RiCE: Research in Chemical Engineering
Volume 5. No 1, 2026
Journal homepage: https://ejournal.ump.ac.id/index.php/rice

Project-Based Learning Approach for Teaching Life Cycle Assessment in an Industrial Pollution Control Engineering Master's Program

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Article Info

Submited:
21 December 2025

Revised:
20 January 2026

Accepted:
20 January 2026

ABSTRACT

Addressing the complex challenges of climate change requires analytical tools that enables evaluation of the environmental performance of industrial activities. Life Cycle Assessment (LCA) has emerged as one such key tool, providing a science-based framework to quantify environmental impacts across product and process life cycles. In Indonesia, LCA has gained increasing attention through policy initiatives such as the Ministry of Environment's PROPER program, which mandates LCA assessments for certain performance ratings. To address the growing demand for LCA applications, higher education must ensure that graduates possess adequate methodological understanding and practical skills to apply LCA effectively in real-world contexts. This study evaluates the effectiveness of teaching LCA through a project-based learning (PBL) framework in the Industrial Pollution Control Engineering Master's Program at Universitas Gadjah Mada (UGM). Survey data from three student cohorts (2023–2025) were used to assess students' perceived learning outcomes, learning experiences, challenges, and post-course application of LCA. The results show that students developed strong conceptual understanding and practical competence in LCA, with high satisfaction regarding theory–practice alignment and instructor feedback. However, several challenges were identified, particularly regarding the transition from simplified exercises to more complex, data-intensive case studies, especially related to software use and inventory development. Importantly, large number of students reported continued interest or intended use of LCA in their academic or professional activities after completing the course. Overall, the findings indicate that a project-based learning approach effectively supports the development of applied LCA competencies and promote sustained participants' engagement with life cycle thinking.

Keywords: Climate Change, Life Cycle Assessment, Project-Based Learning, Industrial Pollution Control Engineering, Learning Outcomes.

1. INTRODUCTION

The Climate change has emerged as one of the most complex and urgent global challenges of the 21st century, driven by accelerated industrialization, resource depletion, and unsustainable consumption patterns [1], [2]. To effectively address these challenges, it is critical to employ robust analytical tools capable of assessing the environmental impacts of products, processes, and services throughout their entire life cycle. Among such tools, Life Cycle Assessment (LCA) has become widely recognized for its comprehensive and systematic approach, enabling quantification of environmental impacts from raw material extraction to end-of-life treatment, therefore enabling policy makers to formulate long-term strategic decisions for environmental sustainability improvement [3]. The cradle-tograve perspectives and science-based framework that LCA offers in supporting decision-making toward sustainability, resource efficiency, and climate change mitigation are the qualities increasingly demanded by industry, policymakers, and society [4], [5].

As global interest in environmental accountability and circular economies intensifies, the role of LCA as a decision-support and design tool continues to expand across sectors. As one of the fastest-growing economies with diverse industrial sectors that heavily rely on natural resource utilization and exert substantial environmental pressures [6], [7], Indonesia urgently requires robust environmental assessment tools such as LCA to facilitate smooth transition to sustainable development especially to achieve Net Zero Emission (NZE) target as well as Enhanced Nationally Determined Contribution (NDC) agenda. In their review, Wiloso et al. [8] identified 107 peer-reviewed LCA studies conducted in or by Indonesian institutions over the past two decades. The number of publications has increased markedly since 2010, which shows rising awareness but still modest engagement with life cycle thinking across academia, research institutions, and industry.

In recent years, the use of LCA has also been strengthened through policy instruments such as the PROPER (*The Public Disclosure Program for Environmental Compliance*), administered by the Ministry of Environment (KLH) [9]. Since 2021, PROPER has formally required companies seeking the highest ratings ("Green" and "Gold") to conduct robust LCAs, verified by certified LCA practitioners in Indonesia [10], [11]. This integration of LCA into PROPER reflects the government's commitment to show evidence-based environmental management and provides strong momentum for industries to adopt life-cycle approaches. Furthermore, the number of Environmental Product Declaration (EPD) Type 3 documents from Indonesian companies also show an increasing trend as a result of the implementation of PROPER program. Despite these advances, challenges remain—particularly the limited availability of localized life-cycle inventory data and the need for broader educational programs to train competent LCA practitioners [8]. These developments collectively emphasize that strengthening LCA education in higher education is critical to support Indonesia's transition toward sustainable and low-carbon industrial practices.

