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# Enhancing Problem-Solving and Critical Thinking in Chemical Engineering Education: Implementing Open-Ended Laboratories in Organic Chemistry and Analytical Lab

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ABSTRACT

*This study explores the impact of Open-Ended Laboratories (OEL) on enhancing problem-solving and critical thinking skills among second-year Chemical Process Engineering undergraduates at MJIIT, Universiti Teknologi Malaysia. A mixed-method approach was employed, combining quantitative data from a structured Likert-scale questionnaire and qualitative feedback from student reflections and instructor observations. The survey comprised of seven key items, assessed cognitive, psychomotor, and affective domains aligned with the course learning outcomes (CLOs). Descriptive statistical analysis revealed high levels of agreement across all dimensions, with mean scores ranging from 4.13 to 4.38 (on a 5-point scales) and standard deviations between 0.96 and 1.17, indicating positive student perceptions toward problem identification, theoretical application, and collaboration. Further analysis incorporating Cohen's d and partial $\eta^2$ demonstrated moderate-to-large effect sizes ($d = 0.0232–0.2732$; $\eta^2 = 0.0115–0.1202$), confirming significant learning gains, particularly in CLO2 and CLO4. Qualitative findings corroborated the quantitative outcomes, with students reporting improved experimental design skills, increased independence, and greater confidence in navigating complex engineering tasks. Comparisons with global OEL initiatives underscore the international relevance of the findings, with performance improvements aligning with reported global deltas of 0.4 standard deviations in problem-solving and engagement metrics. This study supports the integration of OEL in engineering curricula to foster higher-order thinking, teamwork, and self-directed learning, as advocated by Malaysia's MySTIE 10-10 Framework and SDG4/SDG9 imperatives. The findings offer empirical evidence to guide broader adoption of OEL pedagogies in outcome-based engineering education frameworks.*

*Keywords: Open-ended labs; chemical engineering students; critical thinking and problem-solving skills*

## INTRODUCTION

Laboratory-based education is fundamental in chemical engineering, serving as a bridge between theoretical concept and practical application. Traditional laboratories in engineering education have long been structured around well-defined procedures and experiments, with students typically following step-by-step instructions to achieve predetermined outcomes in ensuring the reinforcement of core technical skills. (Felder and Silverman 1988). While this approach is effective in reinforcing fundamental concepts, it often limits the opportunities for students to develop essential competencies such as problem-solving and critical-thinking skills, which are essential and increasingly demanded in modern engineering practices (Prince and Felder 2006). In response to these educational challenges, the Engineering Accreditation Council (EAC) Malaysia has emphasized the need for engineering programmes to cultivate higher-order cognitive skills through Outcome-Based Education (OBE) frameworks. A well-structured curriculum is essential for ensuring the long-term sustainability of a course by aligning the contents of syllabus with the assessment methods with the standards set by the Engineering Accreditation Council (EAC) and the Washington Accord, thereby meeting accreditation requirements and industry expectations.

The research reported that passive learning environments such as traditional laboratory settings, often fail to engage students in higher-order thinking and decision-making, which are critical for real-world engineering challenges (Hmelo-Silver et al. 2007). To address these limitations, open-ended laboratories (OEL) have emerged as an innovative teaching methodology that shifts the focus from instructor-led experiments to student-driven investigations. Globally, engineering education research has documented benefits of transitioning from traditional, structured-based laboratories to openended and inquirybased formats. Chiu and Chiu (2004) revealed that an openended laboratory system could enhances student engagement and laboratory competency over traditional methods. In addition, Prince and Felder (2006) provide a comprehensive review of inductive teaching approaches, noting that inquirybased and studentcantered methods, such as openended laboratory activities are generally more effective than the traditional instruction for achieving a broad range of learning outcomes in engineering contexts. Additional empirical work shows that incorporating openended design experiences into engineering laboratories can increase student engagement, competence, and application of theoretical knowledge compared to nonopenended formats (Cullin et al. 2017).

In open-ended laboratories (OEL), problems presented to students allow for multiple solutions and diverse problem-solving methods, encouraging them to identify the most suitable theoretical concepts for practical implementation (Primer 2006; Land 2000). This approach makes laboratory courses more engaging and exploratory, as students take initiative and apply creativity in designing their own experiments (Chiu & Chiu, 2004). In addition, the self-directed nature of OEL enhances students' learning ability (Berg et al. 2003), creativity (Chiu & Chiu 2004), self-confidence (Brickman 2009), and exposure to the real-world engineering challenges (Domin 2007). Due to these benefits, OEL is broadly adopted across scientific discipline, mainly engineering field where experimental work aligns with open-ended problem-solving scenarios (Domin 2007; Caccavo 2011; Norliza et al. 2010; Tsarpalis & Gorezi 2005).

