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Problem-Based Learning in Sustainable Chemistry: A Student Startup Model with PET as a Case Study.

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Abstract:
This paper presents a problem-based learning (PBL) framework designed to enhance sustainable chemistry education through a simulated student startup model. Implemented in the MSc Sustainable Chemistry programme at UCL, the activity uses polyethylene terephthalate (PET) as a case study to explore circular economy principles and green chemistry strategies. Students adopt professional roles within startup teams to collaboratively design sustainable production and recycling processes. Delivered in a flipped classroom format, the model promotes active learning, career awareness, and interdisciplinary skill development. Preliminary results from two pilot cohorts show high engagement and positive student feedback, with many graduates pursuing careers in sustainability-focused roles. While the sample size limits generalisation, the model demonstrates strong potential for broader application. Future directions include scaling to larger cohorts, adapting the framework to laboratory-based modules, and fostering cross-institutional collaboration. This approach offers a flexible and impactful template for embedding sustainability and circularity into chemical education.

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Problem-Based Learning in Sustainable Chemistry: A Student Startup Model with PET as a Case Study.

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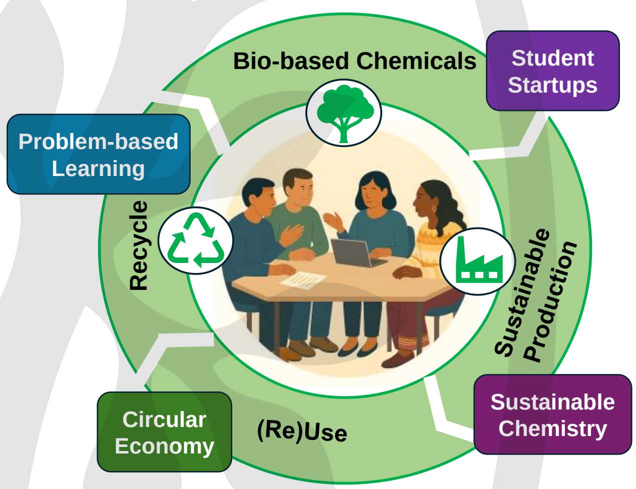
SIGNIFICANCE

This paper introduces a novel problem-based learning model that simulates a student-led startup to teach sustainable chemistry. Using PET as a case study, the approach bridges academic learning with real-world career skills, fostering engagement, interdisciplinary thinking, and professional development. It offers a scalable, adaptable framework for embedding sustainability and circularity into chemical education.



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ABSTRACT

This paper presents a problem-based learning (PBL) framework designed to enhance sustainable chemistry education through a simulated student startup model. Implemented in the MSc Sustainable Chemistry programme at UCL, the activity uses polyethylene terephthalate (PET) as a case study to explore circular economy principles and green chemistry strategies. Students adopt professional roles within startup teams to collaboratively design sustainable production and recycling processes. Delivered in a flipped classroom format, the model promotes active learning, career awareness, and interdisciplinary skill development.

Preliminary results from two pilot

cohorts showed high engagement and positive students' feedback, with many graduates pursuing careers in sustainability-focused roles. While the sample size limits generalisation, the model demonstrates strong potential for broader application. Future directions include scaling to larger cohorts, adapting the framework to laboratory-based modules, and fostering cross-institutional collaboration. This approach offers a flexible and impactful template for embedding sustainability and circularity into chemical education.

Introduction: Sustainability in Chemistry Education

Modern society remains heavily dependent on finite fossil resources, a model that has led to widespread environmental and economic concerns. To address these issues, there is an urgent need to shift towards a circular economy, one that prioritizes resource efficiency, reuse, and regeneration. Chemistry, as a foundational discipline, is central to this transformation. Educators in the chemical sciences therefore hold a crucial role in preparing future professionals to contribute meaningfully to sustainable development.

Global initiatives such as the United Nations Sustainable Development Goals (SDGs)[1] and the Stockholm Declaration on Chemistry for the Future[2] have laid the groundwork for integrating sustainability into education and research. These frameworks promote collaborative action to tackle challenges including climate change, inequality, and environmental degradation. The SDGs, in particular, offer a roadmap for embedding green chemistry principles into areas such as process innovation, waste reduction, and inclusive education. [1]

In response to evolving societal and professional expectations, accreditation bodies like the Royal Society of Chemistry (RSC) have begun to incorporate sustainability metrics into programme evaluations.[3] This reflects a broader recognition of the changing landscape of chemical employment and the competencies required for emerging roles.[4]

Support for curricular reform also comes from organizations such as Beyond Benign,[5] which advocates for the integration of green chemistry through its Green Chemistry Commitment (GCC).[6] This initiative enables institutions to tailor their sustainability efforts to their own timelines and capacities. In partnership with the American Chemical Society Green Chemistry Institute, Beyond Benign also facilitates the Green Chemistry Teaching and Learning Community (GCTLC),[7] a platform for sharing pedagogical resources and fostering collaboration.

As a result, universities are increasingly offering specialized degree programmes and modules focused on green and sustainable chemistry, particularly at the postgraduate level. These developments reflect a growing consensus on the need to align chemical education with global sustainability priorities.

To support this shift, active learning strategies have gained traction. Among these, problem-based learning (PBL)[8,9] stands out for its ability to engage students in authentic, complex challenges. PBL encourages learners to apply theoretical knowledge in practical contexts, promoting deeper understanding and critical thinking.[10,11]

In a PBL framework, students are presented with open-ended problems that require collaborative decision-making and iterative problem-solving. Rather than receiving direct instruction, learners explore solutions independently, guided by facilitators who support reflection and inquiry.[12–16] PBL is particularly well-suited to group work, as it encourages peer-to-peer learning, boosts student motivation, and helps develop key competencies such as independence, communication,
leadership, and self-assessment.[15,17–19] This approach has been successfully implemented in both laboratory and theoretical chemistry settings.[20–27]

This paper introduces a PBL-based teaching model developed for the MSc Sustainable Chemistry at University College London (UCL).[28] Using the case of polyethylene terephthalate (PET), a common plastic with significant environmental implications, we simulate the structure of a startup company to teach concepts of circular economy and sustainable chemistry. In this model, academic staff take on executive roles (e.g., CEO, CSO), Postgraduate Teaching Assistants (PGTAs) serve as Project Managers, and students work in teams, assuming roles inspired by real-world job descriptions.

We outline a detailed framework for implementing this student startup model within a flipped classroom setting, including role definitions, team dynamics, workshop schedules, and assessment strategies. While PET serves as the initial case study, the approach is flexible and can be adapted to other sustainability challenges. We hope this model will be adopted widely across institutions seeking to enhance green and sustainable chemistry education.

Designing the Student Startup PBL Model

In 2023, we launched the MSc Sustainable Chemistry at UCL.[28] Now in its third year, the programme aims to reshape the landscape of chemistry education by promoting a more sustainable approach and preparing the next generation of scientists. The development of this programme also responds to growing demands within the chemical industry for professionals equipped with skills in green and sustainable chemistry. [4]

Our programme is designed for graduates in chemical sciences and related disciplines who may not have prior experience in green and sustainable chemistry. The core theoretical module, Core Concepts in Sustainable Chemistry,[29] introduces foundational principles through case studies relevant to the chemical industry.

A key focus is placed on designing alternative, sustainable chemical processes to replace those based on fossil resources, supporting the transition to a circular economy.
As part of the module syllabus (see **Supporting Information**), we present the circular economy model and the concept of "closing the loop" in sustainability using biomass across three stages:

1. Selection and processing of biomass;
2. Design of chemical processes from bio-based and platform chemicals;
3. Reuse, recycling, and upcycling of post-consumer materials.

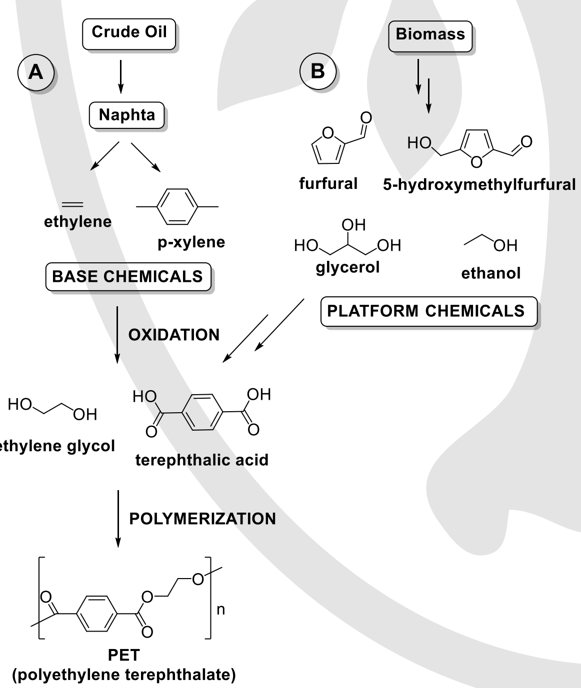
The course is built around an active learning philosophy. We aim not only to teach green and sustainable chemistry but also to empower students to apply their knowledge in real-world scenarios. This approach fosters independence, communication, and leadership skills, while also helping students explore potential career paths after graduation.

As outlined in the introduction, Problem-Based Learning (PBL) provides an ideal framework for this active learning approach. Our
PBL design is structured around three core elements:

1. A relatable context within the chemical industry to enhance engagement.
2. A sustainability-focused objective that allows students to apply their knowledge;
3. Clearly defined participant roles that promote career awareness and professional development.