Higher education plays a pivotal role in this capacity building to solve the complex climate and environmental issues. Teaching LCA in university curricula equips future engineers and environmental professionals with the conceptual understanding and practical skills necessary for sustainability assessment and life cycle thinking. However, achieving these competencies requires not only the inclusion of sustainability content but also the adoption of pedagogical strategies that encourage active, reflective, and self-directed learning. Conventional lecture-based approaches, while effective for delivering theoretical knowledge, may offer limited opportunities for students to develop higher-order thinking and problem-solving abilities relevant to real-world environmental challenges. Consequently, educational reform in engineering and environmental programs has increasingly shifted toward more interactive and learner-centered models that emphasize engagement, collaboration, and critical inquiry as integral components of the learning process [12], [13], [14].

In this context, Student-Centered Learning (SCL) has gained prominence as a pedagogical paradigm that shifts the focus from teacher transmission to active student participation and autonomy in the learning process. SCL emphasizes inquiry, collaboration, and reflection, allowing learners to construct knowledge through authentic experiences rather than passive reception [15], [16]. In engineering and sustainability education, SCL approaches have been shown to enhance critical thinking, problem-solving, and motivation by positioning students as active participants in addressing real-world challenges [17], [18]. Within this framework, Project-Based Learning (PBL) represents one of the most effective implementations of SCL, as it provides a structured environment where students apply theoretical concepts to practical problems, work collaboratively, and reflect on their learning outcomes [19], [20].

Yet empirical evidence on the effectiveness of LCA education remains sparse. Some programs have only recently incorporated LCA into their courses, often on a voluntary basis, and few require it as part of core curricula [21], [22]. Where LCA is taught, the pedagogical approach significantly influences learning outcomes: active and experiential methods, such as project-based learning (PBL), have shown promise in fostering deeper understanding and practical competence [21], [23]

In response to the urgent need to solve the complex and emerging environmental issues by the industrial process, the Department of Chemical Engineering, Universitas Gadjah Mada (UGM), launched Industrial Pollution Control Engineering Master's Program in 2022. This new master's program adopts a pollution-prevention perspective, emphasizing upstream strategies to mitigate environmental impact rather than solely relying on end-of-pipe controls. A cornerstone of this curriculum is the LCA course, designed to combine theoretical foundations with hands-on analytical practices, using open-source software (openLCA) and real-world case studies. Recognizing the methodological complexity of LCA, the program maintains small class sizes to ensure individualized mentoring and thorough guidance.

The LCA course follows a project-based learning (PBL) framework (Figure 1), where students progress from conceptual understanding of LCA principles to practical application through case studies, modelling, and reporting. This pedagogical design aims to bridge the gap between theoretical knowledge and real-world practice, nurturing both analytical competence and sustainability mindset. Given the recent establishment of the program and the emerging status of LCA adoption in Indonesia, it is essential to evaluate the effectiveness of this educational initiative at its early stage to determine whether it achieves its learning objectives, to identify challenges, and to inform future curriculum development. Moreover, to the best of authors' knowledge, no prior study has systematically evaluated the implementation or outcomes of an LCA course at the higher education level in Indonesia. This limited body of evidence highlights the need to document and assess early pedagogical experiences to support the growing integration of life cycle thinking into engineering and sustainability education in Indonesia.

To fill this research gap, this study investigates the learning outcomes, student experiences, encountered challenges, and post-course application intentions associated with the LCA course at UGM. Specifically, the paper addresses the following research questions: (1) How do students perceive their learning outcomes and experiences from the project-based LCA course?; (2) What are the principal challenges encountered by students during the course?; and (3) to what extent do students intend to apply (or have already applied) the acquired LCA knowledge and skills in their academic or professional contexts? By addressing these research questions, this study provides empirical insights into the early implementation of LCA education within a sustainability-oriented engineering curriculum in Indonesia and contributes to ongoing efforts to strengthen capacity building for sustainable industrial development.