In fact, by fostering authentic learning skills, OEL significantly contribute to the development of problem-solving and critical thinking skills in the chemical engineering education, as it provides multi -dimensions of real-world engineering challenges to the students (Wright 1996). Through OEL practice, students have a freedom to design and implement the experiment, thus encouraging innovation, creativity, and deeper understanding of engineering principles that learnt through lecture session (Kolodner et al. 2003). In fact, self-guided experimentation through OEL provides students with the ability in analyzing complex problem, exploring multiple and innovative solutions, and perform well-informed decisions, that are essential competencies in engineering practices; thereby preparing them for real-world engineering problem-solving (Jonassen 2011).

According to the Engineering Accreditation Council and Board of Engineers Malaysia (2024), ensuring high-quality engineering program requires providing students with adequate exposure to the lab work and professional engineering practice. The lab work exercise shall be open-ended to allow students applying related engineering theory in practical settings while addressing relevant Course Learning Outcomes (CLOs) and Program Learning Outcomes (PLOs). Subsequently, this OEL exercises not only reinforce theoretical knowledge but also enhance the practical competence, problem-solving and critical thinking skills, as well as build up confidence level in performing complex engineering challenges. To achieve these educational objectives, the laboratory assessment should integrate both theory and practice comprising all three domains of Bloom's Taxonomy which are cognitive (critical thinking and analytical skills), psychomotor (hands-on experimentation and practical skills), and affective (teamworking skill, communication skill, and professional ethics) (Ali et al. 2014; Narita et al. 2014). It is recommended that students work in team of no more than five members for each group, to ensure effective collaboration and participation.

The level of openness in laboratory activities (0, 1, 2, 3) is determined by the course instructors in ensuring students to progressively transition towards greater independence and complexity in designing experimental work (Ali et al. 2016). This structured approach enables students to gradually develop higher-order thinking abilities and become more proficient in addressing the challenges relating with chemical engineering problems.

In Chemical Process Engineering curriculum at Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia (UTM), the organic chemistry and analytical laboratory is a compulsory lab course offers for the second-year undergraduate students. This course is well designed to integrate outcome-based education (OBE), open-ended laboratory (OEL), and complex engineering problem-solving, that aligning with the Engineering Accreditation Council (EAC) Malaysia standards. The course structure and assessment framework are meticulously developed to enhance problem-solving abilities, critical thinking abilities, and teamworking skills through practical laboratory work.

This course introduces student with the basic experimental techniques including recrystallization, extraction, separation, reflux, and distillation, with an emphasis on microscale laboratory approaches to illustrate green chemistry practices. The practicality of this course combines the guided and open-ended laboratory approaches that enabling students to build up hands-on lab skills while nurturing the analytical reasoning and independent problem-solving as well as critical thinking skills. The students are expected to propose, design, execute, and analyze experiment that provide them with an opportunity to synthesize knowledge and validate the result based on scientific theories. The integration of OEL practice with active learning strategies including project-based learning, complex engineering activities, and peer assessment which further strengthens students' ability to handle real-world chemical engineering challenges.

The Course Learning Outcomes (CLOs) for organic chemistry and analytical laboratory course are strategically affiliate to the programme learning outcomes (PLOs) underlined by EAC to ensure the students foster essential engineering competencies. These include:

1. CLO1 (PLO1: Engineering Knowledge): Understanding the concepts and methods used for the experimental work
2. CLO2 (PLO2: Problem-Solving Skills): Critically analysing the experimental data and relevant theories involved based on the learning in class
3. CLO3 (PLO8: Professional Ethics): Demonstrating good laboratory ethics during laboratory experiment session
4. CLO4 (PLO10: Teamworking): Adopting team working throughout the experiment session

This study explores the execution of OEL in the organic chemistry and analytical lab course that emphasis on its impact on problem-solving abilities, analytical thinking, and the capability of associating the relevant the theoretical knowledge to practical experimentation. Through the OEL frameworks, the students are actively contributed in designing and executing experiments such as Isolation of Pigments and Sublimation, offering exploratory learning and independent decision making. By working in a small and adequate 3-4 students, the learners collaborate on designing the methodologies, collecting results, predicting and interpreting experimental outcomes, and communicating scientific finding effectively by bridging to the relevant fundamental theories learnt during lecture session. Figure 1 exhibits the overall process of OEL implementation exercise adopted for the second-year of undergraduate chemical process engineering 2023/2024 cohort at MJIIT UTM.

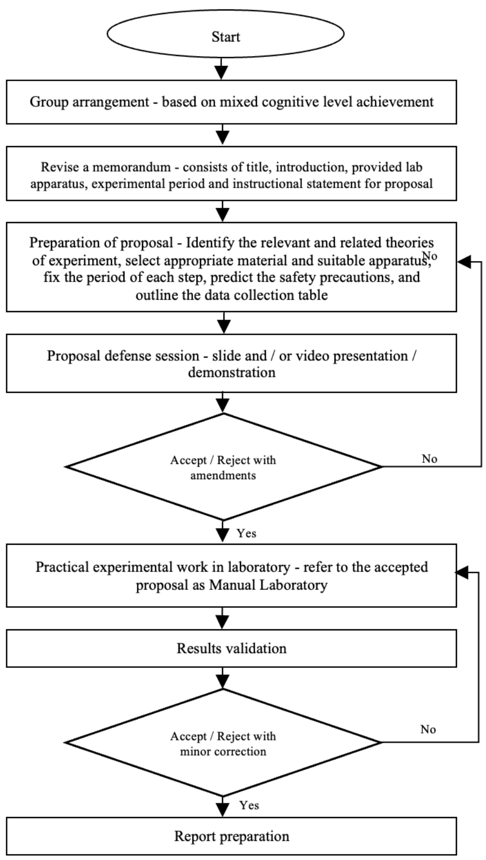


FIGURE 1. OEL Implementation Exercise for Analytical and Organic Chemistry lab-based course