Polyethylene terephthalate (PET), a widely used plastic, serves as the central case study. Traditionally, PET is produced from oil-derived base chemicals, p-xylene and ethylene, which are oxidized to form terephthalic acid and ethylene glycol, followed by polymerization (**Scheme 1A**). With a global recycling rate of only around 10%, PET recycling remains an area of intensive research,[30–33] making it a highly relevant example for our case study.

Importantly, terephthalic acid and ethylene glycol can also be synthesized from biomass-derived platform chemicals (**Scheme 1B**). Sugarcane is a common model taught as an example of biomass used in such processes.[34] This scenario offers an excellent opportunity to design a PBL case study focused on developing a sustainable, biomass-based alternative for PET production and recycling within a circular economy framework.



Scheme 1 Oil-based (A) versus Biomass-based (B) production of PET.

To enhance realism and support our goal of raising career awareness, we structured the case study as a simulated company. Industrial roles were designed based on real job advertisements, and students take responsibility for their own startup companies under the guidance of lead educators and Postgraduate Teaching Assistants (PGTAs).

The core elements of our PBL design are illustrated as shown in **Figure 1**:

- **Scenario**: Real-world challenge in the chemical industry "Production of PET plastics from fossil resources".
- **Objective**: "Designing a sustainable approach to closing the loop in PET production".
- **Roles**: CEO, CSO, Project Manager, Research Scientist, Sustainability Officer, Quality Control Analyst, Marketing Analyst, and Patent Attorney, each inspired by actual job postings and described in detail in the following section.

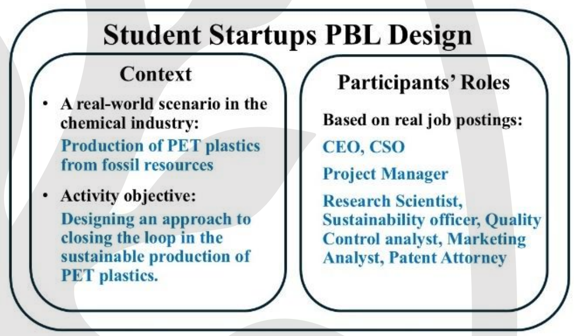


Figure 1 Context and Participants' roles of the PBL Design.

Model Startup Roles and Hierarchy of the Participants

To simulate real-world professional environments and enhance career readiness, the structure and hierarchy of participants in our PBL model are designed to emulate those of a startup company. Lead academics assume executive roles, Postgraduate Teaching Assistants (PGTAs) act as Project Managers, and students work collaboratively in teams to address the real-world challenge of sustainable production and recycling of PET. Each student adopts a role inspired by actual job postings, contributing to a dynamic and professionally oriented learning environment. A visual representation of this hierarchy and a summary of the roles are provided in **Figure 2**.

At the top of the organisational structure are the Lead Academics, who take on executive positions such as Chief Executive Officer (CEO) or Chief Scientific Officer (CSO). In our startup model, the CSO has two primary responsibilities: first, to introduce students to the topic by providing relevant background information (see **supporting information**); and second, to formulate the problem based on the real-world scenario of PET production. CSOs do not actively facilitate discussions unless necessary. Instead, they observe the students' progress, maintaining an objective stance that enables them to provide constructive feedback and assess performance at the end of the PBL session.

PGTAs serve as Project Managers, overseeing team meetings and guiding discussions. Their role is to stimulate critical thinking by posing questions that encourage exploration and problem-solving, without offering direct solutions. Project Managers also ensure effective group dynamics by monitoring participation, maintaining focus on the task, and managing time. Intervention is limited to situations where student safety is at risk (e.g., in laboratory settings) or when discussions reach a dead end.

Students take on a variety of roles within their teams. Initially,

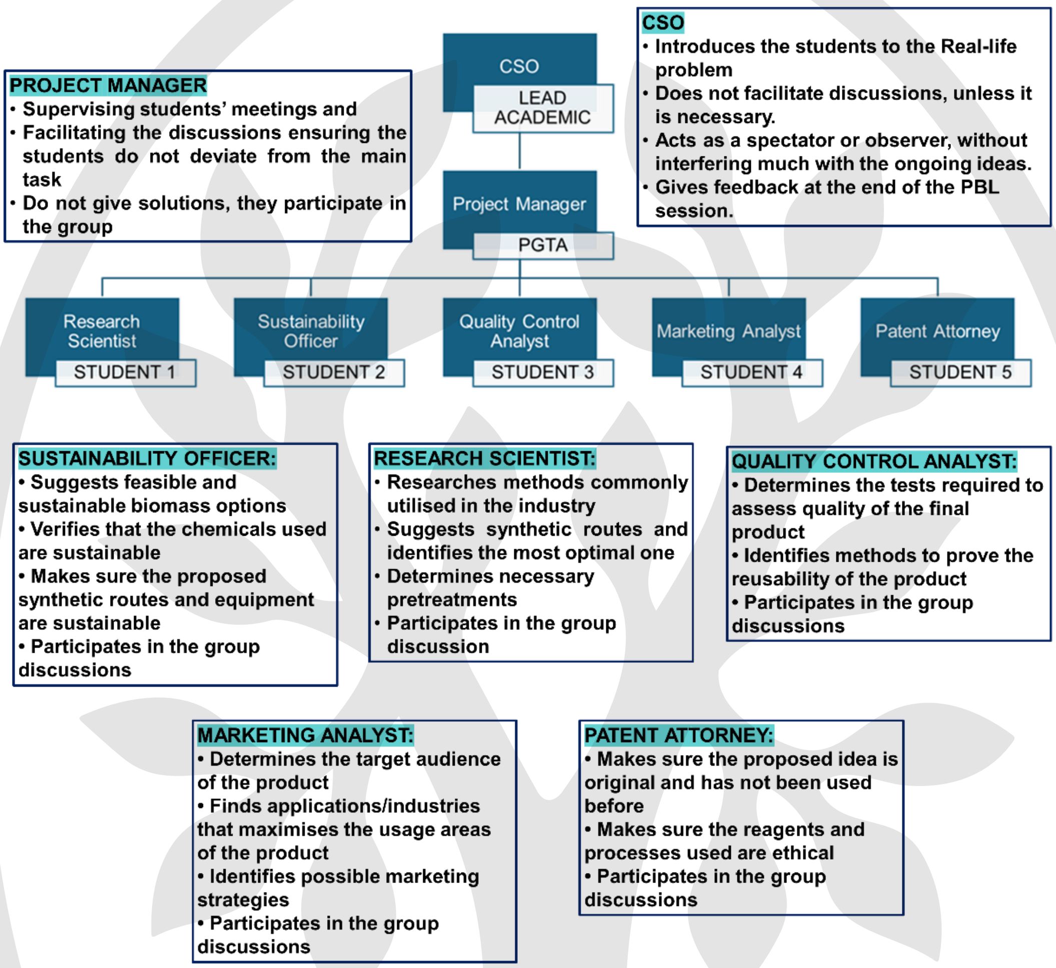


Figure 2 Hierarchy and Summary of responsibilities of all the participants of the student startup PBL model.

roles may be assigned to help students familiarise themselves with the startup model. As they become more comfortable with the PBL approach, students are encouraged to select roles independently. This autonomy supports their understanding of the personnel required to address specific challenges and provides insight into industry practices. Since different problems demand different expertise, students have the opportunity to explore multiple roles, gaining valuable experience that can inform future career decisions.

While each role has distinct responsibilities, all students engage in the tasks of reviewing learning materials provided by the Lead Academics, selecting a role, analysing the problem, formulating solutions collaboratively, and presenting their findings through reports or presentations. Throughout the PBL sessions, students may rotate through roles based on their interests and group dynamics. In some cases, students may hold multiple roles simultaneously, depending on team size and individual motivation.

In our PET-focused case study, we defined five key roles: Research Scientist, Sustainability Officer, Quality Control Analyst, Marketing Analyst, and Patent Attorney. These roles span traditional chemistry-related positions and extend into areas such as sustainability, marketing, and intellectual property, fields that are increasingly relevant to the chemical industry and aligned with the interdisciplinary nature of our MSc programme. This diversity allows students to engage with broader themes such as global markets, ethics, and innovation.

Below is a summary of the responsibilities associated with each role:

- **Research Scientist.** Investigates industry-standard methods, proposes synthetic routes, identifies optimal pathways for PET monomer production, and determines necessary biomass pretreatment.
- **Sustainability Officer**. Evaluates sustainable biomass options, ensures the use of environmentally friendly

chemicals, and assesses the sustainability of proposed synthetic routes and equipment.

- **Quality Control Analyst**. Designs testing protocols to assess the quality of processes and products (e.g., PET derived from biobased chemicals) and identifies methods to verify product reusability.
- **Marketing Analyst**. Researches global markets to identify target audiences, explores potential applications and industries for the product, and develops marketing strategies.
- **Patent Attorney**. Ensures the originality of proposed ideas (intellectual property) and verifies that reagents and processes comply with ethical standards.