2. MATERIALS AND METHODS

2.1 Course Design

The Life Cycle Assessment (LCA) course in the Industrial Pollution Control Engineering Master's Program at Chemical Engineering Department, UGM, is designed using a project-based learning (PBL) framework that emphasizes the integration of theoretical foundations with hands-on analytical and practical skills of using LCA software. The intended learning outcomes of this course are to ensure that students acquire a solid understanding of core LCA concepts, are able to independently construct life cycle inventories, perform life cycle impact assessment and result interpretation, and effectively apply LCA tools in real-world contexts. The overall structure combines lectures, guided exercises, software-based modelling, and project-based case studies to gradually build students' competencies in performing full LCA studies. The learning sequence follows a learning progression from knowledge acquisition to application, aligning with the "learning-by-doing" approach inspired by Cosme et al. [24].

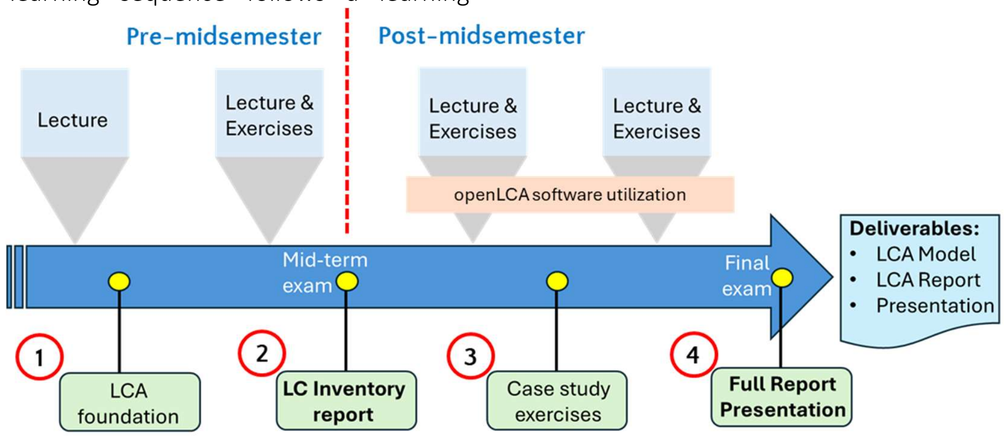

Figure 1. Life Cycle Assessment (LCA) Course Design in Industrial Pollution Control Master's Program, Chemical Engineering Department, UGM, partly inspired by the "learning-by-doing" approach on LCA teaching by Cosme et al. [24].

The pre-midsemester part focuses on the fundamentals of LCA lessons, including the theoretical part of the LCA steps from Goal and Scope, Life Cycle Inventory (LCI), Impact Assessment, and Interpretation (Figure 1). One part of the LCA steps that become the spotlight for the pre-midsemester lesson is the building of life cycle inventory database. Here, the students were given assignments on a specific LCA topic from scientific papers or The Hitch Hiker's Guide to LCA book's case studies [25]. The students develop the Goal and Scope as well as build the LCI data using case on those case studies and later submit it as a report and present it in an oral mid-term exam, where the students receive feedback from the lecturers.

The post-midsemester phase focuses on deepening students' analytical skills through complementary case studies and advanced hands-on exercises using openLCA software. These case studies comprise of contemporary topics in LCA of chemicals, biomaterials, waste management, food systems and electromobility. The purpose of these case-based LCA materials after the mid-term is to stimulate higher-order problem-solving skills, encourage critical interpretation of results, and expose students to current methodological variations in LCA (e.g., alternative waste modelling approaches and combined nutritional quality–environmental assessments of food systems). Guest lectures from experienced LCA practitioners are also included to provide professional context and expose students to real-world challenges and expectations.

The course culminates in two final deliverables: a full LCA report and an oral exam through a presentation session in which students justify their methodological choices, interpret their results, and reflect on data limitations. Throughout the course, regular consultation and feedback sessions support students' progress and allow instructors to guide methodological decisions, troubleshoot software use, and assess draft versions of students' LCA models. This structure ensures that students not only acquire conceptual understanding but also develop practical competence in conducting LCA studies from start to finish.

2.2 Survey Methodology

To collect students' experience and feedback from this LCA course, we conducted survey in November 2025 through an online method as many participants of this course have been graduated or left the campus. In total, the survey consists of 24 questions, divided into five categories. The first category is a general part, where students' undergraduate backgrounds and previous LCA experience were asked. The second category consists of questions on learning outcomes. They are predominantly 5-point Likert scale questions [26] and cover the skills they obtained after taking the LCA course based on students' perspectives, including the goal and scope, inventory, impact assessment, interpretation, and the confidence on using the LCA software (openLCA). This part also asked the students whether they encounter technical difficulties that may hamper their learning in this course.