According to Figure 1, OEL implementation exercise requires about four weeks completion that comprises of four stages including the introductory, proposal preparation and defense session, laboratory experimental work (practical duty), result validation and report preparation. The experimental work and result validation stages are conducted alternately to ensure students have adequate period to achieve the necessary results within this stipulated session. The students are advised to design the experimental work within the maximum period of 2.5 hours to prevent overlimit of laboratory usage. All the guidelines are presented in the form of memorandum that address the title, introduction of experiment, lab equipment and apparatus provided in laboratory, experimental period and necessary instructions that shall be noted in preparing proposal. A memorandum signified the necessary elements for both OEL-based experiments are indicated in Figure 2 and Figure 3, respectively.

**SMJC2701 (Organic Chemistry & Analytical Laboratory)**

**Open-Ended Laboratory 1 (OEL-1)**

**Experiment 2: Isolation of Pigments from Plant Leaves**

Dear Students,

Chromatography is one of the laboratory techniques for the separation of a mixture to its components. It is not just used for analysis but also for purification purposes. The target substances are mixed and dissolved in gas or liquid called a mobile phase, and carried to a separation system called a stationary phase. Then, the substances are separated based on their properties, such as molecular mass, chemical characteristics, etc. during passing through the system. Therefore, there are various types of chromatographies according to the types of the mobile phase, the stationary phase, the separation system and the principle of separation, as well as the detection methods and the total system of equipment.

In this OEL investigation, you are expected to separate photosynthetic pigments from plants by Thin Layer Chromatography (TLC) using a silica gel plate. The pigments, particularly chlorophylls, show the diversity and the evolution of photosynthetic organisms. We can check it using reachable plants around us. You are needed to identify the pigments from its color and Retention Factor (Rf) values. The chemicals, equipment and manual of apparatus will be supplied by the Course Coordinator/Lecturer. The plants materials should be prepared by yourself (group work) under your own cost. Any additional items (except those provided) used should be also under your own cost and responsibilities.

For the initial stage, you are required to prepare a proposal on conducting the experiment by selecting two (2) reachable source of pigments (plants). The selected plants should theoretically result to different color and Rf values. This separation procedure should be carried out in maximum 2.5 hours. The expected outcomes should state the important data such as the color of pigments and orders on the chromatogram. A complete group proposal shall comprises the procedures with related safety precautions, data collection table, expected observation and/or conclusion. The proposal must be presented during proposal defense session to ensure the proposed procedures are manageable and can be achieved within the timeframe.

For the information, the procedures of this experiment will involve organic-type chemicals. Therefore, all the SAFETY PRECAUTIONS relatable to organic type of substances should be listed in the proposal properly and thoroughly. Then, the experimental work will be arranged a week after proposal defense session and an individual report should be submitted a week after conducting experimental works and hand-written.

We wish you all the best and Good Luck!

Dr. Nabilah Zaini
Dr. Eleen Dayana Mohamed Isa

FIGURE 2. A memorandum for experiment entitled 'Isolation of Pigment

**SMJC2701 (Organic Chemistry & Analytical Laboratory)**

**Open-Ended Laboratory 2 (OEL-2)**

**Experiment 3: Sublimation**

Dear Students,

Sublimation is a purification technique, in which a solid is directly converted to vapor phase without passing through liquid phase. However, the compound must have a relatively high vapor pressure, and the impurities must have significantly lower vapor pressures. By heating, the solid will be vaporized and become solid again when the vapor contacts with the cold surface. Several compounds will sublime when heating under reduced pressure. Based on the basic understanding learnt in Organic Chemistry Class, you are required to practice the technique for purifying and crystalizing a selected material via sublimation process. The melting point of the crystal is required to confirm the properties of two (2) selected materials. In this experiment, you are required to prepare the materials under your own cost. If it requires some pre-treatments, you can do it during laboratory session.

In order to perform this task, you will be equipped with a set of small lab kit that containing the common glasswares such as filtering flask, capillary tubes, suction flask, round bottom neck etc. (refer to Figure 1). A complete manual guideline that states the components in the small lab kits, experimental apparatus setup, sequence procedures and precautions should be taken is provided. You are required to give priority to the components available in this small lab kits. Any additional apparatus or equipments or items should be based on the approval made by Course Lecturer (s) and under your own cost and responsibilities.