Implementation and Assessment Strategy

Our student startup PBL approach has been implemented and piloted in the theoretical module Core Concepts in Sustainable Chemistry[29] during the academic years 2023/24 and 2024/25, with cohorts of 11 and 8 students respectively. The module was delivered within a flipped classroom environment, a pedagogical choice informed by the academic team's expertise. This format was selected to maximise the contact time available for hands-on, interactive learning. The flipped classroom model has been shown to enhance student performance and emotional engagement in chemistry and organic chemistry education.[35,36]

The central activity of "Designing an approach to closing the loop in the sustainable production of PET plastics" was structured over three weeks of thematic exploration. For each week, we developed approximately two hours of preparatory educational materials, including video lectures, curated reading resources, and quizzes. These materials were designed to scaffold student understanding. A selection of the materials is available in the **Supporting Information**. Each week culminated in a two-hour active learning session delivered as a PBL workshop, focusing on one of the three key stages of the activity within a circular economy framework (**Figure 3**):

- **Workshop 1**: Biomass Processing
- **Workshop 2**: Design of Sustainable Chemical Processes
- **Workshop 3**: Design of Recycling Protocols

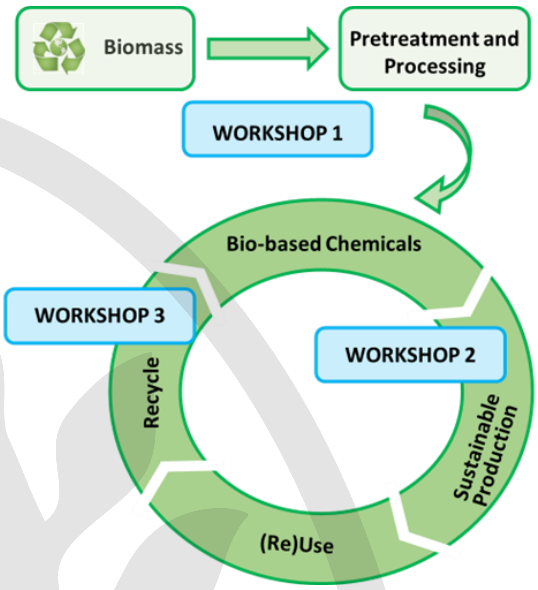


Figure 3 Key steps of the activity's objective and workshops in the context of circular economy.

Associated intended learning outcomes include the following:

- **Describe** the key chemical components and processes involved in conventional and biomass-based PET production.
- **Explain** the principles of circular economy and how they apply to the sustainable production and recycling of PET.
- **Apply** green and sustainable chemistry principles to propose a biomass-based synthetic route for PET production.
- Critically **evaluate** the environmental, economic, and technical feasibility of different biomass sources and recycling strategies for PET.
- **Design** a comprehensive startup strategy including chemical process, sustainability assessment, market analysis, and intellectual property considerations, for a company producing sustainable PET.

The full activity spans six weeks culminating in a summative assessment in the form of a research report. **Table 1** provides a summary of the weekly structure. The process begins in Week 0, a preparatory phase where students are given early access to all educational materials. This pre-engagement period encourages students to begin familiarising themselves with the content before the official start in Week 1, which features a kick-off lecture.

The Week 1 kick-off lecture plays an essential role in setting the tone and expectations for the activity. Importantly, this session does not include chemistry content. Instead, its primary aim is to secure student buy-in and introduce the pedagogical framework. We present the concept of PBL within the context of our student startup model and introduce the activity's objective of sustainable PET production within a circular economy. During this session, we explain the roles of all participants, introduce relevant terminology, and describe the structure and assessment criteria.

To enhance realism and foster professional engagement, we adopt industry-standard language throughout the module. From this point forward, student teams are referred to as "startup companies," PGTAs become "project managers," and the lead academic assumes the role of "CSO." During the kick-off lecture, students form their companies, assign names to their startups, and are matched with a project manager. Based on cohort size, we determined that four members per startup was optimal, allowing flexibility in role distribution and the possibility of sharing or omitting certain roles.

From Week 2 to Week 4, startups work toward the activity objective through the three thematic PBL workshops during which they develop the research report to be submitted in Week 6. Each workshop is treated as a company meeting, facilitated by the assigned project manager. These sessions are designed to simulate real-world professional environments, encouraging students to engage in collaborative problem-solving and strategic planning. Educational materials to guide workshop discussions are provided in the **Supporting Information**.

In Workshop 1, students explore the selection, pretreatment and processing of biomass. While sugarcane is used as a model example in our module due to its prevalence in green and sustainable chemistry education,[34] startups are encouraged to

Table 1 Timeline and description of the different stages of the student startup PBL design.

WEEK	ACTIVITY STAGE	DESCRIPTION
0	**On-line Educational Materials**	Students are given early access to preparatory materials including video lectures, readings, and quizzes. This flipped classroom approach allows them to begin engaging with the content before formal sessions begin.
1	**Kick off lecture**	Introduces the PBL framework and startup model. Students form companies, assign roles, and adopt professional terminology. The session focuses on student buy-in, explaining the circular economy objective, structure, and assessment. No chemistry content is delivered.
2	**Workshop 1. Biomass Processing**	Startups select and evaluate biomass sources, considering geographical, logistical, and chemical implications. Ethical issues around food vs. chemical use of sugarcane are discussed. Students explore pretreatment strategies and the isomerisation of glucose to fructose.
3	**Workshop 2. Design of Sustainable Chemical Processes**	Focuses on synthesising PET monomers from biomass-derived chemicals. Students compare biobased and oil-based routes, assess feasibility, and apply green chemistry principles. Metrics are calculated to support sustainability claims.
4	**Workshop 3. Design of Recycling Protocols**	Students explore PET recycling technologies, comparing chemical and enzymatic methods. Trade-offs in energy use, scalability, and sustainability are analysed. Startups propose recycling strategies aligned with circular economy principles.
5	**Formative Assessment. Group Pitch**	Startups present their sustainable PET strategies in a simulated investor meeting. Each team delivers a 10-minute pitch to a panel of academics acting as investors. All members contribute. Immediate feedback is provided to guide report submission in week 6.
6	**Summative Assessment. Individual Report**	Students submit a reflective research report synthesising the startup experience. The report demonstrates integration of green and sustainable chemistry principles and strategic thinking developed during the activity.

consider alternative biomass sources. This decision introduces a range of considerations, including geographical availability, transportation logistics, and chemical implications. For instance, impurities in certain biomass sources may hinder downstream biological processes. If students choose sugarcane, they encounter their first ethical dilemma: the use of a food resource for chemical production.[37] Sugarcane juice offers a direct route to fructose, a key precursor for PET monomers, but its use competes with food industry applications. Alternatively, students may opt for bagasse, the lignocellulosic residue of sugarcane, which yields glucose. Although glucose is less efficient than fructose as a starting material, this choice opens the door to exploring the isomerisation of glucose to fructose,[38–40] offering a more ethically sound pathway.

Workshop 2 shifts focus to the synthesis of platform and biobased chemicals for PET monomer production. Students compare biomass-derived routes with conventional oil-based processes, assessing feasibility, competitiveness, and sustainability. They are encouraged to explore the current state of the art, considering the implications of investing in new infrastructure versus relying on established technologies. Startups apply principles of green and sustainable chemistry, including the use of green solvents, catalysis, and environmentally benign reagents. They also calculate green and sustainable metrics to support their proposals and justify their strategies in comparison to the oil industry.

Although not a formal objective of the activity, the synthesis of Polyethylene Furanoate (PEF) is introduced in the module as a potential alternative to PET.[41,42] PEF has emerged organically in student discussions as a more feasible and cost-effective option, reflecting authentic decision-making processes in industry. This development is welcomed, as it demonstrates the flexibility and responsiveness of the startup model. In real-world scenarios, companies often pivot toward more promising

technologies. Importantly, the activity does not assume that biomass-based PET is currently competitive with oil-based production. Instead, students are expected to reach their own
conclusions through critical analysis and discussion.

In Workshop 3, startups address the final stage of their objective: designing recycling protocols for PET within a circular economy. PET recycling is a rapidly evolving field, and we provide students with examples from the current literature [30–33]. Startups evaluate various chemical recycling methods, including the use of heterogeneous catalysis and strong bases at elevated temperatures, which offer high conversion rates but come with significant energy demands. Alternatively, students explore enzymatic depolymerisation approaches, which utilise renewable catalysts and operate at lower temperatures. These methods, while more sustainable, often involve longer reaction times and pose challenges for industrial scalability [43–45]. Students must weigh these trade-offs and propose recycling strategies that align with green chemistry principles and industrial feasibility.

The final phase of the activity, during Weeks 5 and 6, is dedicated to assessment. During this period, students engage in both formative and summative evaluations, designed to reinforce learning and simulate professional practice.

In Week 5, each startup participates in a formative assessment in the form of a group pitch. This session is structured as a simulated investor meeting, where students present their sustainable production and recycling strategies to a panel of academics acting as "potential investors." Each startup delivers a 10-minute presentation outlining their project design, feasibility, and key findings. The format is intentionally flexible, allowing students to tailor their presentation style to their communication strengths. The only requirement is that all team members must actively contribute.

The investor panel provides immediate, constructive feedback, highlighting strengths and suggesting areas for improvement. This feedback is intended to guide students in refining their ideas and communication strategies and directly informs the individual research report submitted in Week 6. By removing grading pressure from the formative assessment, we aim to foster a low-stakes environment that encourages experimentation, collaboration, and skill development.

In Week 6, students complete a summative assessment in the form of an individual research report. This report serves as a reflective synthesis of the startup experience, allowing students to articulate their contributions and insights gained through their assigned roles. As previously described, each student assumes a specific professional role within their startup but also learns from peers and engages with the broader strategic objectives of the group. The report is designed to capture this interdisciplinary learning and demonstrate the student's ability to integrate green and sustainable principles into their strategy design.

The grade distribution for the first two cohorts of the programme (2023–24 and 2024–25) as presented in **Figure 4**.

