoning	Compromise between cost reduction, societal needs and environmental compliance
Integration of different perspective	Self-centred proposals being replaced by joint sustainability plan
Holistic sustainability framing	Discussions are aligned with multiple SDGs
Upscale awareness	Relating plant outcomes to global sustainability goals

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They identified leverage points by including renewable energy adoption and workforce development. This demonstrated a shift from the preparation MSDS safety perspective and the role-specific reasoning toward multiple perspectives, systems-oriented sustainability thinking.

Table 5: The alignment of the collective measures to the sustainable development goals

SDG 1: No poverty	**SDG 2: Zero Hunger**	**SDG 3: Good health and well-being**	**SDG 4: Quality education**	**SDG 5: Gender equality**	**SDG 6: Clean water and sanitation**
Addressed by a call to employ community members and offering fair wages, skills development, and community empowerment.	Supported through environmental preservation measures that reduce pollution and land degradation, thereby enhancing soil quality and agricultural productivity, which contribute to improved food security.	Addressed through proposals to reduce pollution, ensure workplace safety, and educate communities about drug overdose and substance abuse.	Evident in the suggestion to invest in bursaries and personnel development, contributing to long-term human capital growth. This demonstrates the value of education in empowering communities	Reflected in calls for equal opportunities and recognition and promotion irrespective of gender or race. Students recognized that sustainable development requires participation by everyone.	Addressed through measures aimed at reducing industrial pollution, improving waste management.
SDG 7: Affordable and clean energy	**SDG 8: Decent work and economic growth**	**SDG 9: Industry, innovation and infrastructure**	**SDG 10: Reduced inequalities**	**SDG 11: Sustainable cities and communities**	**SDG 12: Responsible consumption and production**
Supported by promoting the use of renewable and sustainable energy sources in manufacturing.	Linked to fair wages, reasonable working hours, and local empowerment through inclusive procurement.	Captured through staff development, investment in modern, efficient, and environmentally friendly manufacturing facilities.	Addressed by emphasis on social equity, inclusive decision-making, and fair access to opportunities.	Advanced through the proposal to locate the plant away from residential zones and improve community infrastructure.	Reinforced through commitments to drug abuse awareness, waste minimisation, recycling, and reuse.
SDG 13: Climate action	**SDG 14: Life below water**	**SDG 15: Life on land**	**SDG 16: Peace, justice, and strong institutions**	**SDG 17: Partnerships for the goals**	
Addressed through calls for reforestation and reduction of greenhouse gas emissions through sustainable energy practices.	Indirectly supported by initiatives to protect the environment by minimise water and chemical pollution from manufacturing activities.	Addressed through environmental protection measures such as reforestation, pollution reduction, which promote ecosystem survival.	Stressed on maintaining peace between community members and plant management, and ensuring the right to clean air as a fundamental human right.	Recognize that sustainability cannot be achieved in isolation; instead, it requires leveraging various perspectives, building trust, and creating shared solutions that bridge environmental, societal, and economic concerns.	**Sustainable Development Goals SDGs**

The collective measures also show alignment with the United Nations Sustainable Development Goals (SDGs) (United Nations, 2015), as outlined in Table 5. These findings demonstrate how the role-play activity developed students' ability to connect their immediate decisions to global sustainability needs**.** Importantly, they recognized that sustainable solutions must address not only environmental challenges but also societal injustice, human rights, and economic equity.

iii) Individual post-activity reflection

A post-reflection exercise was rolled out to capture individual students' insights and assess the personal impact of the activity.

Reflection is an essential component of transformative learning, as it allows learners to critically evaluate their assumptions, integrate new perspectives, and consolidate understanding [38,39]. In this context, post-reflection provided an opportunity to evaluate the effectiveness of the activity in developing students' understanding of sustainability.