For the initial stage, you are required to prepare a proposal on conducting the sublimation experiment by selecting the appropriate materials and the pre-treatment process. This sublimation procedure is advised to be carried out in maximum 2.5 hours. The expected outcomes should state the important data such as appearances before and after, temperature at sublime, melting point and all these data shall be recorded properly and structurally in data collection table. A complete proposal consists of procedures with related safety precautions, data collection table, expected observation and/or conclusion and present in week 9. Everyone in a group shall actively take part during the proposal defense session. All the comments as well as advises gained during proposal defense session shall be considered to improvise the proposal and will be submitted after experimental completed in Week 10.

For the information, the procedure in conducting this experiment might involves high temperatures (more than 100 °C). Hence, all the SAFETY PRECAUTIONS must be listed in the proposal carefully. You are advised to include the safety precaution steps for each main procedures from setup of apparatus until the cleaning up step to ensure every student is particular on the relatable safety precautions. The individual report is expected for submission in Week 11 as mentioned in the course planning.

We wish you all the best and Good Luck!

Dr. Nabilah Zaini & Dr. Eleen Dayana Mohamed Isa

FIGURE 3. A memorandum for experiment entitled 'Sublimation'

There are three types of the assessment used as a guideline which are group proposal assessment, individual report assessment, as well as peer assessment method that need to be submitted a week after the practical experimental work stage ends.

This course is promoting an innovation in teaching and learning laboratory based course through OEL implementation approaches by shifting from traditional structured laboratory to the student-driven investigation, where learners employ chemical engineering principles to elucidate the real world problems. In point of fact, this research paper evaluates how OEL approach enriches the cognitive, psychomotor, and affective learning domains of the students in ensuring they inculcate problem-solving, critical thinking and teamworking skills that will be required for their future and brighter careers in this chemical engineering field.

This memorandum provides an insightful and important guidelines for students in structuring their proposal apart of ensuring all experimental activities could be finished within the stipulated period.

## METHODOLOGY

### OPEN-ENDED LABORATORIES (OEL)

The methodology for this study is designed to assess the effectiveness of open-ended lab (OEL) in the organic chemistry and analytical lab course by integrating both quantitative and qualitative analysis comprehensively. The study evaluates effectiveness of OEL in enhancing students' problem-solving and critical thinking abilities, teamworking skill as well as practical applications of theoretical knowledge. This research framework embraces the experimental design, data collection through questionnaires, and analysis of both quantitative and qualitative data.

## RESEARCH DESIGN

This study adopts a mixed-method approach, incorporating both quantitative analysis (statistical data analysis) and qualitative analysis (feedback and reflections of students).

## PARTICIPANTS

This study covers second-year undergraduate students enrolled in organic chemistry and analytical lab course at Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia. The sample consists of students from two cohorts:

1. Pre-OEL Cohort (2019/2020) - Students who underwent a traditional laboratory approach
2. Post-OEL Cohort (2023/2024) - Students who had experienced open-ended laboratory (OEL) framework

## RESEARCH VARIABLES

The study evaluates the impact of OEL based on the following variables:

1. Independent Variable: An implementation of open-ended laboratory (OEL)
2. Dependent Variable: Cognitive Learning Outcomes (critical thinking and analytical skills), psychomotor skills (hands-on experimentation and practical skills), and affective skills (teamworking skill, communication skill, and professional ethics)

## DATA COLLECTION METHODS

To evaluate the impacts of OEL, this study employs two data collection methods:

1. Quantitative Data Collection
2. Qualitative Data Collection

## QUANTITATIVE DATA COLLECTION

A structured questionnaire using a likert scale (1 - Strongly Disagree to 5 - Strongly Agree) is being administered to measure the students' perceptions of OEL effectiveness. The questionnaire is designed to measure the achievement level of following skills:

1. Problem-Solving and Critical Thinking Skills
2. Application of Engineering Knowledge
3. Practical and Technical Skills
4. Teamworking and Communication Skills
5. Student Engagement and Learning Experience

The questions address the achievement skills of students based on their OEL learning experiences are indicated in Table 1. All questions are structured to measure the perceptions of students on how OEL exercise affects their ability in analyzing problems, applying theoretical knowledge, freely designing an experiment, critically and logically think of relevant theories, collaboratively communicating with peers, and nurturing confidence in independent learning.

TABLE 1. Questions based on the measured individual achievement skills

| Achievement Skills | Question |
|---|---|
| Problem-Solving and Critical Thinking Skills | Q1: The OEL approach enhanced my ability to identify and analyze the experimental problems and determine the appropriate approach for conducting the Sublimation and Isolation of Pigments experiments. |
| | Q4: The OEL format encouraged me to enhance my skill to critically evaluate data, troubleshoot errors, and modify experimental procedures when necessary. |
| Application of Engineering Knowledge | Q2: The OEL experiments helped me bridge the gap between theoretical concepts and their practical applications in chemical engineering. |
| Practical and Technical Skills | Q3: I was able to design and plan the experiments effectively, allowing for better decision-making and adaptation during laboratory work. |

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| | |
|---|---|
| Teamwork and Communication Skills | Q5: The teamwork fostered in the OEL sessions enhanced my skills in discussing, defending, and refining experimental strategies with my peers. |
| Student Engagement and Learning Experience | Q6: The open-ended nature of the experiments boosted my confidence in conducting independent research and applying engineering problem-solving techniques effectively. |
| | Q7: The OEL approach significantly enhanced my problem-solving and critical-thinking skills compared to traditional structured labs. |

## QUALITATIVE DATA COLLECTION

Apart of Likert scale questionnaire, open-ended questions are included to capture perspectives of students on OEL implementation exercise. These questions assess learning experiences, challenges, as well as suggestions for improvement as indicated in Table 2.