In 2023–24, all 11 students submitted their reports, while in 2024–25, 7 out of 8 students completed the assessment. All submitted reports achieved a passing grade (≥50%). Notably, 64% of students in 2023–24 and 71% in 2024–25 earned a grade of 70% or higher, qualifying for Distinction. While the sample size is small and individual grades can significantly influence cohort trends, these results suggest that the student startup PBL model has positively impacted student performance.

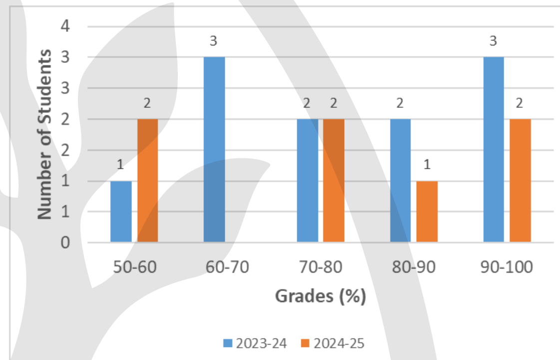


Figure 4 Grade distribution for individual research report submissions following the student startup PBL activity in 2023–24 and 2024–25.

Overall engagement throughout the PBL activity was excellent. While it is true that small cohorts, such as ours, make active learning more manageable and impactful, preliminary student feedback suggests that the student startup model was well received as a novel and engaging approach. It was particularly appreciated for its role in bridging the gap between academic study and future professional careers. Although our sample size is too small to draw definitive conclusions, we have observed encouraging signs of impact on students' attitudes toward career planning and further education. Many of our graduates have pursued advanced studies or entered industry roles specifically within green and sustainable chemistry, rather than general chemistry. Notably, one student has taken a less conventional path for chemistry graduates, entering a consultancy role focused on sustainability, highlighting the broader relevance and adaptability of the skills developed through this activity.

Conclusions and Future Outlook

This paper presents a novel problem-based learning (PBL) framework designed to enhance student engagement and career readiness in sustainable chemistry education. By simulating a startup environment and using polyethylene terephthalate (PET) as a case study, we have demonstrated how active learning can be effectively integrated into postgraduate curricula. The student startup model encourages learners to adopt professional roles, collaborate on real-world challenges, and apply green and sustainable chemistry principles within a circular economy framework. Preliminary results from two pilot cohorts indicate strong student engagement, high performance in assessments, and positive feedback regarding the relevance of the activity to future career aspirations.

While our findings are promising, they are based on small cohort sizes, which limits the generalizability of our conclusions. Nonetheless, the observed trends, such as increased interest in sustainability-focused careers and interdisciplinary roles, suggest that the model has potential to influence student trajectories meaningfully. The diversity of roles within the startup teams also allowed students to explore non-traditional career paths, including sustainability consulting and intellectual property management, broadening their understanding of opportunities within the chemical sciences.

Looking ahead, we envision several avenues for expanding and refining our student startup PBL model. First, scaling up to larger cohorts will enable more robust data collection and allow us to draw statistically significant conclusions about the model's impact. Larger groups may also facilitate more diverse team compositions and richer peer-to-peer learning experiences. To support this, we plan to develop additional role templates and guidance materials to ensure consistency and manageability across expanded cohorts.

Second, we aim to adapt the startup PBL framework to other modules within the MSc Sustainable Chemistry programme, including laboratory-based courses. Integrating the model into practical settings will allow students to apply their startup strategies in experimental contexts, bridging the gap between theoretical design and hands-on implementation. This extension will also provide opportunities to assess the feasibility of proposed sustainable processes and recycling protocols in real laboratory conditions.

Finally, we are exploring the potential for cross-institutional collaboration and would like to extend an invitation to other institutions interested in embedding sustainability and circularity into their programmes. This would enable students from different universities to form virtual startups and collaboratively address global sustainability challenges. Such initiatives could foster international perspectives, enhance digital collaboration skills, and further align chemical education with the interdisciplinary demands of the sustainability workforce.

In summary, the student startup PBL model offers a flexible, impactful approach to teaching sustainable chemistry. With further development and scaling, it holds promise for transforming how we prepare future chemists to address the pressing sustainability challenges of our time.

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Primary Data

NO

Conflict of Interest

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Problem-Based Learning in Sustainable Chemistry: A Student Startup Model with PET as a Case Study.

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6.1 Re-use, recycling and upcycling of post-consumer materials

2. Selection of recommended readings

Textbooks on the use of biomass in the chemical industry

- Clark, J. H., & Deswarte, F. (Eds.). (2015). Introduction to chemicals from biomass. John Wiley & Sons.
- Cavani, F., Albonetti, S., Basile, F., & Gandini, A. (2016). Chemicals and fuels from bio-based building blocks. John Wiley & Sons.

Reviews on the preparation of bio-based and platform chemicals from biomass and applications

- Mika, L. T., Cséfalvay, E., & Németh, Á. (2018). Catalytic conversion of carbohydrates to initial platform chemicals: chemistry and sustainability. Chemical reviews, 118(2), 505-613.
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Article on the ethics of using biomass for food or chemicals

- Henning, B. G. (2015). The ethics of food, fuel & feed. Daedalus, 144(4), 90-98.

Reviews on the isomerisation reaction of glucose to fructose

- Delidovich, I., & Palkovits, R. (2016). Catalytic isomerization of biomass-derived aldoses: A review. ChemSusChem, 9(6), 547-561.
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Articles on Circular Economy in the context of the chemical industry

- Sheldon, R. A. (2020). Biocatalysis and biomass conversion: enabling a circular economy. *Philosophical Transactions of the Royal Society A*, *378*(2176), 20190274.
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- Barnard, E., Arias, J. J. R., & Thielemans, W. (2021). Chemolytic depolymerisation of PET: a review. Green Chemistry, 23(11), 3765-3789.
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Reviews including PEF as an alternative to PET

- Cui, Y., Deng, C., Fan, L., Qiu, Y., & Zhao, L. (2023). Progress in the biosynthesis of bio-based PET and PEF polyester monomers. Green Chemistry, 25(15), 5836-5857.
- Sanders, J. H., Cunniffe, J., Carrejo, E., Burke, C., Reynolds, A. M., Dey, S. C., ... & Argyropoulos, D. (2024). Biobased Polyethylene Furanoate: Production Processes,

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Articles and Reviews on enzymatic depolymerisation of esters

- Shi, L., Liu, P., Tan, Z., Zhao, W., Gao, J., Gu, Q., ... & Zhu, L. (2023). Complete depolymerization of PET wastes by an evolved PET hydrolase from directed evolution. Angewandte Chemie, 135(14), e202218390.
- Tournier, V., Duquesne, S., Guillamot, F., Cramail, H., Taton, D., Marty, A., & André, I. (2023). Enzymes' power for plastics degradation. *Chemical Reviews*, *123*(9), 5612-5701.
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3. Selection of slides to introduce the PBL startup model and activity