Students were asked to identify which sustainability sub-system they would prioritise when designing a sustainable chemical process. 84% of students indicated that balancing all sustainability sub-systems, people, planet and profit should be equally prioritised. Rather than prioritising a single dimension, students acknowledged the interdependence of these subsystems, which is a core principle of systems thinking according to Meadows[20] and Broman[33]. The ability to consider these dimensions simultaneously is consistent with the objectives of the role play activity which encouraged students to extend their thinking by incorporating environmental, economic and societal considerations associated with chemical processes.

Further evidence of systems-based reasoning was evident when 59% of students recognised that discontinuing aspirin production would impact everyone. This suggest that students were able to consider the long-term implications and ripple effects of decisions within a chemical production system. By recognising that decisions about chemical production influence healthcare access, industrial activity and societal well-being, students demonstrated an ability to move beyond the process level to the broader socio-economic and environmental consequences of chemical processes.

In addition, 90% of students agreed that consumers should understand how products are manufactured, highlighting recognition of the ethical, societal and environmental implications of production systems. This type of response reflects students' ability to identify connections between chemical processes and societal players, including consumers and policymakers, who influence and are influenced by production decisions. Such perspectives align with calls within chemistry education to include systems thinking and sustainability contexts into chemistry curricula, enabling students to connect molecular transformations with broader societal outcomes. [6,7]

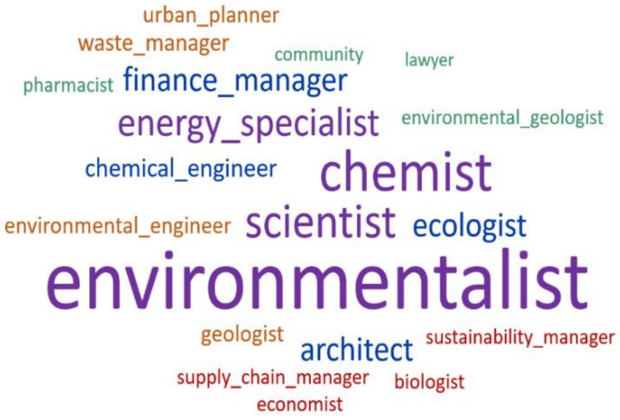

Figure 8: Emerging professions that student engineers would like to partner with for sustainability

As part of the post-intervention reflection, students were asked to identify professions with whom they would collaborate to ensure sustainable production. In Figure 8, approximately 74% of students identified environmental related professions such as environmentalist, waste manager and ecologist. These professions study the environment, assess the impact of human activities, and provide insights for engineering projects. Their dominance indicates that environmental considerations were a central component of students' reasoning about sustainable chemical production.

63% of students referred to professions within the scientific domain, such as chemists, scientists and chemical engineers. These professionals have knowledge of chemical processes at molecular levels. With these professions on board, the designing of greener synthesis routes, improving process efficiency, and implementing green chemistry principles will be prioritised. These are required for sustainability.

Notably, 34% of students also recognised built and management professions beyond the natural sciences, such as architects, sustainability managers and finance managers. These professions are required for design and construct sustainable green infrastructure, resource management, and economic decision-making. which indicates that some students extended their thinking beyond the laboratory and production process.

Other supporting and regulatory professions mentioned less frequently are urban planners, lawyers, pharmacists, and biologists. These professions represent important roles within sustainability systems as they relate to regulation, proper urban development, healthcare implications, and biological impacts. This highlighting that sustainable production requires policy, public health, and ecological considerations in addition to technical solutions.

