Cross-curricular project-based laboratory learning enables hands-on interdisciplinary education for chemical engineering students

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Abstract

To enhance students' interdisciplinary awareness and understanding of (i) high-pressure reactors, (ii) zeolites as catalysts and (iii) analysis of complex reactor effluents with unknown compounds, the laboratory exercises of two courses are coupled into a cross-curricular Project-Based laboratory Learning trajectory. The alkylation of anisole with 1-hexene proves to be an excellent case study for students to learn new objectives and strengthen the skills acquired in prior courses, emulating the work of expert engineers and analytical chemists. The time-efficient cross-curricular project proves effective in fostering teamwork and addressing complex engineering and analytical challenges. Student testimonials highlight the integrated project's success in providing new insights and cultivating advanced decision-making skills during experimentation. This approach also encourages future interdisciplinary collaborations between chemical engineering and analytical practice classes.

KEYWORDS: cross-curricular, interdisciplinary education, Project Based Learning (PjBL), zeolites, laboratory exercise

1. Introduction

Heterogeneous catalysis is one of the pillars on which our society is built upon, as it is estimated to contribute to 35% of the world's gross domestic product (GDP) [1]. Its key role in society is clearly translated to academic research, *e.g.* searching for "heterogeneous catalysis" in Web of Science generates over 45,000 research papers. However, of all these papers, only 54 are categorized as educational ("Education Scientific Disciplines" or "Education Educational Research"). This indicates that research and the educational program are often treated as being two different entities, where there is little research on educational practices concerning heterogeneous catalysis [2, 3], or at least it is not being published. Nevertheless, a significant number of students in chemical engineering, chemistry, biochemical engineering, ... are studying these subjects and might even perform research in the field in their later careers. In this regard, open-ended project-based laboratory exercises [4] that provide students with insights into heterogeneous catalysis, adaptable for and implementable in various master-level courses with distinct focuses, become highly valuable. Project-based learning (PjBL) approaches have been applied to help and motivate students to better understand complex subjects in chemical engineering curricula. Gomez-del Rio and Rodriguez have implemented PjBl in a mechanical laboratory, taught in the Chemical Engineering Bachelor degree. A high student satisfaction level for the complex mechanical laboratory was achieved [5]. Aranzabal et al. used PjBL in a "Process and Product Engineering" course, which is a part of the Chemical Engineering Bachelor degree. Aranzabal et al. studied the effect of team formation strategies and found that teams based on Belbin role theory perform better than self-selected teams in project-based learning, as it encourages improving group working skills and ultimately team performance [6]. Hernáiz-Pérez et al. used PjBL in a computer-aided design (CAD) laboratory to engage first-year chemical engineering students in their training of graphic expression, where the students replicate 2D and 3D plans of industrial engineering equipment. Overall, the project-based approach increases the students' satisfaction and score compared to the classical approach before [7]. Hence, project-based learning is implemented in quite some chemical engineering programs at the Bachelor level, nevertheless, reports of PjBL approaches at a master level are scarce. Although improved methods to convey concepts of chemical reactor/reaction engineering are reported, such as a virtual laboratory concept [8] and a combined kinetic measurement and simulation laboratory class [9], no reports of PjBL in chemical reactor/reaction engineering courses are found. In this contribution, we implement project-based learning at a master level and apply it to chemical reactor/reaction engineering in the context of experimental (zeolite-based) catalysis and chemical analysis. To the best of our knowledge, this has not yet been reported in literature. Furthermore, we have exploited project-based learning in an interdisciplinary project encompassing heterogeneously catalyzed chemical reactions and chemical analysis, rather than a single focus point such as kinetics or chemical equilibrium [10].

In catalysis there have been efforts towards benchmarking research results [11], similarly, implementing a form of benchmarking during Laboratory exercises could be of interest for educational programs. Within the category of heterogeneous catalysts, zeolites are, from an industrial perspective, one of the most important ones [12]. This is largely related to their unique properties, such as shape-selectivity dependent on their topology, which revolutionized oil refining [13]. The ability to steer reactions towards certain products based upon confinement at the active site - which is essentially a proton attached to the zeolite framework – has led to numerous studies and industrial applications [13, 14]. Although zeolites are widely used, paradoxically, they are – to the best of our knowledge – only briefly mentioned in educational programs and barely touched in educational research papers concerning heterogeneous catalysis [15]. Therefore, an open-ended laboratory exercise where the shape-selectivity of zeolites is utilized, allows students to get introduced to, and gain a better general understanding of zeolites. The ability to steer product selectivity with zeolites [16-18] makes them not only interesting from a research point of view, it also allows students to comprehensively grasp the importance of catalyst properties when converting reactants to products, as subtle differences in pore geometries can lead to vastly different results. Yet, this relation in zeolite topology – product pool, or more general: catalyst property – function, is one of the key focus points of the newly introduced open-ended PjBL [19] for Chemical Engineering Technology master students at Ghent University. Another important aspect of the new project is the analysis of the rather complex product pool. In industry, often complex mixtures are encountered, such as mineral oils and bio-oils. The composition of these mixtures is sometimes unknown and hence, multiple or complex analytical methods are necessary to determine their composition. Especially the combination of having students on the one hand analyze the product pool, which is considered challenging by them, and on the other hand relate the obtained results to the catalyst properties is highly interdisciplinary and allows for ample learning opportunities. Furthermore, confronting the students with the complexity of analyzing the product pool in order to be able to compute selectivity/product yields,... and other quantities related to the catalyst and reactor setup, allows students to better appreciate/understand the importance of chemical analysis. The project-based laboratory learning moreover illustrates the limited amount of resources and time to screen heterogeneous catalysts, bearing in mind the safety aspects, as well as the coupling and feedback between an industrial process and the analytical department. In addition, this project familiarizes students with certain challenges the industry faces (*e.g.,* a wide range of possible analysis techniques and the synthesis and analysis of unknown products).