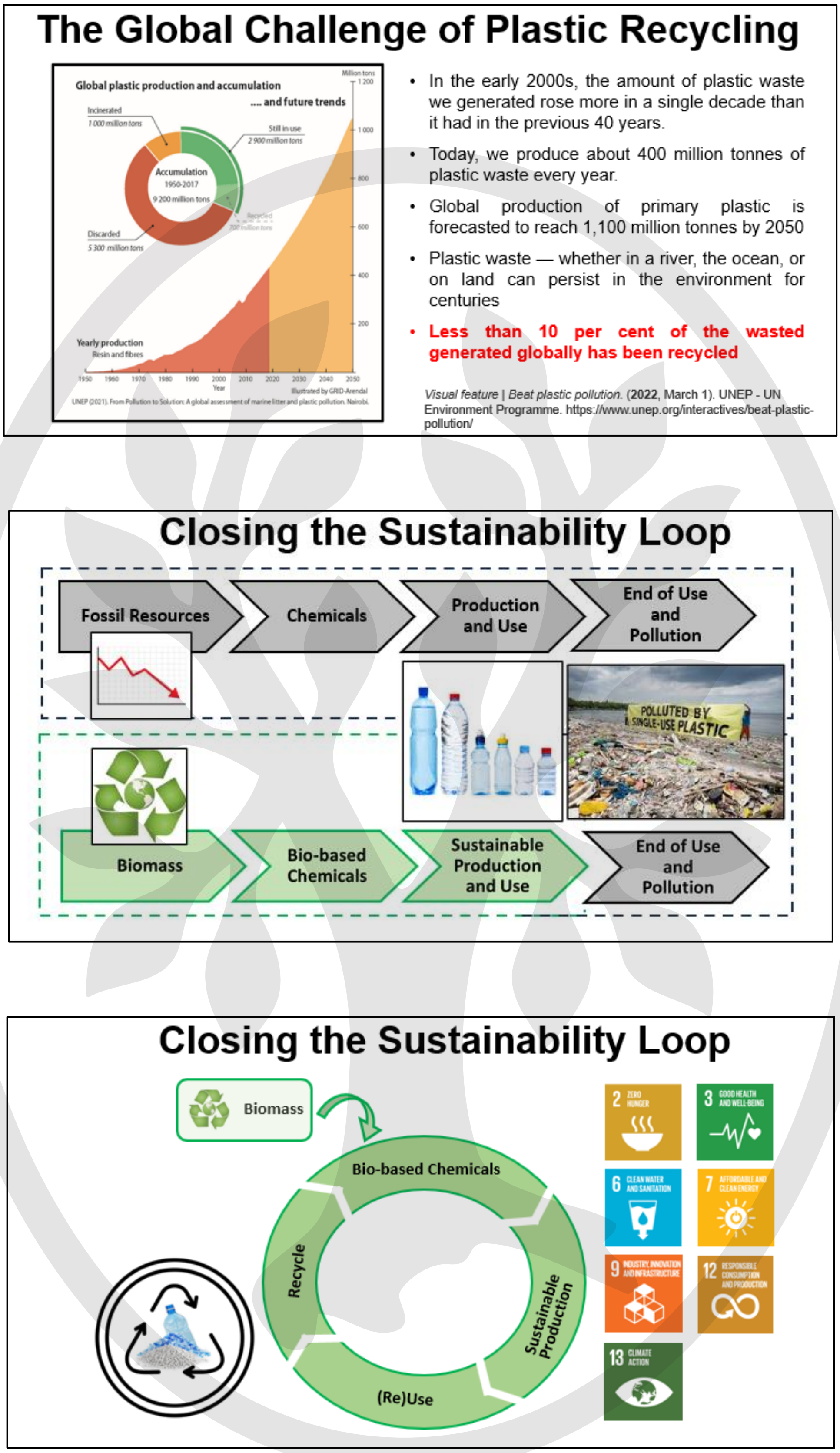


Figure 1. Selection of slides to introduce circular economy

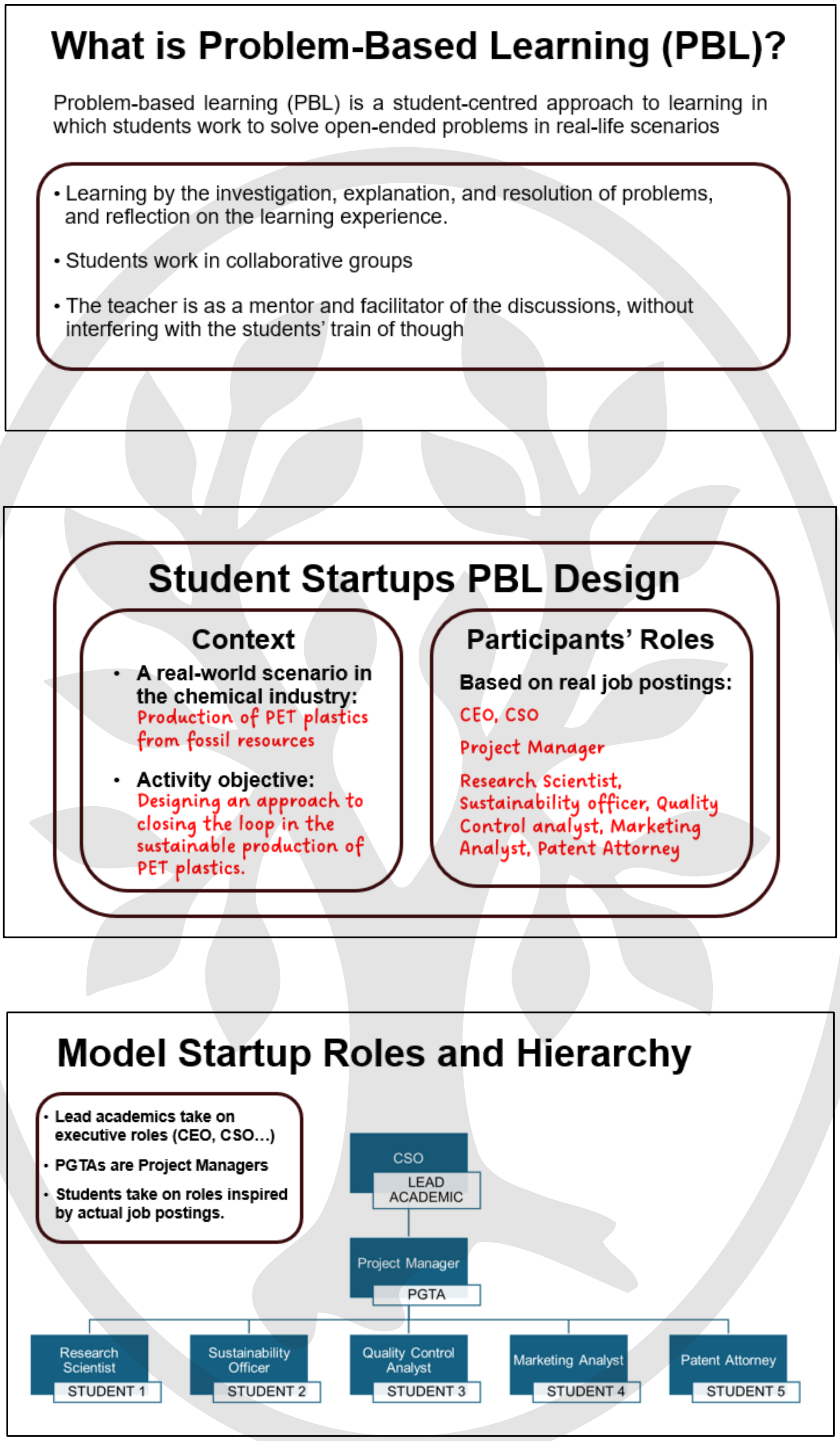


Figure 2. Selection of slides to introduce the student startups PBL approach

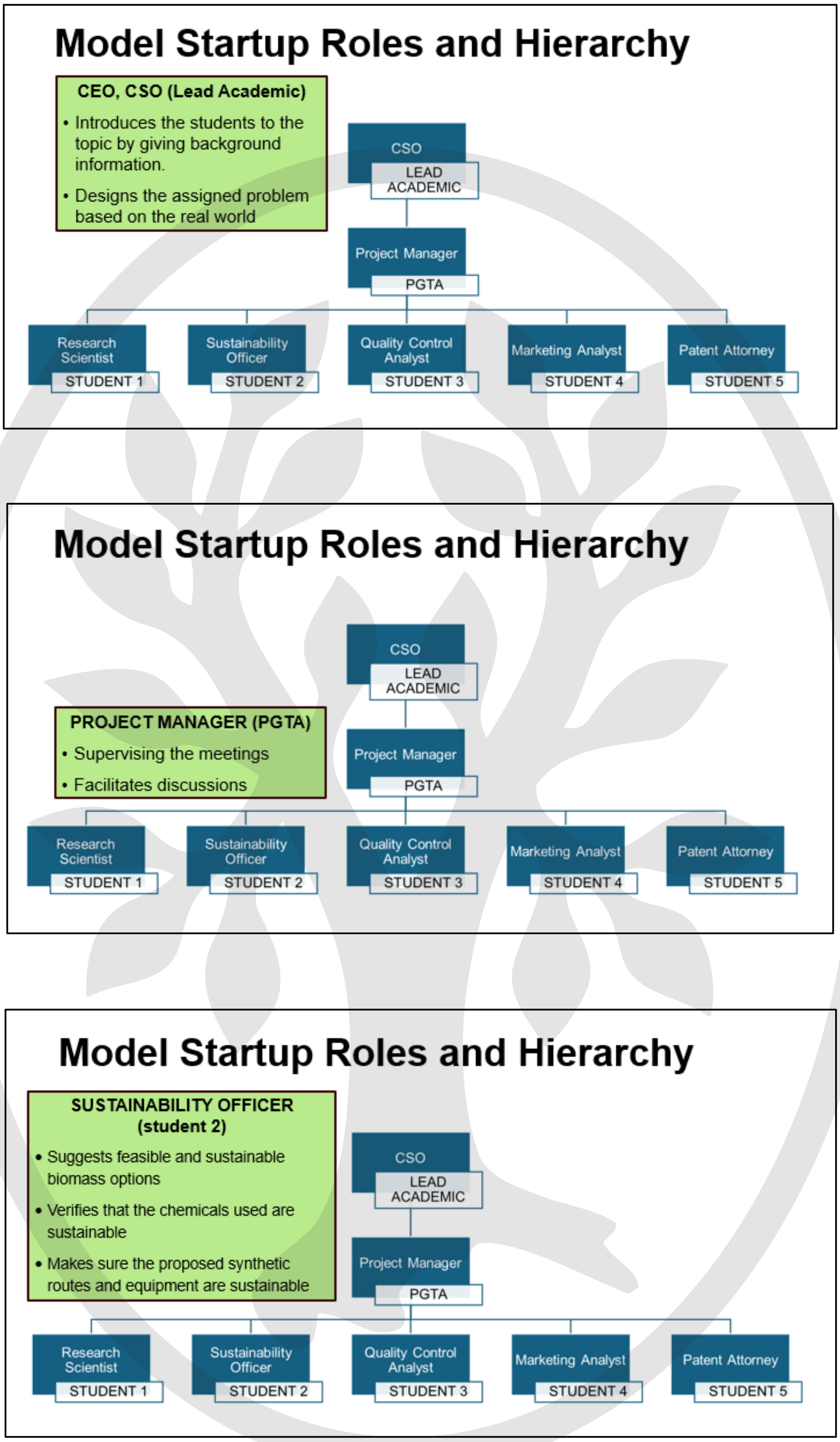


Figure 3. Selection of slides to introduce the different roles of the student startup PBL approach