Meanwhile, the third category of the questionnaire was about the course design and learning experience. Again, this part was dominated by 5-point Likert scale and cover the students' evaluation on the project-based learning (PBL) approach adopted in the course, the most interesting part of course case studies, the feedback by the lecturers during the lecture and oral exams, and the alignment between the fundamental theory with the practical or course project parts. In the fourth category, students were asked about the challenges encountered during the course and the post-course plan on using LCA through multiple response (select-all-that-apply) items. The students were also asked about the overall satisfaction of the course, on a 5-point Likert scale. Finally, the last category of questions asked open feedback by the students, exploring the most useful aspects of this course and suggestions for the future.

3. RESULTS AND DISCUSSION

Since the establishment of Industrial Pollution Control Master's Program at Chemical Engineering Department of UGM in 2022, fifteen students have taken this LCA course, including one Doctoral student from the Environmental Science Program. Table 1 shows the respondent's profile who took the LCA course at Industrial Pollution Control Master Program. Thirteen of them respond to the survey, yielding a high response rate of 87%, which is considered satisfactory for pedagogical evaluation studies. As this LCA course was only offered once per academic year, it has been conducted three times to date (2023–2025), with student enrolment distributed relatively evenly across those cohorts (Table 1). Regarding the academic background, most respondents hold undergraduate degrees in Chemical Engineering (30.8%), followed by Chemistry (23.1%) and Environmental Engineering (or related major) (15.4%). This distribution suggests that the program attracts students either continuing along a chemical engineering pathway or transitioning from other science and engineering fields with an interest in environmental sustainability.

A notable finding from the survey is the lack of prior LCA experience before taking this course (61.5%). This is consistent with the authors' general observation that LCA is rarely taught at the undergraduate level in Indonesia, and students often encounter a deeper methodology and case studies on LCA for the first time in graduate programs. Around 23% of students have read materials related to LCA and only one student (7.7%) had ever worked with LCA project before. Despite this limited prior experience, the academic backgrounds of the respondents (primarily in chemical and environmental engineering) are well aligned with the analytical and system-thinking competencies required for mastering LCA. To assess students' perceptions of their learning outcomes and course experience, multiple questions involving five-point Likert scale were asked in the survey. To describe the results, a diverging bar chart based on five-point Likert scale was visualized (Figure 2). Overall, the general responses were strongly positive, with mean scores ranging from 4.23 to 4.85 across all evaluated aspects. The highest-rated items were Understanding LCA concepts and Understanding system boundaries (both 4.85), indicating that the course effectively strengthened students' foundational methodological knowledge in LCA, which is mainly covered in the pre-midsemester part. Similarly high scores were observed for

Alignment between theory and project, Instructor feedback, and Overall satisfaction (all 4.77), suggesting that the project-based structure and interactive instructional approach were well received by students.

Table 1. Respondents' profile who took the LCA course at Industrial Pollution Control Master Program at Universitas Gadjah Mada (UGM).

Variable	Category	n (%)
Academic year	2023	5 (38.5)
	2024	4 (30.8)
	2025	4 (30.8)
Undergraduate Major	Chemical Engineering	4 (30.8)
	Chemistry	3 (23.1)
	Environmental Engineering	2 (15.4)
	Others	4 (30.8)
Prior LCA experience	None	8 (61.5)
	Read materials	3 (23.1)
	Short course	1 (7.7)
	Project	1 (7.7)
Operating System on Computers	Windows	12 (92.3)
	MacOS	1 (7.7)