TABLE 2. Question based on the measured students' perspectives

| Students' Perspectives | Question |
|---|---|
| Challenge | Q1: What were the most challenging aspects of designing and conducting the OEL experiments (Sublimation and Isolation of Pigments), and how did you address these challenges? |
| Learning experiences | Q2: In what ways did the OEL approach enhance your problem-solving and critical-thinking skills compared to traditional lab sessions? |
| Suggestions for improvement | Q3: What improvements would you suggest to further enhance the OEL learning experience in Organic Chemistry and Analytical Lab (SMJC2701)? |

## DATA ANALYSIS METHODS

There are two (2) analysis methods analyzed:

1. Quantitative data analysis
2. Qualitative data analysis'

## QUANTITATIVE DATA ANALYSIS

The descriptive statistics (mean and standard deviation) are being used to analyze the responses of students to Likert-scale questionnaire item. Apart of that, a comparative analysis is conducted between pre-OEL (2019/2020) and post-OEL (2023/2024) cohorts using i-OBE system developed by Universiti Teknologi Malaysia (UTM) to determine significant differences in students' learning outcomes.

## QUALITATIVE DATA ANALYSIS

Thematic analysis is being carried out on the OEL responses to identify the recurring themes that related to problem-solving skills, experimental work challenges, and student engagement. As part of the qualitative component of this study, the instructor's feedback was collected to gain deeper insights on the implementation and effectiveness of OEL approach in SMJC 2701. The semi-structured reflections were obtained from instructors who facilitated the course, focussing on the observations regarding engineering knowledge, problem-solving development, students' participation, and adaptability to open-ended format.

This methodology provides a structured and comprehensive framework in order to evaluate the effectiveness of the open-ended laboratory exercise implementation in chemical engineering education. by employing both quantitative and qualitative data approaches, this study targets to capture the learning experiences of the involved students holistically, in ensuring evidence-based improvements in lab-based instruction at MJIIT UTM.

## RESULTS AND DISCUSSION

### CLO AND PLO ACHIEVEMENT

The comparison of results achieved by students from two (2) cohorts represented before and after the OEL exercise that mapping the PLO correlation to CLO are graphically showed in Figure 4 and Figure 5, respectively.