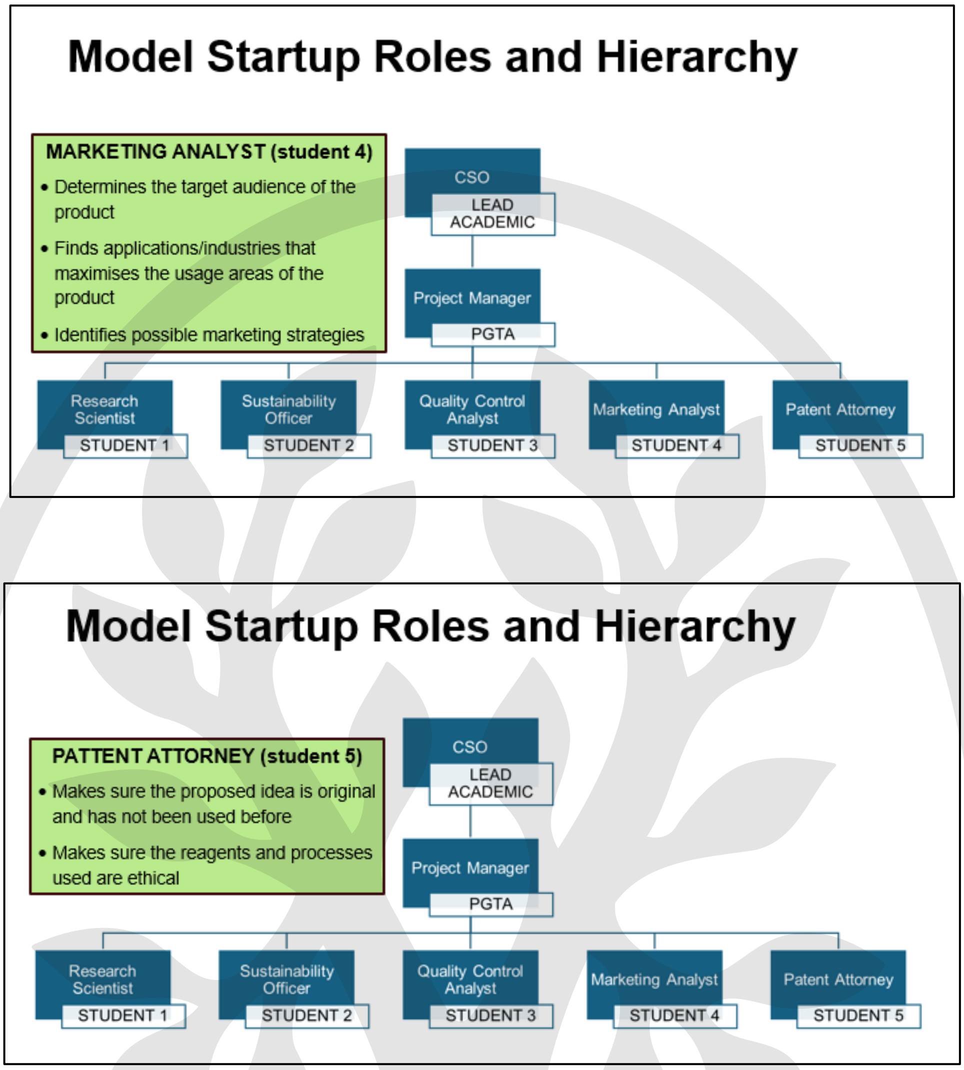
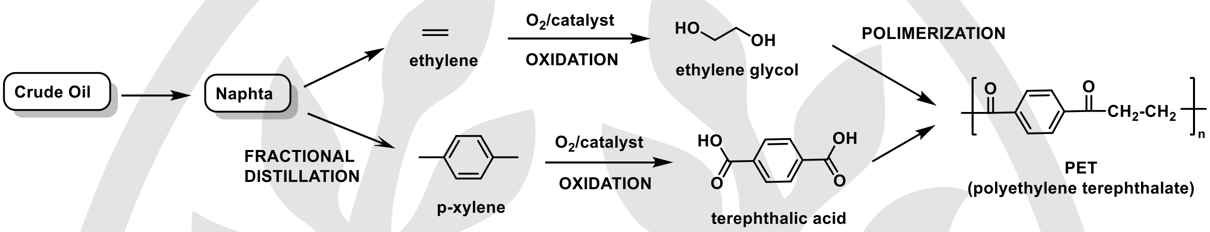


Figure 4. Selection of slides to introduce the different roles of the student startup PBL approach

4. Assessment sample for instructors with a selection of educational materials to guide the discussions during the workshops

<u>Summative Assessment: "Designing an approach to closing the loop in the sustainable production of PET plastics"</u>

The preferred industrial route for the synthesis of Polyethylene terephthalate (PET) involves the use of crude oil–derived base chemicals, ethylene and p-xylene, as illustrated in the scheme below:



Scheme 1. Production of PET from crude oil

Your startup company is tasked with proposing a sustainable strategy for the production and recycling of PET. This will be achieved through the following objectives, explored across three workshops:

- **<u>Workshop 1 (week 2):</u>** Select an appropriate biomass feedstock and design pretreatment and processing protocols. Your discussion should include potential ethical considerations.
- **<u>Workshop 2 (week 3):</u>** Design chemical processes for the production of PET from your selected biomass. Apply principles of green and sustainable chemistry and consider the feasibility and environmental impact of your proposed route.
- **<u>Workshop 3 (week 4):</u>** Develop protocols for the recycling of PET. Explore both chemical and enzymatic recycling methods.

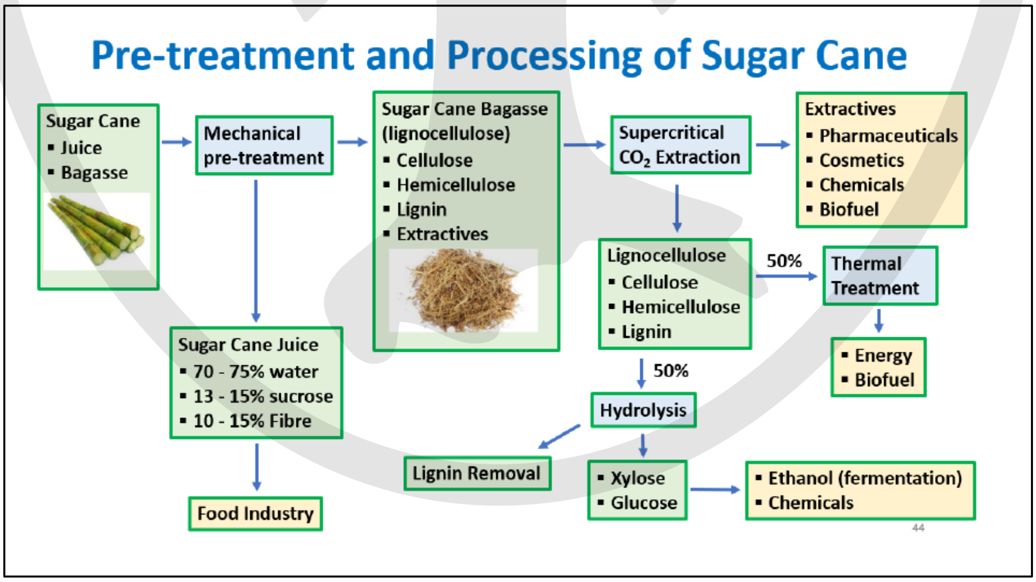
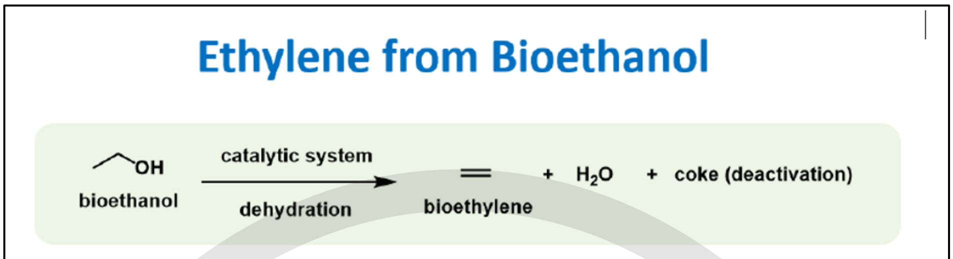


Figure 5. Summary of pretreatments of sugar cane



Catalytic System	Description
Al_2O_3–MgO/SiO_2	Selectivity >97%, 99% conversion, catalyst regeneration every 8–12 months

Figure 6. Example of production ethylene from bioethanol

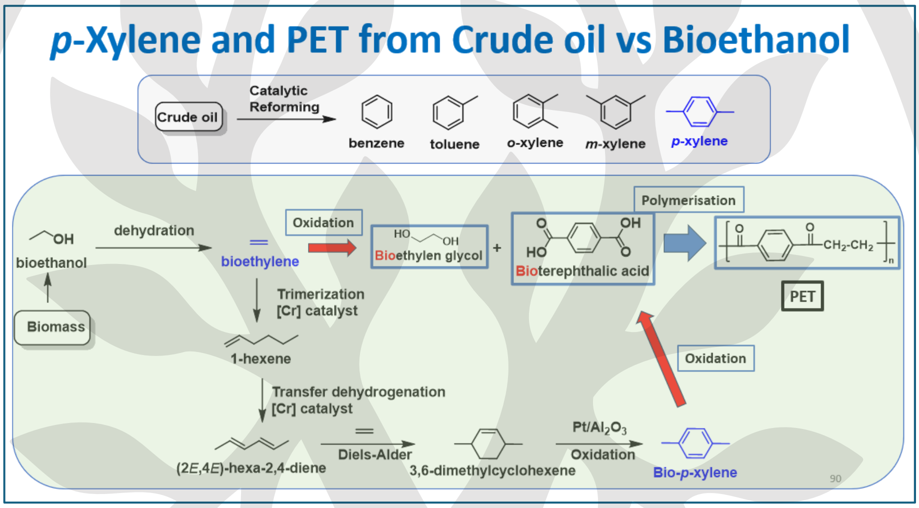
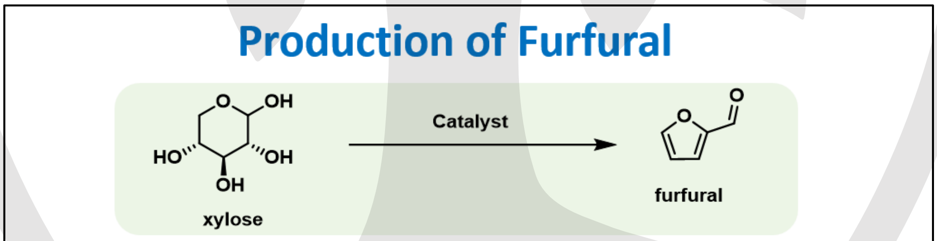