The diversity of professions identified suggests that students were able to recognise the interdisciplinary nature of sustainability challenges. Broman and Robert [33] indicated that sustainability issues are complex and require coordinated contributions from multiple sectors that impact environmental, economic and societal systems. Matlin et al.[36] highlights the need for interdisciplinary collaboration to address global sustainability challenges, while Azapagic et al.[37] discusses sustainability education and the need for cross-sector thinking. Students' recognition of cross-disciplinary collaboration reflects the broader sustainability principle that complex global challenges cannot be addressed by engineers alone.[7,8,9] This perspective aligns with Sustainable Development Goal 17: Partnerships for the Goals, showing that they understood sustainability as a shared responsibility requiring contributions from multiple disciplines. [9]

When asked who should be responsible for addressing sustainability issues, 84% of students indicated that it is the responsibility of everyone, not just scientists or policymakers. This response demonstrates an understanding of sustainability as a shared obligation, requiring coordinated contributions from communities, industry, and government. Such perspective aligns with the principles of systems thinking, where sustainable outcomes emerge from interactions among multiple players and subsystems rather than from isolated decisions. [20,33]

Furthermore, 83% of students expressed a willingness to act as sustainability advocates, while 11% indicated that they might

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consider this role in the future. These responses highlight a commitment toward advancing sustainability principles beyond academic settings. This advocacy emphasises the role of sustainability education in developing the knowledge, values, and competencies necessary for individuals to engage in responsible environmental and societal decision-making.[31,32]

A significant proportion of students also recommended that sustainability education should be introduced early in schools**.** Instilling sustainable values from a young age can support the development of responsible citizens capable of considering environmental, societal, and economic dimensions in their decision-making processes. [31,32]

Collectively, the individual post activity responses suggest that there is evidence of the developing key systems thinking competencies, including identifying relationships among sustainability subsystems, considering the broader impacts of chemical processes and identifying multiple stakeholders within production chain systems.

Attitude towards the activity. Students had to mention what they enjoyed or disliked most about this activity, and some of the responses highlighted are:

1) New knowledge

> *I learned that there are a lot of green chemistry metrics to consider ... I now understand that you cannot only consider the waste outputs … when deciding if it's sustainable or not, other factors are equally as important. I also wasn't aware that you need to consider economic and social impacts when looking at sustainability. ... I also learned about a gate-to-gate approach and what a Life Cycle Assessment is for the first time. (S108)*

> *Firstly, learning the concept of mass balances was not only interesting but will likely prove extremely useful going forward. Furthermore, the concept of systems thinking was completely new to me, and it will always be something I consider when analysing even theoretical reaction pathways. (S024)*

2) Accessible pedagogy

> *[I enjoyed] working with others, … that we were able to apply the textbook knowledge and theory of chemistry to our daily lives. We were able to relate our studies to real concerns not only to the present but also the future. I enjoyed that we as students contributed to a study which makes me feel more involved in real life issues ... (S174)*

> *The systems thinking simulation was fun and enabled us to think together in our different roles. I thoroughly enjoyed this practical and learnt a lot about sustainability which is necessary for us engineers working in industry in the future. (S004)*

3) The relevance of chemistry was made obvious

> *… I didn't [realize] the role of Chemistry in Civil engineering and as an aspiring civil engineer this was very informative for me. (S291)*

> *… grounds students to some major factors in chemistry that many overlook and it is good to understand how such processes operate in the real world ... (S284)*

4) Importance of the topics of systems thinking and sustainability

> *… Sustainability and systems thinking practical foster a holistic approach to problem-solving … crucial for addressing complex challenges. (S063)*

> *… how engineers can partner with industries to design and develop newer systems that enable socio-economic growth without harming the environment and causing sustainability issues. (S004)*

Recommendation of the activity for future students. As a final stage of evaluation, students were asked whether they would recommend the activity for future students. The response was overwhelmingly positive, with 93% of students supporting its continuation. The results affirm that the activity was effective and well-received. The students found the activity to be valuable in applying chemistry in everyday decision making.

A small minority (5%**)** were not in favour of the activity. Their feedback suggested that a few found the topic too broad for the allocated time and information provided. Others preferred traditional wet laboratory experiments over discussion-based or theoretical activities. Alternatively, some expressed discomfort with working in groups.

Despite these minor reservations, the overall results affirm strong student endorsement and support the integration of this activity into the chemistry syllabus.