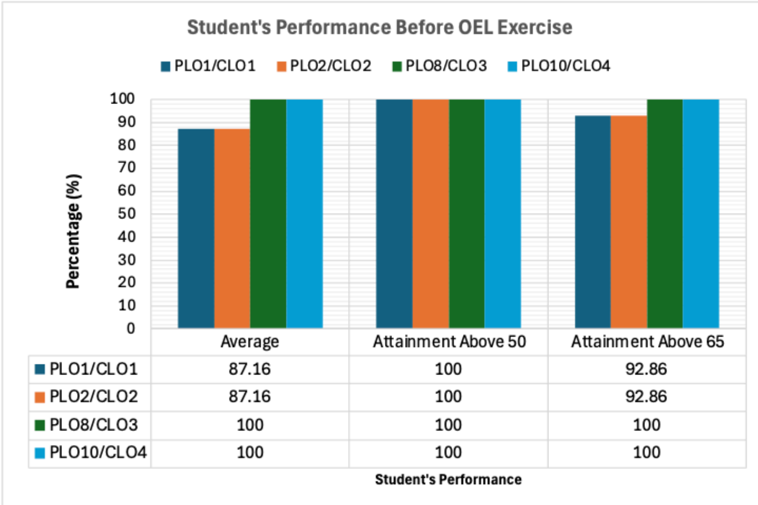


FIGURE 4. Student's achievement before OEL exercise

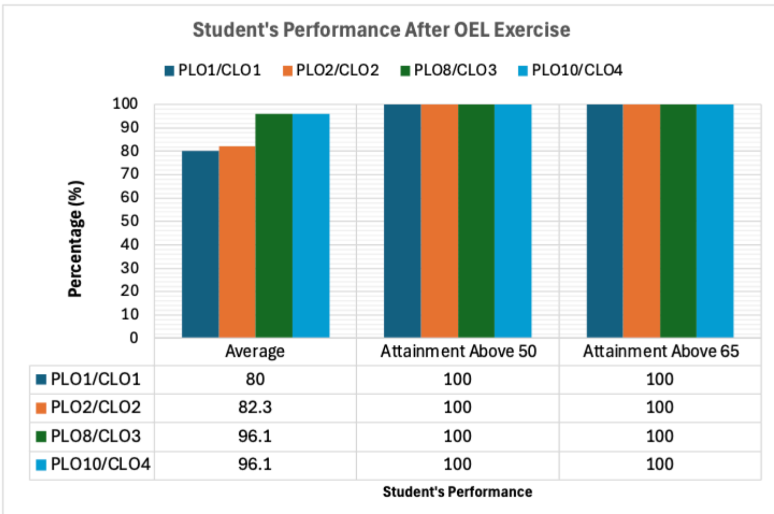


FIGURE 5. Student's achievement after OEL exercise

The comparative analysis presented in Figures 4 and illustrates students' performance before and after the implementation of Open-Ended Laboratory (OEL) exercise in Organic Chemistry and Analytical Lab (SMJC2701). Before OEL implementation (2019/2020 cohort), students showed high performance, with average attainment scores for CLOs ranging from 87.16% to 100%. Following the introduction of OEL in the 2023/2024 academic session, students maintained consistently strong performance, particularly in CLO3 (ethics) and CLO4 (teamworking), both achieving an impressive average of 96.1%. These findings affirm the literature that open-ended laboratories effectively foster teamworking skills, ethical conduct, and communication skills (Freeman et al. 2014).

However, slight variations were noted in CLO1 (engineering knowledge) and CLO2 (problem-solving skills), where the average attainment scores marginally decreased from 87.16% before OEL to around 80.0%–82.3% for post-OEL exercise. Such observation indicates natural initial challenge when students transition from structured lab (guided-lab) to more autonomous formats which was open-ended formats. Literature has recognized that students may initially face difficulty adapting to self-directed experimental designs, which require additional cognitive effort and independence (Hmelo-Silver et al. 2007). Despite these minor differences, all students consistently exceeded 65% attainment after participating in OEL exercise, suggesting successful achievement of critical thinking and complex problem-solving outcomes that is corresponding to the targets underlined by Engineering Accreditation Council (EAC) standards.

Overall, the results substantiate the pedagogical value of OEL by demonstrating improvements or consistent attainment across various outcomes, aligning strongly with the literature advocating active learning strategies to promote deeper conceptual understanding and problem-solving skills (Jonassen, 2011). The data clearly indicates that OEL implementation at MJIIT positively influences students' cognitive and practical competencies, essential in preparing future chemical engineers.

## QUANTITATIVE DATA ANALYSIS

The descriptive statistics for each questionnaire item including the mean and standard deviation are presented in Table 3. These results provide insights into students' perceptions of open-ended laboratory (OEL) experience and its impact on their learning outcomes.

TABLE 3. Descriptive statistics of students' perception of OEL exercise

| Question | Focus Question | Mean | Standard Deviation | Interpretation |
|---|---|---|---|---|
| Q1: The OEL approach enhanced my ability to identify and analyze the experimental problems and determine the appropriate approach for conducting the Sublimation and Isolation of Pigments experiments. | Problem Identification & Analysis | 4.19 | 1.05 | High Agreement |
| Q2: The OEL experiments helped me bridge the gap between theoretical concepts and their practical applications in chemical engineering. | Application of Theoretical Knowledge | 4.31 | 1.01 | High Agreement |
| Q3: I was able to design and plan the experiments effectively, allowing for better decision-making and adaptation during laboratory work. | Experimental Design & Execution | 4.13 | 0.96 | High Agreement |
| Q4: The OEL format encouraged me to enhance my skill to critically evaluate data, troubleshoot errors, and modify experimental procedures when necessary. | Critical Thinking Development | 4.38 | 1.02 | High Agreement |
| Q5: The teamwork fostered in the OEL sessions enhanced my skills in discussing, defending, and refining experimental strategies with my peers. | Collaboration & Communication | 4.19 | 1.17 | High Agreement |
| Q6: The open-ended nature of the experiments boosted my confidence in conducting independent research and applying engineering problem-solving techniques effectively. | Confidence in Independent Learning | 4.13 | 1.02 | High Agreement |
| Q7: The OEL approach significantly enhanced my problem-solving and critical-thinking skills compared to traditional structured labs. | Overall Effectiveness of OEL in Learning | 4.25 | 1.00 | High Agreement |

The bar chart (Figure 6) shows students' Likert-scale responses towards 7 key items evaluating their experience in SMJC 2701 Organic Chemistry and Analytical Lab, a course implementing Open-Ended Laboratory (OEL) exercises. Each bar reflecting the mean agreement score on a 5-point Likert scale (1 = Strongly Disagree; 5 = Strongly Agree), while error bars representing the standard deviation that indicate the variation in responses.