Figure 7. Production of PET from crude oil vs biomass



Solvent	Catalyst	Catalyst concentration	T (ºC)	t	yield (%)
water	Microwave/no catalyst	------	200	1 h	49
water	HCl NaCl	50 mM 3.5 wt%	200	7 min	76
water:toluene (1:4.4)	[BMIM][HSO_4]	5 wt %	140	6 h	71
water:toluene (1:1)	$MPrSO_3$HMCM-41	1 wt %	155	2 h	93
Water:MeTHF (1:2)	Glu-TsOH-Ti	1 wt %	180	30 min	51
γ-Valerolactone (GVL)	$FeCl_3 \cdot 6H_2O$	0.6 wt %	170	10 min	87

Figure 8. Examples of production of furfural from xylose

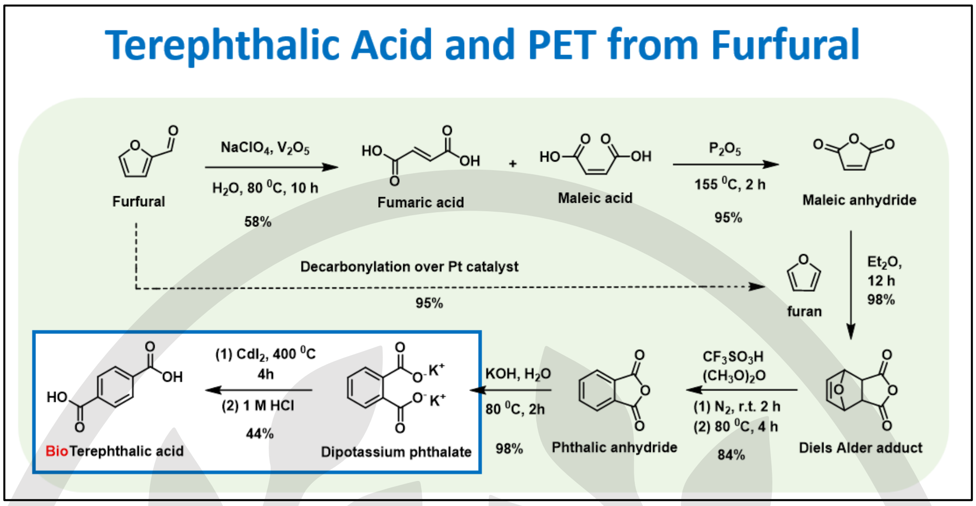


Figure 9. Production of PET from furfural

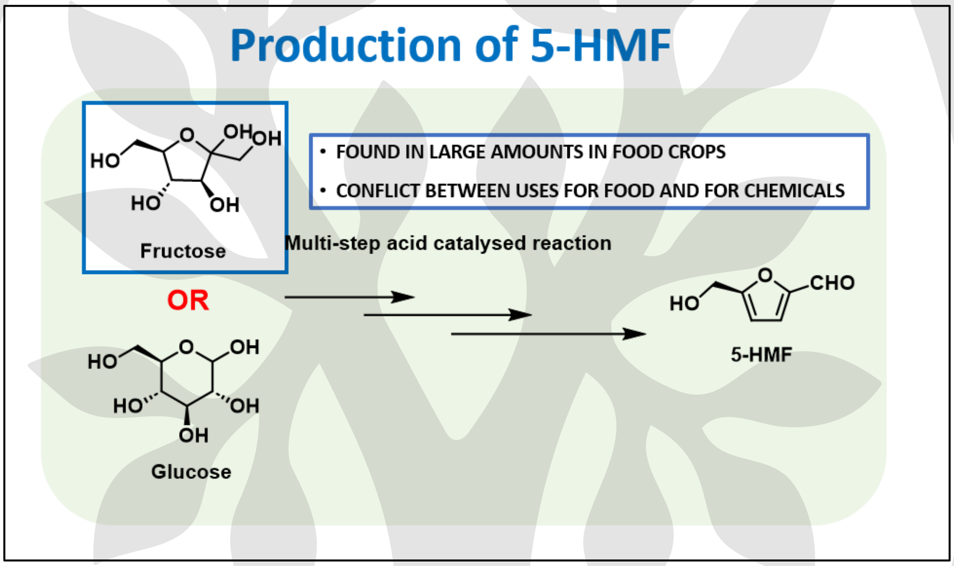


Figure 10. Production of 5-HMF from fructose vs glucose

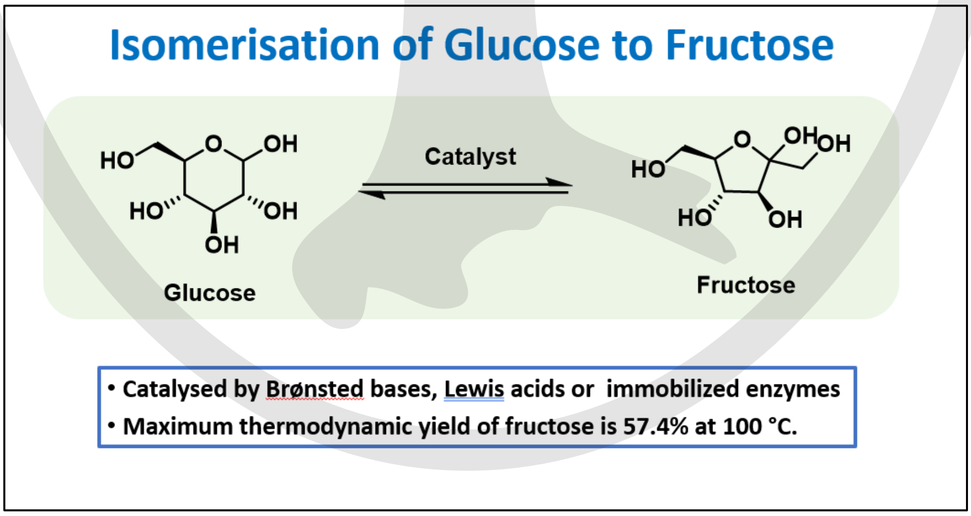
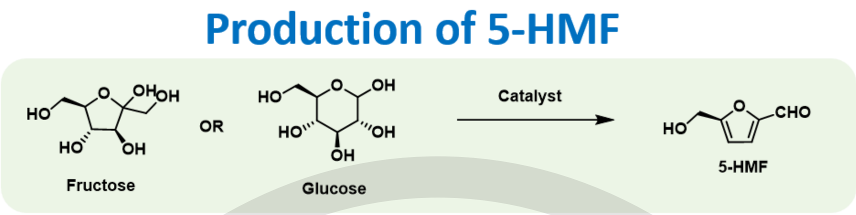


Figure 11. General description of the process of isomerisation of glucose to fructose



Starting Material	Solvent	Catalyst	T (ºC)	t	yield (%)
Fructose	water	AgSTA	120	120 min	86
Glucose	water	PCP(Cr)-SO_3H· Cr(III)	180	4 h	81
Fructose	n-butanol	$[MIMPS]_3PW_{12}O_{40}$	120	2 h	75
Fructose	DMSO	Microwave radiation	900 W	4 min	92
Fructose	[BMIM][Cl]	$FeCl_3$	100	4 h	91
Glucose	GVL:water = 9:1	amberlyst-70	130	30 min	32