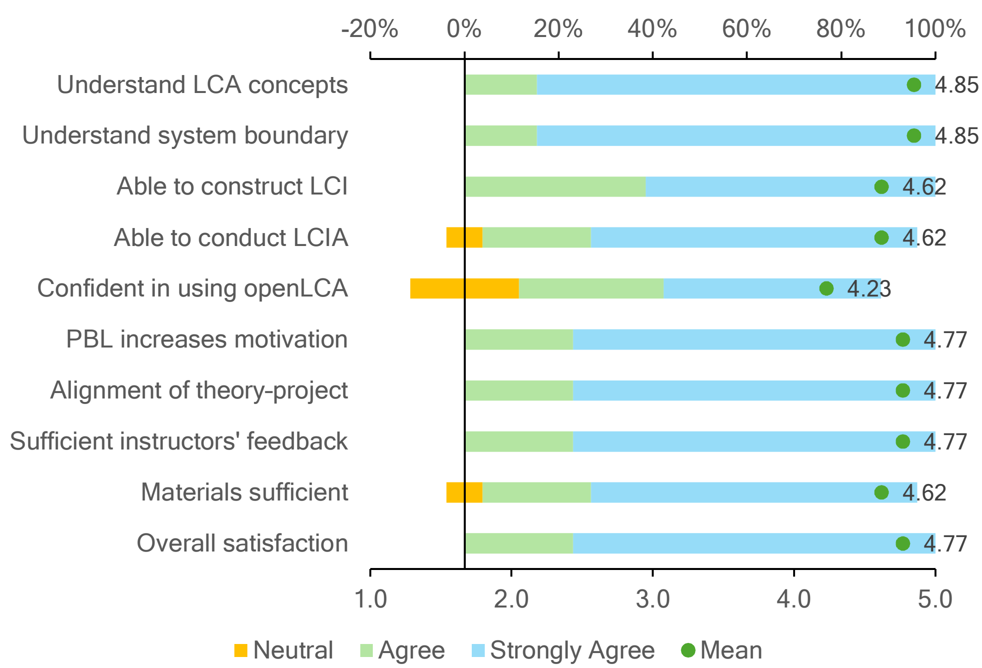

Figure 2. Diverging bar chart illustrating the distribution of Neutral, Agree, and Strongly Agree responses across survey items, based on a five-point Likert scale (upper x-axis), together with corresponding mean scores (lower x-axis).

Furthermore, skills- and practical-oriented items such as Ability to construct LCI and Ability to conduct LCIA also received strong agreement (mean: 4.62), although a small fraction of students expressed neutrality, reflecting the inherent complexity of these analytical steps in LCA. The lowest mean score was associated with students' confidence in using openLCA software (4.23), accompanied by a visibly larger proportion of neutral responses, indicating that students may require additional practice or guided support when working with LCA software. Although multiple case studies and hands-on exercises using openLCA software were provided during the post-midsemester period, the results indicate a practical skills gap between conducting relatively simple LCA exercises, such as comparing two plastic bottle options with limited system boundaries as given in the lectures, and performing more complex, data-intensive LCA case studies typically found in the Hitch Hiker's LCA book [25] or in scientific literature. This gap becomes particularly evident when students are required to independently develop comprehensive LCI datasets and to conduct a full LCA study for the project-based activities that lead to final report and oral examination based on more complex case studies in Hitch Hiker's book. Consequently, students may experience increased difficulty when transitioning from simplified instructional examples to realistic, multi-process LCA applications. Nevertheless, the course also provides sufficient time for discussions, questions-answers sessions, and software troubleshooting during the project-based case activities. Furthermore, the overall distribution remains skewed toward positive responses, demonstrating that the LCA course successfully met its intended learning outcomes and provided a meaningful learning experience for most students.

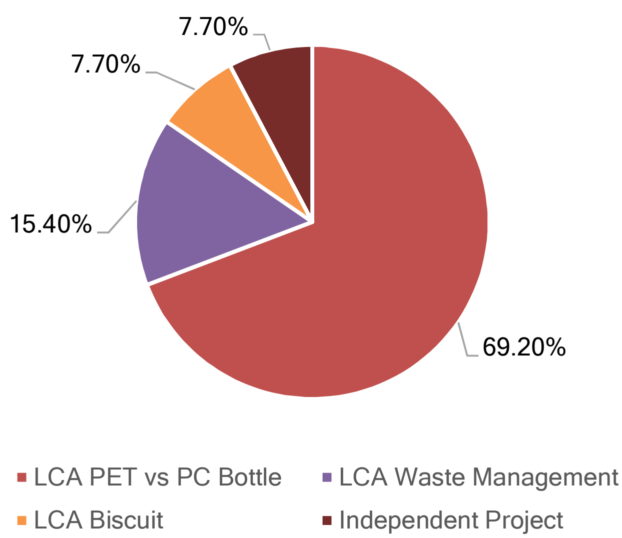

Figure 3. Students' selection of case studies they found most useful and engaging for enhancing their comprehension and practical application of LCA.