Given its interdisciplinary nature encompassing reaction engineering and reactor effluent analysis, this new project-based laboratory learning is implemented in two separate courses (*i.e.* "Chemical Reactors" and "Applied Instrumental Analysis") of our master program. The overarching project covering both courses is the so-called PjBL [20] which has been proven to be an effective means to implement the teaching outcomes within limited teaching hours, stimulate the students' ability of interdisciplinary thinking and dealing with complex problems [21] and develop students with high-level engineering skills [4]. In the Chemical Reactors course, the fundamental knowledge and practical skills are taught by a combination of lectures and three individual laboratory exercises spread throughout the 2nd semester of the final year. The order of the laboratory sessions is random, though the results of the PjBL are orally presented at the end of the semester. Hence, this cross-curricular project can be seen as an end-of-term project. The Applied Instrumental Analysis course consists solely of laboratory exercises. The theoretical knowledge and practical skills in analytical chemistry, spectroscopy and chromatography have already been mastered by preceding bachelor courses. In the bachelor courses, the degree of independence is gradually increased to master level, where they must design experiments independently. In brief, in the Analytical Chemistry course (3rd BEng), students are guided via well written instructions. In the Instrumental Analysis (3rd BEng) and Spectroscopy (3rd BEng) laboratory courses, students perform the analyses without standard protocol but within an education frame with limited degrees of freedom. In the Applied Instrumental Analysis course (master course), students are tasked to choose appropriate analysis techniques to successfully answer the research questions within the exercise. To aid students in the decision making process, problem-based Learning (PBL) Tutorials are organized prior to each laboratory exercise. This approach is familiar for our students, since it is already used in the complete analytical chemistry learning trajectory of the educational program. In these brainstorm sessions, the tutor takes on the role of expert to guide students through complex research questions and to design an experimental set-up to reach the goals of the specific experiment. In this way, students are triggered to apply their knowledge for complex issues with instant feedback.

In the Chemical Reactors part of the project, students are tasked in groups of four to alkylate anisole with 1-hexene towards mono-alkylated hexyl anisole compounds (see Figure 1), using different zeolites as catalysts. Because their knowledge of zeolites is limited, they are only allowed to choose from four of the "big five" zeolites: MFI (Zeolite Socony Mobil-5), MOR (mordenite), FAU (faujasite), BEA (beta) (FER, ferrierite, is not included) in its Brønsted acidic proton or H-form (i.e. H-MFI, H-MOR,..), which have distinct physicochemical properties, and they receive a table with information about pore dimensions, surface area and acidic sites. During the project, they study the zeolite structures more indepth through 3D visualization tools (IZA, [22]) and they are given 3D-structures of the reaction products. This allows them to critically assess and discuss their results. Through this approach, PjBL is enabled, where the students come in group to insights, inside and outside of the lab.

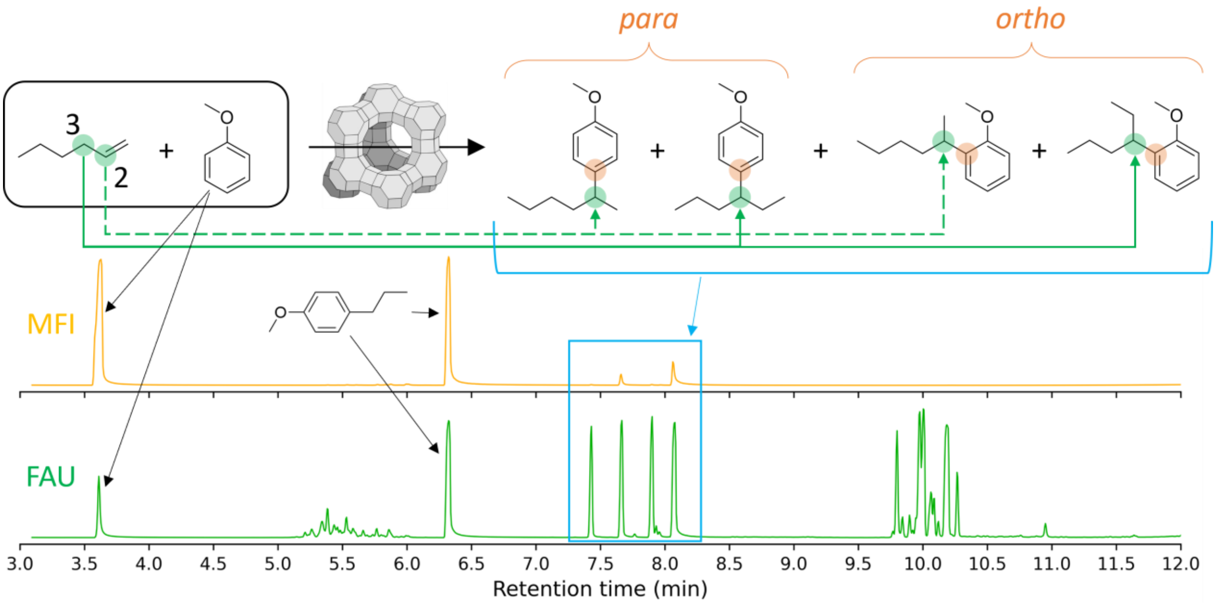

Figure 1 Scheme of the alkylation of anisole with 1-hexene into a variety of mono-hexyl substituted anisole compounds with the chromatograms of the reactor effluents obtained with H-MFI and H-FAU as catalysts.

Students know beforehand that the setup consists of 6 reactors which run simultaneously, and are given the task to screen the zeolites and analyze the product pool with the aim of determining the conversion and selectivity (see section 3A). Students use gas and liquid chromatography and spectroscopic techniques to identify and quantify the product pool in two laboratory sessions of the Applied Instrumental Analysis course (see section 3B). Since the obtained reaction products are unknowns, the project takes students out of their comfort zone (*i.e.* analytical standards are not available, product spectra are not included in the NIST database). For example, students need to record the mass spectra and link the fragmentation patterns with the products and determine the response factors in GC-MS/FID (Figure 1). This prepares the students to work with industrial samples such as new bio-oils or product pools of which the exact composition is often unknown and therefore analysis techniques do not immediately result in satisfied insights (*e.g.* 'black box' of occurring reactions and consequently products as well). Combining these challenges of unknowns with the alkylation reaction and the complexity of the zeolites themselves, lead to a new interdisciplinary and challenging PjBL experience, appropriate for master students.

Through this approach, we envisage various educational goals and competences. Critical thinking and problem solving is a common thread in our laboratory exercises [4] and with the PjBL approach we can teach content through knowledge and skills, create a need to know environment and fundamental content, we stimulate critical thinking, problem-solving and collaboration, and develop investigation skills [5, 23]. This cross-curricular PjBL aims to be an effective and activating means to trigger the students' ability to work as a team to tackle challenges. To successfully participate in the exercise, students must apply interdisciplinary reasoning skills.