Figure 12. Selection of reactions to obtain 5-HMF from glucose and fructose

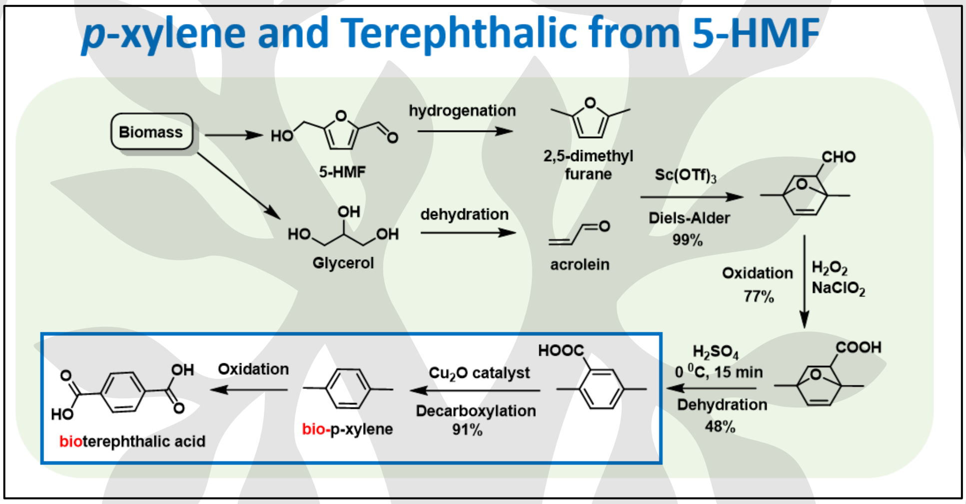


Figure 13. Synthesis of terephthalic acid from 5-HMF

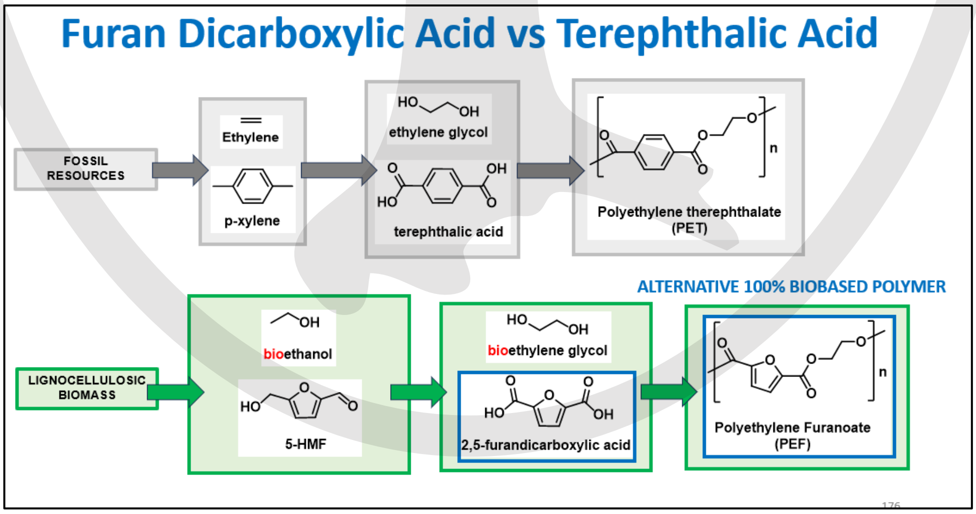
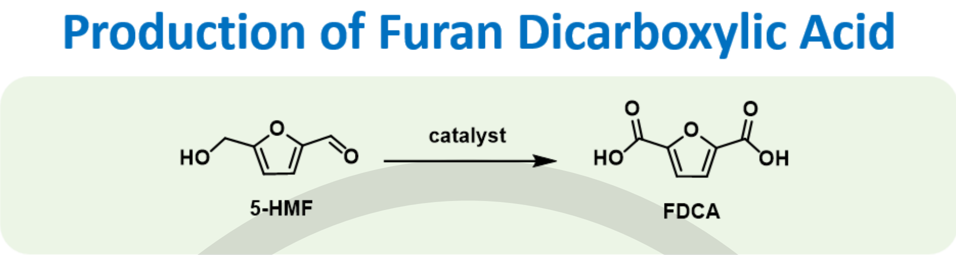


Figure 14. Synthesis of PET from crude oil vs synthesis of PEF from biomass



Oxidant	Base	Solvent	Catalyst	T (ºC)	t	yield (%)
Air (40 bar)	Na_2CO_3	water	Pt–Bi	100	2.5 h	>90
O2 (1 bar)	---	water	Au/HT	95	7 h	>99
O2 (10 bar)	NaOH	water	Au–Cu/TiO_2	95	4 h	90-99
CO_2/O_2(60 bar)	---	Acetic acid	$Co(OAc)_2$/$Mn(OAc)_2$/HBr	180	0.5 h	83

Figure 15. Selected examples of the Production of FDCA from 5-HMF

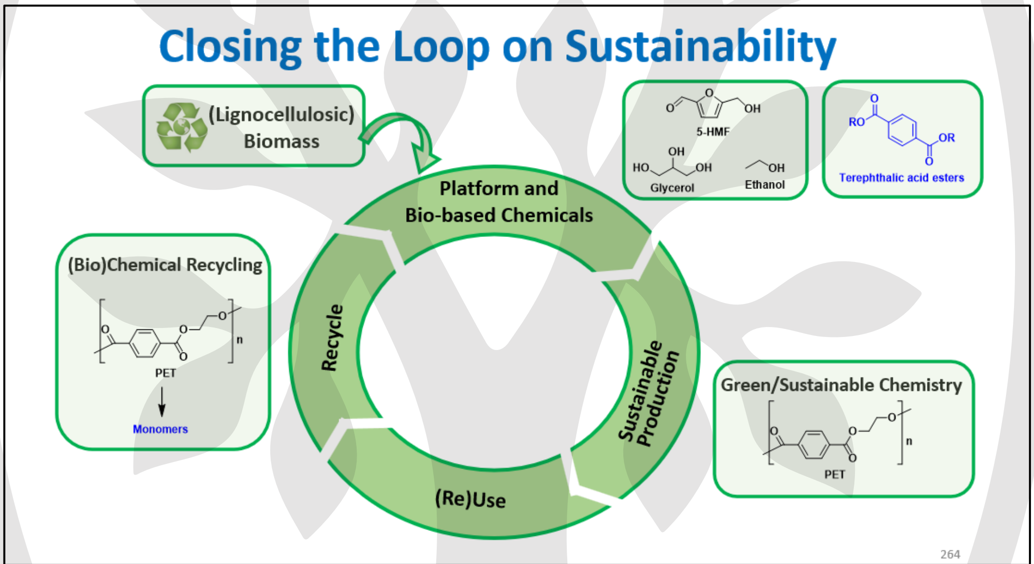


Figure 16. Closing the loop in sustainability for the production of PET

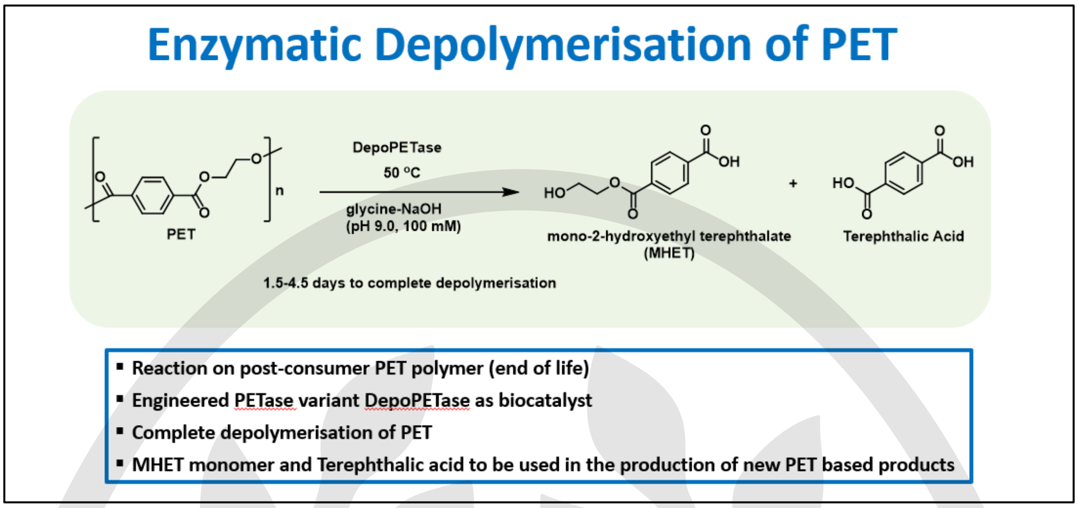


Figure 17. Example of enzymatic depolymerisation of PET

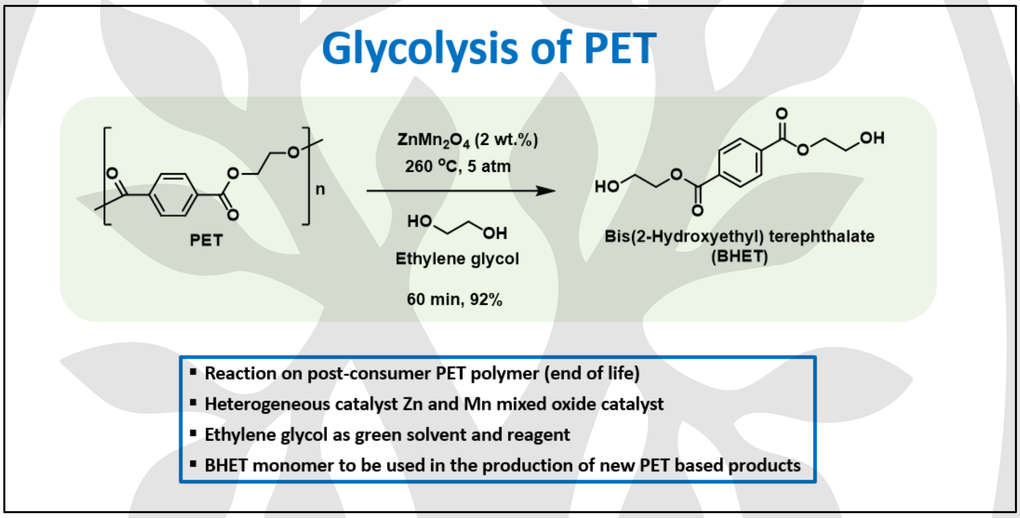


Figure 18. Example of glycolysis of PET