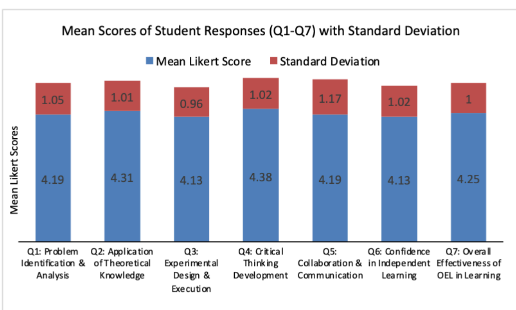


FIGURE. 6. Students' Likert-scale responses on 7 key items reflecting their perspectives on OEL exercise

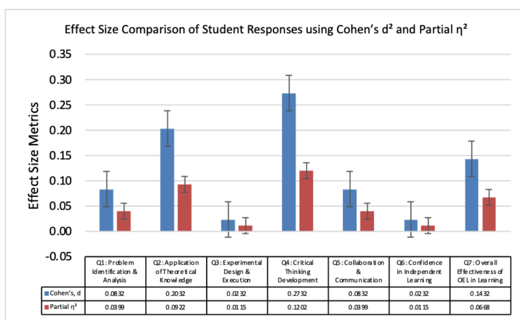


FIGURE. 7. Effect size comparison of Student Responses using Cohen's $d^2$ and partial $\eta^2$ following the implementation of Open-Ended Laboratory

Based on the descriptive statistics of students' perception of OEL exercise, all items scored exceed 4.0 that indicating a strong positive perception (high agreement) of the OEL approach for all dimensions (focus). The highest mean (4.38) was observed for Critical Thinking Development (Q4), that supports the literature that OEL promotes the enhancement of higher-order thinking skills amongst undergraduate Chemical Engineering students. The gained standard deviation falls in between 0.96 to 1.17 implying the moderate variation, typically for subjective learning experiences such as team-based and self-confidence settings. This data supports the arguments that OEL enhances multiple domains of student learning such as cognitive outcomes (problem-solving and critical thinking skills), psychomotor outcomes (hands-on experimental skills) and affective outcomes (team-working skill, communication skill, and professional ethics) which are the core elements to the Outcome-Based Education (OBE) and the EAC Accreditation standards. The extensive discussions for each key items are summarized in Table 4.

To evaluate the magnitude of learning gained, Cohen's $d^2$ and partial $\eta^2$ values are computed for each question (Q1-Q7). As indicated in Figure 7, the largest Cohen's $d^2$ is observed for Q4: Critical Thinking Development ($d^2 = 0.2732$) and Q2: Application of Theoretical Knowledge ($d^2 = 0.2032$), confirming that OEL significantly impacts these learning domains. The corresponding partial $\eta^2$ values further support this trend, with Q4 ($\eta^2 = 0.1202$) and Q2 ($\eta^2 = 0.0922$) indicating medium-to-large effect sizes by social science standards.

In contrast, relatively smaller effect sizes are recorded for Q3: Experimental Design & Execution and Q6: Confidence in Independent Learning, with Cohen's $d^2 = 0.0232$ and partial $\eta^2 = 0.0115$, highlighting areas where instructional design or student support might be improved.

TABLE 4. Extensive discussion on the respective key items of students' perception of OEL exercise

| Question | Discussions |
|---|---|
| Q1: The OEL approach enhanced my ability to identify and analyze the experimental problems and determine the appropriate approach for conducting the Sublimation and Isolation of Pigments experiments. | Students reported strong confidence in recognizing and framing chemical engineering problems. This aligns with the emphasis on independent analysis in OEL, where learners face non-routine tasks requiring analytical strategies (Jonassen, 2011). |
| Q2: The OEL experiments helped me bridge the gap between theoretical concepts and their practical applications in chemical engineering. | This reflects students' ability to bridge theory from lectures with practical lab work, affirming that OEL encourages deep learning and theory-practice integration (Freeman et al. 2014). |
| Q3: I was able to design and plan the experiments effectively, allowing for better decision-making and adaptation during laboratory work. | Slightly lower variation suggests students felt consistent competency in designing and executing their own experiments, a hallmark of inquiry-based and constructivist lab models (Kolodner et al. 2003). |
| Q4: The OEL format encouraged me to enhance my skill to critically evaluate data, troubleshoot errors, and modify experimental procedures when necessary. | The highest mean score reinforces literature that OEL enhances higher-order thinking and metacognitive engagement (Hmelo-Silver et al. 2007). Students likely experienced cognitive challenges that deepened conceptual understanding. |
| Q5: The teamwork fostered in the OEL sessions enhanced my skills in discussing, defending, and refining experimental strategies with my peers. | A slightly higher SD suggests varied group experiences. Nonetheless, collaborative problem-solving is central to OEL, improving soft skills essential to engineering practice (Chiu & Chiu, 2004; Narita et al. 2014). |
| Q6: The open-ended nature of the experiments boosted my confidence in conducting independent research and applying engineering problem-solving techniques effectively. | This demonstrates the success of OEL in fostering student autonomy and learner ownership. Students developed resilience in handling open-ended tasks, consistent with findings by Berg et al. (2003). |
| Q7: The OEL approach significantly enhanced my problem-solving and critical-thinking skills compared to traditional structured labs. | This confirms that students perceive OEL as a valuable learning approach that prepares them for real-world engineering problems—supported by the Engineering Accreditation Council (EAC, 2024) and Washington Accord principles on complex problem-solving and lifelong learning. |

## QUALITATIVE DATA ANALYSIS

### THEMATIC ANALYSIS OF OPEN-ENDED RESPONSES

The thematic analysis of Open-Ended Responses is considered to analyse the reflective assessment of the students experienced with OEL exercise. All the responses gained from 16 students that experienced OEL exercise are categorized into the specified four (4) thematic categories which extensively described as follow.