2. Learning objectives

The cross-curricular project is part of two individual courses with both their own lab session(s); the catalyst screening laboratory is part of the Chemical Reactors course and the identification and quantification of the products obtained from the catalyst screening laboratory is part of the Applied Instrumental Analysis course. The specific learning objectives for the Chemical Reactors course are: **(1)** consider and apply the correct safety regulations when working with a high-pressure batch reactor at lab scale; **(2)** design a catalyst screening experiment with a limited number of reactor vessels (by taking into account the different properties of zeolites) and **(3)** engage in teamwork with team members to successfully finish the lab course from start-up to work-up in 4h. In the Applied Instrumental Analysis course, students are introduced to the following learning objectives: **(4)** identifying the necessary analyses from a reaction perspective and translating this into the design of the chemical analyses integrating multiple analytical techniques; **(5)** making informed decisions regarding sample preparation; **(6)** efficiently planning laboratory work as a team and applying this plan to qualitatively and quantitatively characterize the reactor effluents in two times 4h. The final overarching goal for both courses is to interpret the qualitative and quantitative results, calculate anisole conversion, the selectivity for the different hexyl anisole compounds for each catalyst and relate these findings to the experimental design in the Chemical Reactors course, *i.e.* reaction conditions and zeolite properties. Consequently, the interdisciplinary approach leads to additional overall learning objectives such as **(7)** a comprehensive grasp of zeolite characteristics and their role as catalysts; **(8)** the ability to correlate analytical findings with catalyst properties in order to design a new set of experiments and **(9)** understanding data ethics related to multiple datasets (from different groups in the Applied Instrumental Analysis course) and diverse analysis techniques (*i.e.* GC-MS; GC-FID, UV-VIS, HPLC).

3. Methods and experimental setup

The open-ended PjBL approach is applied to a cross-curricular, hence an interdisciplinary, case-study, which is related to the current sustainability challenges in industry, c.q. the transition of a fossil-based towards a biomass-based and circular one. In this transition, heterogeneous catalysis plays an important role [24, 25], as well as the identification and quantification of unknown reaction products and feedback to the production process [26]. Laboratory sessions, feedback, open discussions, PBL and just-in-time information [27] are implemented as teaching methods throughout the project. The student learning process and product of the project are evaluated via written examinations, participation behavior, observations and an oral examination, a final presentation and a structured datasheet with all relevant data. The latter evaluation methods are implemented to reduce the workload for all stakeholders. The cross-curricular project is divided into catalyst screening for the synthesis of hexyl anisole products as part of the Chemical Reactors course (3 ECTS; 36 contact hours) and the subsequent identification and quantification of the product pools in the Applied Instrumental Analysis course (3 ECTS; 36 contact hours) as illustrated in Figure 2. Both courses are instructed in the last semester of the master program of Chemical Engineering Technology at Ghent University. This project builds upon previous courses in the Chemical Engineering Technology education program such as Organic Chemistry (2nd BEng), Physical Chemistry (3rd Beng), Analytical Chemistry (3rd Beng) and Instrumental Analysis (3rd Beng).

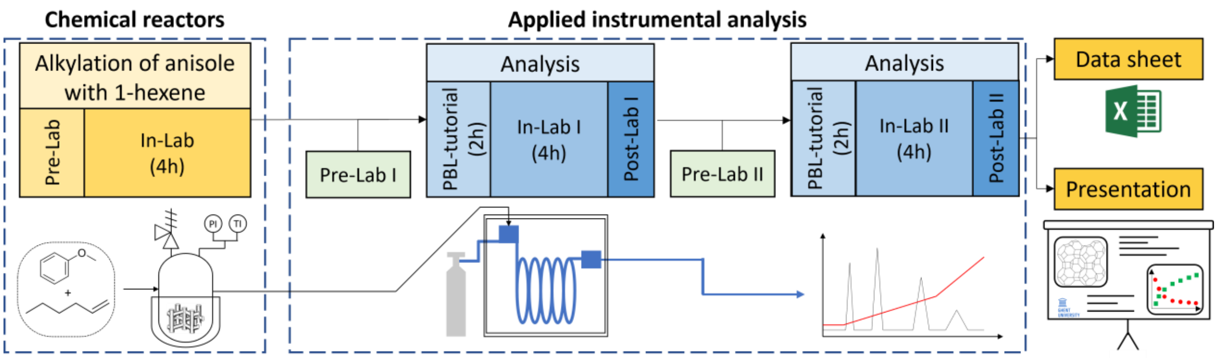

Figure 2 Schematic overview of the open-ended project-based laboratory learning.

A. Catalyst screening – alkylating anisole with 1-hexene

A parallel catalyst screening reactor (fabricated by Amar Equipments, Mumbai, India) equipped with a pressure gauge and 6 individual reactor vessels is used (see Figure 3). Each reactor vessel contains a polytetrafluoroethylene (PTFE) liner, to protect the steel, and a sealing ring to make the setup airtight. An AREX Digital PRO hot plate stirrer with a thermocouple is used to heat up the reactor to the desired reaction temperature. In addition, the reactor is placed under an extraction arm and connected to N_2 gas supply (10 bar).

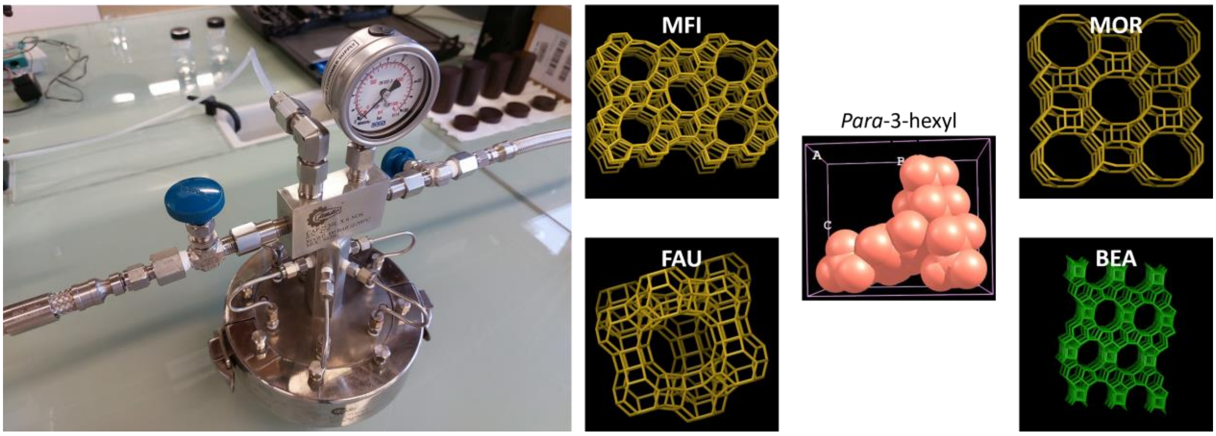

Figure 3 Parallel catalyst screening reactor (left) and structure of para-3-hexyl anisole and the different zeolites (right) with BEA as benchmark.