During the course, multiple case studies were discussed during the lecture and exercise sessions. Figure 3 reveals that most students (69.2%) found the simplified LCA PET vs PC Bottle project to be the most useful and engaging. This preference likely reflects the familiarity and relevance of plastic packaging issues in everyday life, allowing students to connect theoretical principles with tangible environmental implications. In contrast, smaller proportions of students selected the LCA Biscuit (15.4%), LCA Waste Management

(7.7%), and Independent Project (7.7%) cases as their preferred learning experiences. Although these projects offered diversity in system scope and methodological challenges, they may have required more complex data acquisition or interpretation, which could explain the lower engagement levels. These results suggest that case studies grounded in familiar, real-world materials and products can enhance students' comprehension and engagement in LCA learning.

The survey also explored the main challenges students encountered during the Life Cycle Assessment (LCA) course, through a multiple-response question. As illustrated in Figure 4, the most frequently reported difficulties were related to completing assignments or projects (23.1%) and unclear instructions (23.1%), followed by software-related and inventory-related challenges (both 15.4%). A smaller proportion of students cited heavy workload (7.7%), while 15.4% of students reported experiencing no major challenges.

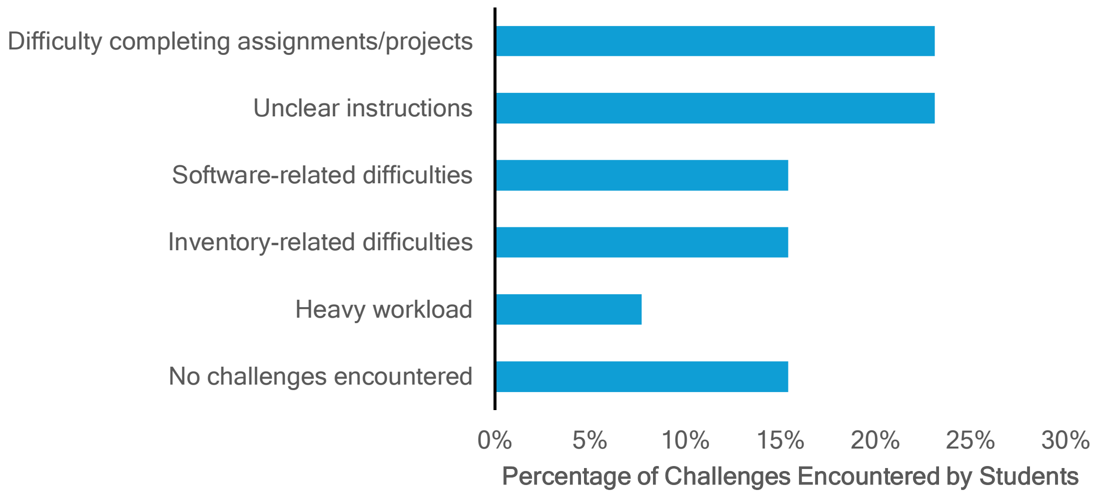

Figure 4. Student-reported challenges experienced throughout the LCA course, expressed as percentages of total respondents.

The variation in perceived difficulties can be partially attributed to differences in project design across cohorts. In 2023, students were assigned to reproduce and verify data from a published LCA study on biscuit production. This project required close attention to methodological detail and database consistency, which some students found technically demanding. In contrast, students in the 2024 and 2025 cohorts conducted individual projects based on The Hitch Hiker's Guide to LCA by Baumann and Tillman [25], which involved developing system boundaries and impact assessments for diverse product case studies. The "unclear instructions" reported by some respondents appear to be related not only to guidance from instructors but also to the inherent complexity and interpretive nature of the Hitch Hiker's text itself, which requires a high degree of independent judgment and conceptual understanding. This suggests a more thorough guideline and boundary of instructions are needed when releasing the project-based case studies to students in the future.

Software-related and inventory-related challenges were also common, reflecting the steep learning curve associated with openLCA. Despite these challenges, the relatively low proportion of students reporting major obstacles indicates that most participants were able to navigate the LCA process effectively. This suggests that the integration of project-based learning and openLCA practice, although demanding, successfully promote problem-solving and analytical skills central to the objectives of the program.