Limitations

While the findings provide insight into how the activity supported students' engagement with sustainability and emerging systems thinking, several limitations should be acknowledged. First, the intervention was implemented within a relatively short timeframe, which may limit the extent to which deeper systems thinking skills could fully develop. Systems thinking typically evolves through repeated exposure and iterative practice; therefore, longer-term implementation across multiple activities or courses may yield stronger evidence of conceptual development.

Second, although student responses were analysed using qualitative coding to identify recurring themes and patterns, a fully formal qualitative framework with inter-coder reliability was not implemented. As such, the analysis should be interpreted as providing indicative insights into student reasoning rather than a thorough qualitative interpretation. In addition, some responses, particularly those related to renewable energy and electricity use may have been influenced by students' prior knowledge and the broader South African context, where electricity supply challenges are widely recognised.

Finally, the study focused on a single case study of aspirin synthesis and relied primarily on written reflections and activity outputs to infer students' reasoning. While the data provide valuable evidence of conceptual engagement, they may not fully capture the dynamic processes through which students negotiate ideas during discussion and collaborative work.

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Conclusions

This study demonstrates that systems thinking activities can significantly influence first-year engineering students' awareness of and attitudes toward sustainability. Using aspirin synthesis as a case study, students developed an understanding of how chemical processes interconnect with societal, economic, and environmental systems. They understood the importance of interdisciplinary collaboration, their obligation towards sustainability and the SDGs, and expressed a willingness to advocate for sustainable practices.

Students' attitudes to sustainability progressed throughout the activity; their perspectives shifted toward a more holistic view**,** acknowledging trade-offs, partnerships, and systemic interconnections. The role play exercise enhanced the development of holistic thinking considerably. By the end of the activity, students demonstrated ownership of their role in promoting sustainability and acknowledged their responsibility as future engineers.

Importantly, students appreciated the central role that chemistry plays in contributing to sustainability and how their chemistry training connects to their future professions. The activity helped to bridge the gap between the theory taught in classrooms and the real-world challenges.

Overall, students embraced the activity and the teaching approach, demonstrating that systems thinking and sustainability were successfully introduced to first-year engineering students.

With the sustainability challenges facing the world, it is necessary to incorporate sustainability and systems thinking in tertiary education. By introducing students to different perspectives early in their education, we can equip the next generation to innovate responsibly.

Recommendations

The following recommendations are proposed for educators, curriculum designers, and future researchers aiming to strengthen sustainability and systems thinking in science education.

It is recommended that sustainability principles be introduced early in the higher education system.

Sustainability concepts should not be treated as supplementary but embedded within the core chemistry curriculum.

The role play activity used in this study proved effective in promoting deeper learning and understanding of sustainability. Role play exercises can be included in learning activities to promote important skills such as negotiation and scenario-based decision making necessary in and trade-offs in sustainability issues.

In closing, a longitudinal study to investigate how the knowledge and attitudes gained are retained or enhanced as students move through higher education and how they translate into workplace behaviour and innovation is recommended.

Author contributions

Dorine Dikobe contributed to the conceptualisation of the activity, supervised the MSc research of Cathrine Chimude, and led the design of the study and its methodology. She was responsible for data analysis and contributed figures for data visualisation. Dorine Dikobe also wrote the first draft of the manuscript and contributed to its subsequent review and editing.

Lynne Pilcher contributed to the conceptualisation of the project and was responsible for securing ethics approval and funding, as well as supervising the MSc research of Cathrine Chimude. She contributed to the analysis of the student reflections and provided figures for data visualisation. Lynne Pilcher also contributed to the writing of the first draft of the manuscript and to its review and editing.

Cathrine Chimude designed the activity and the methodology for the pilot study that formed the foundation of this research. She contributed to the review of the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

The supporting data has been provided as part of the Supplementary information.

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Data availability

The supporting data has been provided as part of the Supplementary information.