Students are divided into groups of 4 to 5 people (learning objective 3) and provided with the guidelines and protocol in advance (online) to operate the high-pressure reactor (including the reactor specifications). The protocol includes instructions in order for the students to distribute tasks within the team prior to the lab session (learning objective 3), a simplified P&ID of the reactor setup and several questions at certain steps in the protocol to prepare students to think ahead regarding safety (Pre-Lab – learning objective 1). The students have to make an experimental design, considering 6 reactor vessels (Pre-Lab – learning objective 2), that allows to gain insight in how the zeolite properties affect the reaction in order to select a performant catalyst (based on the available acidic sites, surface area and pore dimensions given to the students in the instruction sheets – see Table 1). For zeolite beta (BEA), literature is available for alkylation of anisole with 1-hexene. Hence, the students can use this zeolite to benchmark their results and critically evaluate available literature [28]. In addition, students are instructed to search for 3D representations of reagents and products to give them preliminary insights in shape selectivity. At the start of the laboratory (In-Lab), the students submit their experimental design which is immediately reviewed by the tutor in terms of the maximum loading volume, the selected types of catalysts and corresponding amounts and whether a blank experiment (without catalyst) is considered (learning objective 2). The students are orally questioned as a group on the rationale for their choices (blank or no blank experiment, which catalysts and the amount,..) as part of the evaluation. After a positive assessment or after some adjustments, students follow the protocol to transfer reagents (anisole, 1-hexene and zeolite) in the reactor vessels and to assemble and pressurize the reactor under permanent supervision. The tutor evaluates their performance (such as safety aspects; are the students aware of the valve positions, do they consider a leak test,.. – learning objective 1) and insights (*e.g.* collaborating, communicating and lab skills – learning objective 3) and questions them orally to evaluate their critical thinking of the steps in the protocol (= Pre-Lab). During the reaction (0.5 hours of heating to the desired reaction temperature and 1.5 hours of reaction at a fixed temperature e.g. 180 °C, which can be varied every year or between student groups) students receive just-in-time information regarding the framework of the zeolites (*i.e.* visualization tool for the channel systems in zeolites) and molecular dimensions of the mono-alkylates (see Figure 3) to further broaden their knowledge and assist them to correlate their findings with the catalyst properties. Additionally, they perform a written examination (± 10 minutes) – during the reaction experiment – to evaluate their Pre-Lab work regarding theoretical aspects (*e.g.* important zeolite properties, the reaction mechanism to turn anisole into a mono-alkylated product and the role of the methoxy group as an *ortho*- and *para*-director). After reaction, the reactor is quenched, depressurized and dismantled according to the guidelines, followed by the sampling and work-up of the reactor effluent. The samples are stored in 20 mL glass vials and analyzed in the subsequent Applied Instrumental Analysis 1st laboratory session of this project.

Table 1 Properties of the different zeolites – searching for a performant catalyst.

Zeolite topology	Acid sites (mol kg^{-1})	Specific surface area (m^2 g^{-1})	Pore dimensions (nm^2)
H-MFI	0.43	425	0.51 X 0.55
H-FAU	0.39	740	0.74 X 0.74
H-BEA	1.25	445	0.66 X 0.67
H-MOR	1.02	455	0.65 X 0.70

B. Product analysis – qualitative and quantitative characterization

In the analytical part of the project, students, initially organized in groups of 4 to 5, are subsequently sub-divided into 2 student teams of 2 to 3 students. Both sub-divided teams separately characterize the identical reactor effluents from the Chemical Reactors laboratory session. In this way, a high level of variation is introduced in the analytical set-up and the experiment is repeated in different ways to determine accuracy. Students are also instructed to apply internal replication and subsampling. In this way students can determine the 3 levels of precision: repeatability, intermediate precision and reproducibility and can validate the analysis method and evaluate their results.

Unlike traditional laboratory instructions, this project provides students only with the projects' objective, learning outcomes, practical guidelines, standard operating protocols and scouting methods. Over the course of two 4h lab sessions, students are tasked with the following objectives: identifying reaction products, quantifying the concentrations of anisole and mono-alkylated hexyl anisole compounds in each reactor vessel (learning objective 6) and evaluating the reliability and reproducibility of their results (as stipulated in learning objective 9).

The primary challenge consists of translating the research questions and hypotheses posed in the project into an experimental setup capable of analyzing the 6 alkylation reactions (cfr. 6 reaction vessels) within the limited timeframe (as outlined in learning objective 4). To accomplish this, students can select two analytical methods from a range of instrumental techniques such as GC (utilizing various columns) coupled with either FID or MS detection, UV-VIS and HPLC (with C18 reversed phase column) with UV detection. Each lab session is preceded by a 2h PBL-tutorial led by a tutor, with a specific focus on the selection of suitable solvents and sample preparation techniques for the chosen analytical method (in accordance with learning objective 5). Students are guided in selecting appropriate methods and drafting their own protocols through a PBL approach (covering learning objective 6).

Students prepare the PBL-tutorials and the associated analytical experiment by completing a three-task Pre-Lab I & II (as depicted in Figure 2). Task 1 involves reviewing prior knowledge and key concepts from Organic Chemistry, Analytical Chemistry and Instrumental Analysis. Task 2 consists of devising an analytical setup for standards and samples, addressing practical considerations such as solubility, solvent choice, working volumes, stock solutions of standards, dilution factors, methods, and detection wavelengths. Task 3 involves identifying and documenting questions and challenges encountered in the Instrumental Analysis course (3rd Beng) or other issues they face. This is schematically visualized in Table 2 This Pre-Lab is submitted as a one-page summary with a detailed scheme of the experimental setup and serves as the entry ticket for PBL-tutorials.

Table 2: Scheme of the three-task Pre-Lab to be submitted by the students.

Task 1: Lessons learned	Task 2: Draft setup	Task 3: Questions/challenges
Regioselectivity in organic chemistry reactions	Choice of dilution factor	Elution order of products?
Choice of gas chromatography column	Choice of solvent	Response of isomers?
Choice of internal standard	Choice of gas chromatography temperature gradient	Solubility of products?
…	…	Di-alkylated anisole?

During the PBL-tutorials, the tutor uses a template to pose a series of preparative questions to students as stepping stones throughout the project. These questions include parameters they need to look up as well as choices to be made (see Table 2). During the PBL-tutorials, students are encouraged to ask questions to fine-tune their experimental set-up and document the final methods and protocols in their Lab Notebook. The tutor uses their expertise to facilitate problem-solving through reflection/evaluation and encourages higher-order thinking by posing questions instead of providing direct answers [29]. The tutor therefore acts as a guide and is responsible that all student groups cover these topics, by using the template as a framework.

Students come to the laboratory with their revised Pre-Lab I notes to perform their planned experiments (In-Lab I) and record their data. The first experiment includes all “wet volumetric work”, including the dilutions of standards and reaction samples, as well as the analysis of reaction samples using a first analysis technique. Subsequently, students perform calculations and graphically process their In-Lab I data at home. Based on these results, they reflect on lessons learned and make adjustments to their experimental setup, deciding on the next steps for In-Lab II. In PBL-tutorial II, students can revise their experimental decisions based on the results obtained with the first analytical technique. The tutor is present to structure knowledge in an accessible and integrated manner, guiding students through questioning until they arrive at a second experimental design according to a repetitive feedback loop: (1) experimental design; (2) executive laboratory course and (3) data analysis. During In-Lab II, students perform their analyses with a second technique, process all results, and make final calculations. All findings are documented with visuals and conclusions in the final Post-Lab data sheet that serves as part of the assessment and evaluation for the Applied Instrumental Analysis course.