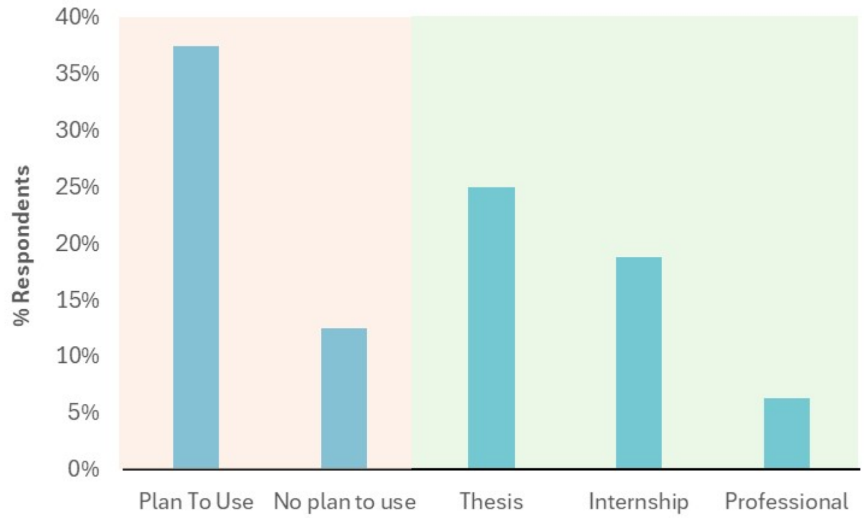

Figure 5. Post-course applications of LCA as reported by students (multi-response question). The bar chart within the green boxes indicates the percentage of respondents that have use LCA after the course.

Furthermore, an important finding from the survey was about post-course application of the LCA and its associated software among students. Respondents were allowed to select multiple options in this question, resulting in a total of 16 reported applications. Following the completion of this course or graduation from the master's program, only 12.5% of respondents do not have plan to use (Figure 5). Around 50% of respondents have continued using this tool (indicated in bar graphs within the green boxes in Figure 5), such as for thesis work within the master's program (25%), in the internship or faculty research project (18.8%), or even in the professional settings or in the job following graduations (6.3%). The rest of the respondents (37.5%) reported not having used the tool yet but expressed their intention to do so in the future.

This result indicates the high rate of students' willingness to continue utilizing the LCA as a tool, either for further study (e.g. thesis) or in professional context. This sustained interest reflects not only the relevance of LCA as a practical environmental management tool but also the effectiveness of project-based learning in stimulating applied understanding. Although the number of respondents is small, the trend suggests that early exposure to LCA through experiential coursework can positively influence students' willingness to integrate environmental sustainability assessment methods into their future careers.

4. CONCLUSION

This study evaluated the early implementation of a project-based Life Cycle Assessment (LCA) course within the Industrial Pollution Control Engineering Master's Program at Universitas Gadjah Mada. Based on survey responses from three cohorts, the findings demonstrate that the course effectively achieved its intended learning outcomes, particularly in strengthening students' conceptual understanding of LCA, system boundary definition, and the integration of theory with practical project work. High levels of agreement across most learning outcome indicators and overall satisfaction suggest that the project-based learning (PBL) framework successfully fostered active engagement, motivation, and applied learning. Importantly, despite the majority of students having no prior LCA experience, they were able to develop competencies in constructing life cycle inventories and conducting life cycle impact assessments, highlighting the suitability of PBL for teaching complex sustainability assessment tools at the graduate level.

Nevertheless, the results also reveal challenges, particularly related to software proficiency and the transition from simplified instructional exercises to more complex, data-intensive case studies. These findings underscore the need for enhanced and clearer project guidelines, and additional hands-on support when introducing advanced LCA modelling tasks. Despite these challenges, the high proportion of students who have already applied, or intend to apply, LCA in thesis work, internships, and professional contexts indicates a strong transfer of learning beyond the classroom. Overall, this study provides empirical evidence that project-based LCA education can play a critical role in capacity building for sustainable industrial development in Indonesia. Future research should involve larger cohorts and longitudinal assessment to further evaluate learning outcomes, effectiveness, and professional impact.

ACKNOWLEDGMENT

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Rio Aryaprataman: Conceptualization, methodology, validation, formal analysis, investigation, data curation, writing-original draft, writing-review editing.
Muhammad Mufti Aziz: Conceptualization, methodology, writing-review editing.

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