1. Emergent Theme 1: *Enhanced Problem-Solving and Critical-Thinking Abilities*

   Students have expressed that designing and conducting their own experiments under the OEL framework improved their problem-solving skills. One student noted, "The open-ended nature of the labs challenged me to think critically and develop my own approaches to experiments". In addition, a positive feedback reveals that "Overall, OEL exercise improved my ability to assess challenges critically, and develop effective strategies".

2. Emergent Theme 2: *Increased Engagement and Motivation*

   Many students reported that the autonomy provided by OEL increased their interest and motivation. A participant mentioned, "Being able to design our experiments made the lab sessions more engaging and enjoyable".

3. Emergent Theme 3: *Development of Teamwork Skills*

   The collaborative aspect of OEL was highlighted as a positive experience. Students appreciated working in teams, stating that it enhanced their communication and collaborative problem-solving abilities.

4. Emergent Theme 4: *Application of Theoretical Knowledge*

   Students felt that OEL allowed them to apply classroom knowledge to real-world scenarios, deepening their understanding of chemical engineering concepts. One student responded that " The OEL approach requiring me to apply theory to real-world challenges, make quick decisions, analyse results deeply, and adapt to different methods of handling materials". One respondent revealed that "OEL emphasizes solving real-world problems rather than just following predefined experiment, encouraging deeper understanding and adaptability".

Based on these collective feedbacks, it is proven that most of the students that experienced with OEL exercise received positive and encouraging learning environment in expanding their self-potential and the abilities to design, analyse and evaluate.

## INSTRUCTOR FEEDBACK

The instructor observed that students in the post-OEL cohort have demonstrated greater initiative and creativity in their experimental designs. They also noted that OEL exercise provides opportunity to the students to improve collaboration and engagement to the higher level during the laboratory sessions.

The integration of Open-Ended Lab (OEL) into SMJC 2701 course has generally yielded significant improvements in various student learning outcomes. The quantitative data collected indicates substantial enhancements in the problem-solving and critical-thinking abilities, engagement and motivation level, development of teamwork skills, and applications of theoretical engineering knowledge. These outcomes corroborated with the qualitative feedback collected from students and instructors that highlighting the multi-faceted benefits of OEL exercises amongst the chemical engineering undergraduate students.

## ALIGNMENT WITH EXISTING LITERATURES

The positive outcomes observed in this study are consistent with existing research on the benefits of open-ended and problem-based learning approaches in engineering education. For instance:

1. Development of Critical Thinking: The past studies by Hesser, T. & R. Bunyea, S. (2016) have demonstrated that open-ended problem-solving with structured teamwork enhances critical thinking and communication skills in chemical engineering students.
2. Improved Engagement: Research by Martin, M. (2019) indicates that problem-based learning methods, similar to OEL, lead to increased student engagement and motivation.
3. Enhanced Practical Skills: Rajesh et. al. (2013) revealed that the shift formats from the traditional

to open-ended lab (OEL) has associated with improvements in students' practical and experimental skills.

## IMPLICATIONS FOR CURRICULUM DEVELOPMENT:

The successful implementation of OEL in SMJC 2701 course suggests that incorporating open-ended, student-centered learning approach is significantly enhance the educational experience in the Chemical Engineering Programme. This aligns with the goals of Outcome-Based Education (OBE) frameworks, that emphasize the development of problem-solving, critical thinking, and teamworking skills.

As future practices, it is recommended to provide appropriate scaffolding support to assist the students navigate the challenges of OEL experimentation. To promote effective OEL implementation, providing a training for instructors in facilitating OEL is crucial. Finally, implementing continuous and formative assessment methods provide timely feedback to the student that further enhance their learning outcomes and experience on OEL implementation exercise.

## CONCLUSION

The implementation of open-ended laboratories (OELs) in the Organic Chemistry and Analytical Lab course demonstrated a significant positive impact on student learning outcomes across multiple dimensions. Quantitative data collected through a structured Likert-scale questionnaire revealed high levels of student agreement (mean scores ranging from 4.12 to 4.38 with standard deviations between 0.96 and 1.17) across seven key competencies: problem identification, theoretical application, experimental design, critical thinking, collaboration, independent learning, and overall effectiveness. Effect size analysis further supported these findings, with Cohen's d and partial $\eta^2$ values indicating moderate to strong practical significance in learning gains.

Complementing these results, qualitative feedback from students and instructor reflections highlighted increased engagement, ownership of learning, and enhanced collaboration during the OEL implementation. Students appreciated the opportunity to propose hypotheses, design their own procedures, and troubleshoot real experimental challenges, leading to deeper conceptual understanding and improved soft skills. The open-ended structure also aligned well with Bloom's three learning domains, fostering cognitive, psychomotor, and affective development.

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## DECLARATION OF COMPETING INTEREST

None.

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