As an example of data visualization, Figure 4 shows potential results obtained for the activity and selectivity of mono-hexyl substituted anisole compounds (after the product analysis in the Applied Instrumental Analysis part of the PjBL). The most abundant mono-hexyl anisole alkylates are para-2-hexyl anisole (2-PHA), ortho-2-hexyl anisole (2-OHA) as well as the para- and ortho-3-hexyl anisole (3-PHA and 3-OHA). The results visualized in Figure 4 depend on the amounts of every (type of) catalyst used in the reactor vessels, determined by the students in preparation for the laboratory session. In their Post-Lab presentation, students are expected to discuss the relation between zeolite properties and the results obtained during the In-Lab.

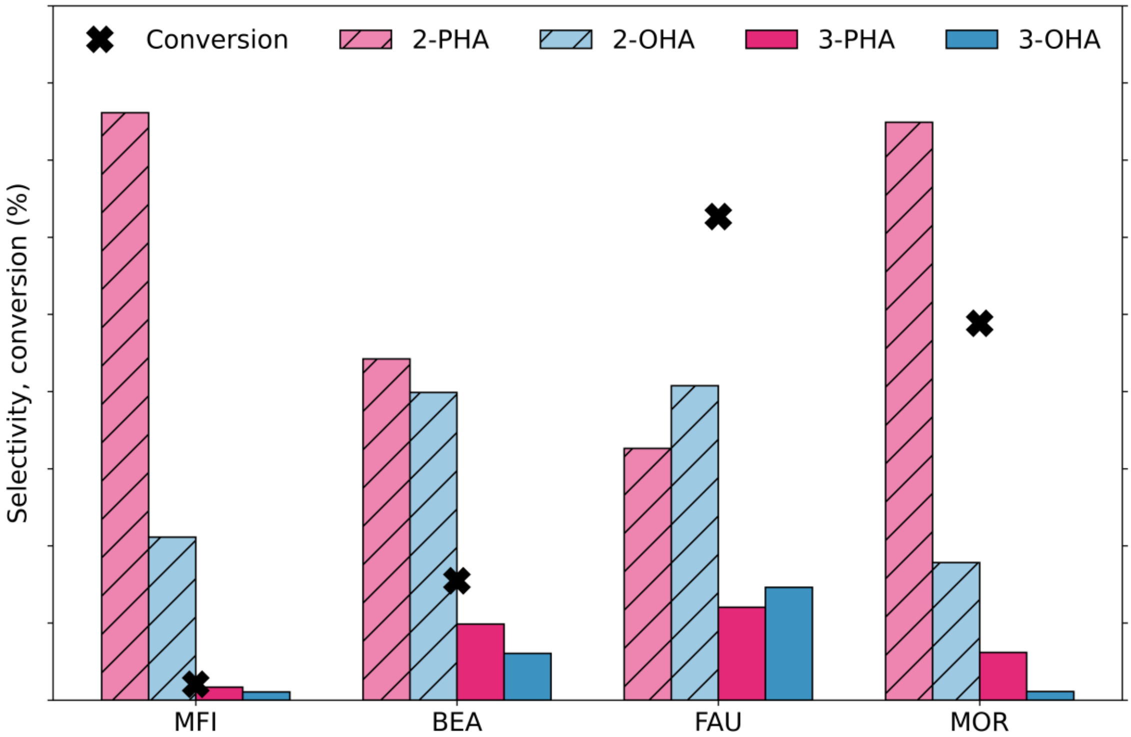

Figure 4 Possible activity and selectivity results obtained by students for the mono-hexyl substituted alkylates for the 4 studied catalysts.

C. Versatile approach

This PjBL approach, intertwined with experimental cycles, provides tutors with a high degree of flexibility, which makes it possible to alter the exact implementation in the curriculum. For example, to have a stronger focus on chemical reactors and catalysis, more laboratory sessions for catalytic anisole conversion could be implemented, e.g. to allow the determination of kinetic parameters. To increase or decrease the focus on the subsequent analyses, the tutors can also encourage students to brainstorm the advantages and disadvantages of gas-phase versus liquid-phase analyses to achieve the desired outcomes, allowing students to experience challenges through trial and error in the laboratory. Alternatively, tutors can guide students towards a specific technique available in their laboratory. There is also the option to provide students with protocols, eliminating the need for analytical decision-making, or to give students a set of results once they have submitted a well-constructed experimental setup (which may be ideal during lockdown periods). Moreover, tutors can adapt the analytical methods and timeframe, compressing or expanding the analysis to 3 or 4 sessions of 2 to 4 hours. This adaptability accommodates changes in the focus and time allocated for analysis from year to year, depending on the number of students, rotation system challenges, or the availability of techniques in the laboratory. The mentioned chromatographic and spectrometric analysis techniques are widely used in both academic and industrial settings. To ensure the effectiveness of this approach, a judicious selection of techniques is paramount, such as the choice between gas and liquid chromatography, or the use of gas chromatography with two different detection methods. Ultimately, the tutor can opt to introduce these degrees of freedom which allows validation of the analysis techniques and evaluation of the results.

4. Performance-based and survey-based assessment

A. Performance-based assessment

In line with the chosen teaching methods and PjBL approach, a joint evaluation moment is chosen in the form of a 10-minute presentation followed by a 10-minute oral questioning. This reduces the workload for all stakeholders. In the presentation, the students have to relate their results with the zeolite properties. Prior to the presentation, each group has already submitted an elaborate spreadsheet with the raw and processed data, calculations, visual representations, a one-paragraph discussion of the experiment and a conclusion for each research goal. This final evaluation allows a critical assessment of their findings and their catalytic screening experimental design choice. In addition, both courses individually evaluate how well students prepared the In-Lab and how they handled the project during the In-Lab.

For the Chemical Reactors course, the final score is based on (1) lab practices (/20) and (2) the final presentation (/50). Lab practices scores are divided into attitude (/10) and a written examination (/10). The laboratory attitude and participation (learning objectives 1 to 3) behavior of students is evaluated by how well each student knows the hazards and properly takes the correct safety precautions, the oral questions that examine the preparation and insights of the students and finally the laboratory skills and how students communicate and cooperate during the laboratory session. During the written examination, the students are individually questioned on the theoretical aspects of their laboratory work. In short, the Pre-Lab is assessed theoretically through the written test, and how well their practical exercise is prepared, whilst the performance of the exercise is evaluated In-Lab; the lab practices thus refer to the combination of Pre- and In-Lab. In the final presentation and oral interrogation, objectives 7 to 9 are assessed for every group as a whole. The questions challenge the students' critical thinking and confront them with their choices they made throughout the project. When students reflect and evaluate their own work, this is taken into account in their evaluation. Figure 5 (left) shows the score distributions of the different laboratory exercises in the Chemical Reactors course (resp. the alkylation of anisole (A) and two other classical exercises, i.e. reaction kinetics (B) and chemical equilibrium (C)). For the alkylation of anisole project, the mean and median are 13.5 out of 20 and are both higher compared to the other laboratory exercises.

For the Applied Instrumental Analysis course, the scores are based on the assessment of the Pre-Labs (/20) and the Post-Lab data sheet (/20). The Pre-Lab score is based on the submitted Pre-Labs with the three tasks mentioned in Table 2 (objectives 4 to 6). During the oral presentation, one specific analytical question is asked to assess analytical knowledge and immediate feedback is given on the submitted data sheet. For both assessments, a rubric with open comments is used. Figure 5 (right) shows the score distributions of the different laboratory exercises in the Applied Instrumental Analysis course (resp. the alkylation of anisole (D) and two other exercises, i.e. soil analysis (E) and characterization of lean black liquor (F)). For the alkylation of anisole project, the median of 13.2 is highest compared to the other laboratory exercises and the distribution shows a high number of students with a score of 12, 14 and 15 while the other laboratory exercises have a more disperse distribution (E) or higher number of students with lower scores (F). Although the laboratory exercises of two courses are coupled, the number of students following both courses is not always identical. In this context, the flexibility in this project is a major advantage. When more students follow the chemical reactor course, we provide them the analytical results and they process the data themselves to obtain the activity/selectivity of the different zeolites. Vice versa, we provide the students who follow only the Applied Instrumental Analysis course, 6 reaction samples from other student groups and they characterize these samples in the two laboratory sessions.

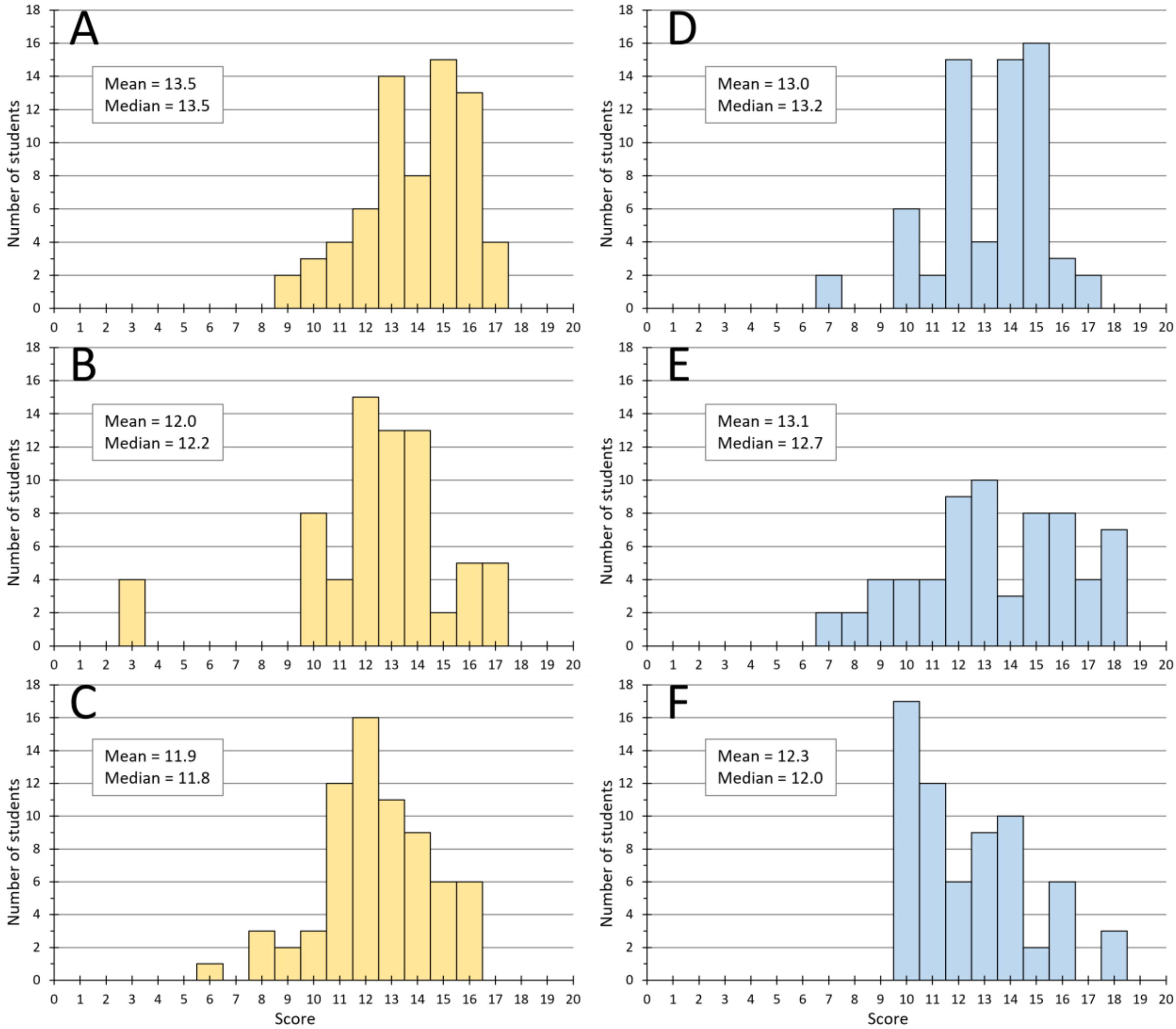

Figure 5 Score distributions of the Chemical Reactors (left - 69 students) and Applied Instrumental Analysis (right – 65 students) laboratory exercises of AY 2021 – 2022 and 2022 – 2023 combined. (A = anisole alkylation; B = kinetics; C = equilibrium; D = anisole alkylation; E = soil analysis; F = lean black liquor analysis).

In conclusion, for both courses, the cross-curricular project covering the alkylation of anisole leads to high mean and median values in combination with a high number of students obtaining higher scores, which could be related to the students viewing these laboratory sessions as more valuable and challenging compared to standalone laboratory exercises (viz. survey-based assessment).

B. Survey-based assessment

Feedback of the students was obtained via an anonymous and non-obligatory survey. 69 students (81% male; 19% female) over the academic years 2021 – 2022 and 2022 – 2023 responded. The survey consists of three parts, each assessing a specific stage in the project. The 1st part relates to the efficiency and added value of the PjBL approach. The 2nd part involves assessing the innovativeness of the Chemical Reactor course regarding the use of zeolites, handling the high-pressure reactor and safety aspects that are taken into consideration during the laboratory session. Finally, the 3rd part evaluates what stage of the project students consider to be the most helpful/educational in the Applied Instrumental Analysis exercise since students were able to engage with challenges, data and tutors at different stages/levels.

Table 3 clearly confirms the benefits of the cross-curriculum project over standalone laboratory exercises by the students (83%) with the majority of the participants indicating an improved multi-disciplinary thinking and obtaining new insights (78%). In the educational program, courses often cross at a theoretical level while laboratory exercises in the bachelor are in a standalone format for the students to grasp the principles. Therefore, it is important for students to be able to benefit from an interdisciplinary approach at a practical level as well, as proposed in this work. Coupling the practical exercises has allowed students to solve authentic problems as a team, which is essential in PjBL [30]. The chemical analysis is performed on reaction products they obtained and is crucial to obtain insights into their catalytic experiment. The high student appreciation of the coupled exercises is therefore likely related to the PjBL approach. The evaluation (= Post-Lab) as a final (10 minutes) presentation followed by a 10-minute oral questioning was initiated to reduce the workload for all stakeholders and to improve the oral presentation skills of the students. The teaching staff and the majority of the students (65%) favor this presentation to increase time efficiency.

Table 3 Added value and efficiency of the PjBL - Survey 2021 - 2023

	Percentage of students who agreed with the statement (%)
Coupling two courses resulted in added value compared to standalone laboratory exercises.	83
Coupling both courses resulted in inter-disciplinary thinking and/or new insights.	78
A pitch presentation instead of a lab report improved time efficiency.	65

The 2nd part of the survey involves the innovativeness of the Chemical Reactors session (Table 4). Students evaluated the use and principles of zeolites as catalysts in chemical reactions as primary innovative (87%). During their study program, students come into limited contact with heterogeneous catalysts in comparison with homogeneous catalysts. Therefore, zeolites are a rather under explored type of catalyst in the educational program. The safety aspects of a reactor were evaluated as low innovative (25%). This low evaluation score can be attributed to the fact that students are introduced to the safety aspects in the Chemical Reactors laboratory session while the 2 subsequent Applied Instrumental Analysis laboratory sessions do not involve reactor handling. Additionally, the oral presentation and questioning focuses more on the results (*i.e.* conversions, selectivities, mapping the effect of zeolite properties…) rather than the safety aspects of the reactor in the laboratory. The majority of the students (55%) indicate they found it inspiring and renewing to handle a high-pressure reactor in the laboratory sessions to get a better understanding of it.

Table 4 'What did you find innovative or did you remember from the Chemical Reactors laboratory session' – Survey 2021 - 2023

	Percentage of students who agreed with the statement (%)
Use and principles of zeolites as heterogeneous catalysts in chemical reactions.	87
Use of a high-pressure batch reactor (assembly, reactor loading, pressurization, disassembly)	55
Safety aspects of a high-pressure batch reactor	25

The 3rd part of the survey evaluates the stages that were offered to the students to learn the objectives as part of the Applied Instrumental Analysis laboratory exercises (Table 5). Rather similar values are obtained for the different stages indicating they were all valuable. The PBL-tutorials are ranked highly important by students (63%) in order to help finish the project successfully, which is likely related to the PjBL approach, where teamwork and participation in search for answers to the research questions is enabled [31]. More than 50% of the students indicate that they learned the dedicated objectives while the experiment is performed (56%) or during the processing of the results (56%). The preparation prior to the PBL-tutorials and laboratory exercises is regarded as the least valuable by the students (41%), which can be caused by the independence they faced in the initial stage whereby the PBL-tutorials were of excellent help.

Table 5 'Which parts of the project helped you the most to successfully finish the Applied Instrumental Analysis laboratory -)sessions' – Survey 2021 - 2023

	Percentage of students who agreed with the statement (%)
PBL-tutorials	63
While the experiment was conducted	56
During the processing of the results	56
Contact moments with the tutor	54
Preparation prior to the PBL-tutorials and laboratory sessions	41

In addition to the survey, students were allowed to bring forward positive and negative aspects anonymously. In conclusion, students mentioned two points of attention limits in their view of the project. (1) One of the constraints is the mandatory order of the cross-curricular project. Therefore, it is important to avoid scheduling of the three laboratory sessions with a gap of several weeks in between them. Especially when teaching large groups of students, careful planning should proceed the start of the project. (2) In the Applied Instrumental Analysis course, groups from the Chemical Reactors course are split in two in order to let all students interact with the equipment. However, this results in a final presentation at the end of the semester with 4 – 5 students and two different datasets. It was observed during the oral presentations and the survey that students find it challenging to properly handle two datasets regarding the same experiments but with different results. However, this challenge is part of the interdisciplinary project regarding ethical data management.

5. Conclusion

This work presents a novel cross-curricular PjBL trajectory for chemical engineering technology students. In this project, the students are first tasked with the alkylation of anisole with 1-hexene as a team, utilizing industrially relevant zeolite catalysts. In here, students consider several variables to develop a design of experiments to obtain as much knowledge as possible regarding the effect of different zeolite structures on the conversion and selectivities. Within the first part of the project, the students' knowledge building is performed gradually, through enabling just-in-time information such as the molecular dimensions of the alkylated products and 3D visualization of the zeolites which becomes available during the catalytic experiment. This information is processed then and linked to the results obtained in the Applied Instrumental Analysis laboratory sessions. In the latter, the students analyze the complex product pool through multiple analytical methods and they evaluate the results with the reaction conditions (*i.e.* choice and amount of catalyst). The second part of the project allows students to critically assess the process of obtaining analytical results for the Chemical Reactors experiment.

Coupling the Chemical Reactors laboratory session with the instrumental analysis of the reactor effluent enables interdisciplinary thinking, allows for more insights and is considered by students as more valuable compared to standalone laboratory exercises. Furthermore, presenting the results in an oral presentation instead of a written report has allowed for a more time-efficient evaluation and feedback procedure for both the students and the tutors.

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References

[1] Z. Ma, F. Zaera, Heterogeneous Catalysis by Metals, Encyclopedia of Inorganic Chemistry2005.

[2] J.C. Ganley, A heterogeneous chemical reactor analysis and design laboratory: The kinetics of ammonia decomposition, Education for Chemical Engineers, 21 (2017) 11-16.

[3] V. Cybulskis, A. Smeltz, Y. Zvinevich, R. Gounder, W.N. Delgass, F. Ribeiro, Learning the fundamentals of kinetics and reaction engineering with the catalytic oxidation of methane, Chemical Engineering Education, 50 (2016) 202-210.

[4] M. Zhang, C. Newton, J. Grove, M. Pritzker, M. Ioannidis, Design and assessment of a hybrid chemical engineering laboratory course with the incorporation of student-centred experiential learning, Education for Chemical Engineers, 30 (2020) 1-8.

[5] T. Gomez-del Rio, J. Rodriguez, Design and assessment of a project-based learning in a laboratory for integrating knowledge and improving engineering design skills, Education for Chemical Engineers, 40 (2022) 17-28.

[6] A. Aranzabal, E. Epelde, M. Artetxe, Team formation on the basis of Belbin's roles to enhance students' performance in project based learning, Education for Chemical Engineers, 38 (2022) 22-37.

[7] M. Hernáiz-Pérez, J. Álvarez-Hornos, J.D. Badia, J.B. Giménez, Á. Robles, V. Ruano, P. San-Valero, Contextualized project-based learning for training chemical engineers in graphic expression, Education for Chemical Engineers, 34 (2021) 57-67.

[8] J. Naukkarinen, T. Sainio, Supporting student learning of chemical reaction engineering using a socially scaffolded virtual laboratory concept, Education for Chemical Engineers, 22 (2018) 61-68.

[9] S. Herrmann, D. Felder, M. Padligur, S. Brosch, M. Geiger, F. Stockmeier, K. Baitalow, D. Rall, R. Femmer, F. Roghmans, M. Hauser, J. Mehlis, J. Linkhorst, M. Wessling, Hands-on kinetic measurements and simulation for chemical process engineering students, Education for Chemical Engineers, 41 (2022) 14-21.

[10] M.D. Koretsky, An interactive virtual laboratory addressing student difficulty in differentiating between chemical reaction kinetics and equilibrium, Computer Applications in Engineering Education, 28 (2020) 105-116.

[11] T. Bligaard, R.M. Bullock, C.T. Campbell, J.G. Chen, B.C. Gates, R.J. Gorte, C.W. Jones, W.D. Jones, J.R. Kitchin, S.L. Scott, Toward Benchmarking in Catalysis Science: Best Practices, Challenges, and Opportunities, ACS Catalysis, 6 (2016) 2590-2602.

[12] J. Čejka, R.E. Morris, D.P. Serrano, Catalysis on Zeolites – Catalysis Science & Technology, Catal Sci Technol, 6 (2016) 2465-2466.

[13] W. Vermeiren, J.P. Gilson, Impact of Zeolites on the Petroleum and Petrochemical Industry, Top Catal, 52 (2009) 1131-1161.

[14] A.A. Vasconcelos, T. Len, A.d.N. de Oliveira, A.A.F.d. Costa, A.R.d.S. Souza, C.E.F.d. Costa, R. Luque, G.N.d. Rocha Filho, R.C.R. Noronha, L.A.S.d. Nascimento, Zeolites: A Theoretical and Practical Approach with Uses in (Bio)Chemical Processes, Applied Sciences, 13 (2023) 1897.

[15] J. Wang, J. Wu, X. Luo, X. Han, H. Tian, R. Su, Hands-On Approach to Structure Activity Relationships of Substituted MIL-101(Fe)-X Nanozymes: Synthesis, Characterization, and Hammett Analysis, Journal of Chemical Education, 100 (2023) 2755-2761.

[16] A. de Reviere, T. Vandevyvere, M. Sabbe, A. Verberckmoes, Renewable Butene Production through Dehydration Reactions over Nano-HZSM-5/γ-Al2O3 Hybrid Catalysts, Catalysts, 10 (2020) 879.

[17] A. de Reviere, D. Gunst, M. Sabbe, A. Verberckmoes, Sustainable short-chain olefin production through simultaneous dehydration of mixtures of 1-butanol and ethanol over HZSM-5 and γ-Al2O3, Journal of Industrial and Engineering Chemistry, 89 (2020) 257-272.

[18] A. de Reviere, D. Gunst, M.K. Sabbe, M.-F. Reyniers, A. Verberckmoes, Dehydration of butanol towards butenes over MFI, FAU and MOR: influence of zeolite topology, Catal Sci Technol, (2021).

[19] M.J. Zhang, E. Croiset, M. Ioannidis, Constructivist-based experiential learning: A case study of student-centered and design-centric unit operation distillation laboratory, Education for Chemical Engineers, 41 (2022) 22-31.

[20] D. Kokotsaki, V. Menzies, A. Wiggins, Project-based learning: A review of the literature, Improving Schools, 19 (2016) 267-277.
[21] W. Zhang, J. Zheng, J. Wang, J. Dong, Y. Cheng, Design and implementation of the interdisciplinary curriculum for intelligent chemical engineering program at Taiyuan University of Technology, Education for Chemical Engineers, 42 (2023) 1-6.
[22] C. Baerlocher, L.B. McCusker, Database of Zeolite Structures, International Zeolite Association.
[23] F.L. Vallera, Durkheim Said What?: Creating Talking Textbooks With Augmented Reality and Project-Based Activities, Journal of Research on Technology in Education, 51 (2019) 290-310.
[24] C.M. Friend, B. Xu, Heterogeneous Catalysis: A Central Science for a Sustainable Future, Accounts Chem Res, 50 (2017) 517-521.
[25] P. Sudarsanam, R. Zhong, S. Van den Bosch, S.M. Coman, V.I. Parvulescu, B.F. Sels, Functionalised heterogeneous catalysts for sustainable biomass valorisation, Chemical Society Reviews, 47 (2018) 8349-8402.
[26] B. Jacobs, Y. Yao, I. Van Nieuwenhove, D. Sharma, G.-J. Graulus, K. Bernaerts, A. Verberckmoes, Sustainable lignin modifications and processing methods: green chemistry as the way forward, Green Chemistry, 25 (2023) 2042-2086.
[27] L. Kester, P.A. Kirschner, J.J.G. van Merriënboer, Just-in-time information presentation: Improving learning a troubleshooting skill, Contemporary Educational Psychology, 31 (2006) 167-185.
[28] P.V. Surse, S. Wagholikar, S. Mayadevi, S. Sivasanker, Alkylation of anisole with 1-hexene and 1-hexanol over zeolite H-beta, Reaction Kinetics, Mechanisms and Catalysis, 103 (2011) 481-491.
[29] R.L. Miller, J.F. Ely, R.M. Baldwin, B.M. Olds, Higher-order thinking in the unit operations laboratory, Chemical engineering education, 32 (1998) 146-151.
[30] P.C. Blumenfeld, E. Soloway, R.W. Marx, J.S. Krajcik, M. Guzdial, A. Palincsar, Motivating Project-Based Learning: Sustaining the Doing, Supporting the Learning, Educational Psychologist, 26 (1991) 369-398.
[31] J.S. Krajcik, N. Shin, Project-Based Learning, in: R.K. Sawyer (Ed.) The Cambridge Handbook of the Learning Sciences, Cambridge University Press, Cambridge, 2014, pp. 275-297.