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Application of the CDIO Approach in Developing Student's Chemistry Experimentation Competencies: Theory and Practice

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Abstract

Background/purpose. The current trend of training Chemistry teachers focuses on innovating pedagogical methods and developing students' holistic competencies, particularly their chemistry experimentation competencies (CEC). The CDIO (Conceive - Design - Implement - Operate) framework effectively combines theoretical knowledge with practice and enhances professional skills and teamwork skills, thereby developing experimental competency for students. The primary purpose of this study is to learn the principles of CDIO workspace design, provide the process of building the student's CEC framework according to the CDIO approach, publish the CEC framework built and conduct pedagogical experiments on the effectiveness of the CDIO workspace in improving students' CEC.

Materials/methods. The research employs expert surveys and pedagogical experiments with students to assess the impact of CDIO-aligned workspaces on students' CEC. These methods allow for the evaluation of both theoretical and practical aspects of the CDIO framework's integration into chemistry laboratory settings.

Results. The study finds that integrating CDIO-based workspaces into university chemistry laboratories significantly enhances students' practical laboratory skills. This integration was shown to support ongoing educational reforms and align with broader efforts to improve educational standards.

Conclusion. The research concludes that CDIO workspaces play a critical role in advancing students' CEC and contribute positively to the quality of teacher training in chemistry. The findings highlight the potential of the CDIO framework to foster more effective and holistic educational practices in the sciences.

1. Introduction

The CDIO approach (Conceive - Design - Implement – Operate) is one of the effective approaches deployed and applied in over 30 countries in more than 100 universities to improve training quality and meet social requirements based on determining output standards to design training programs and plans effectively. It originated from the idea of engineering faculties at four universities, including Chalmers University of Technology in Göteborg, Royal Institute of Technology in Stockholm, Linköping University in Sweden, and the Massachusetts Institute of Technology (MIT) in the USA during the 1990s. In a broader sense, CDIO can be applied to establish standardized processes for various fields of education beyond engineering, as it ensures a solid framework of knowledge and skills (Campbell, 2007). In Vietnam, Vinh University is one of six members of the International CDIO Association that has been training pedagogical students under the CDIO approaches since 2017 to fulfill the training goals, meet social needs, and build quality training that meets international standards. The process of joining the CDIO of Vinh University is carried out through the illustrations in Figure 1.

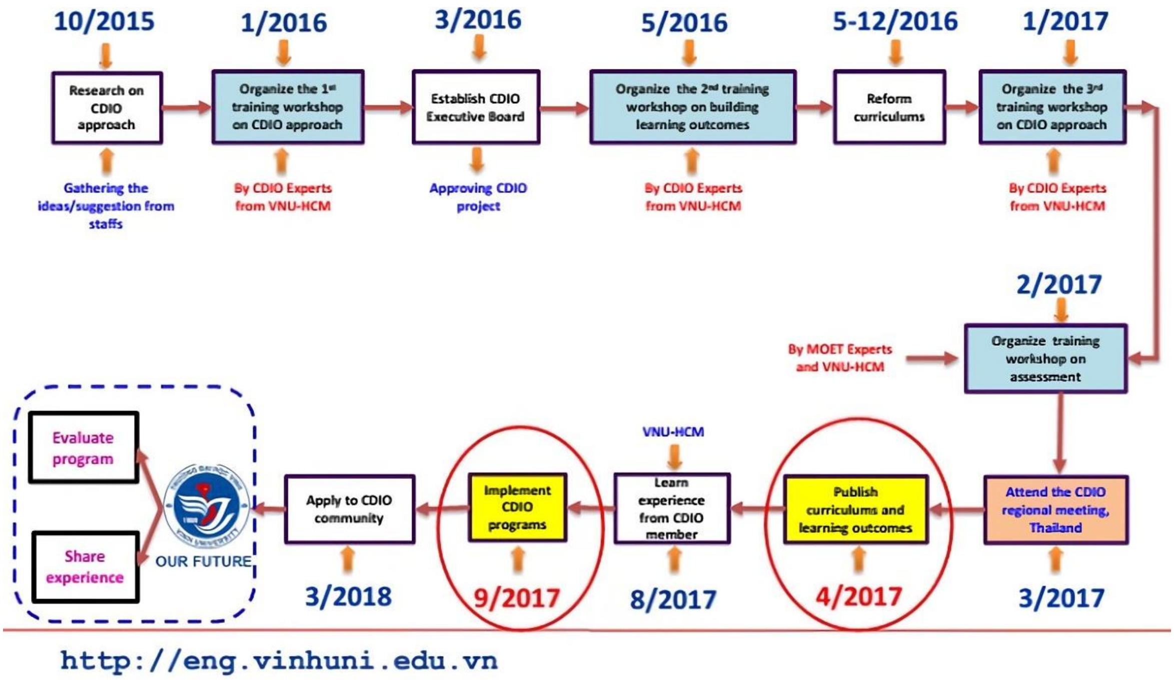

Figure 1. The process of joining CDIO of Vinh University, Vietnam

(Source: Vinh University)

The CDIO (Conceive-Design-Implement-Operate) approach has become a leading pedagogical framework in engineering education, emphasizing an integrated model that combines theoretical knowledge with practical application. This approach fosters the development of critical competencies such as problem-solving, creativity, and teamwork, which are essential in preparing students for real-world challenges in engineering. CDIO has been shown to enhance student engagement, improve collaborative skills, and promote leadership, making it a widely adopted framework across engineering programs worldwide (Crawley et al., 2014). Furthermore, CDIO has been credited with enhancing students' skills in designing, implementing, and managing complex systems with key engineering practice skills (Martseva et al., 2021). However, the CDIO approach was initially created for engineering disciplines, which can make its application in fields like social sciences or economics challenging. Each discipline has unique characteristics that can complicate the adaptation of this approach (Nguyen, 2018). Furthermore, evaluating students' learning outcomes using the CDIO framework requires implementing new assessment methods. These methods can be complex and time-consuming, as they significantly emphasize practical skills and problem-solving abilities (Le, 2019).

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Research on the outcome standards of undergraduate programs utilizing the CDIO approach has shown that experimental practice competency is one of the most crucial skills in teacher education programs (Crawley et al., 2014). It allows students to apply core knowledge and develop other essential abilities, including logical reasoning, analytical thinking, problem-solving, scientific inquiry, personal and professional development, teamwork, and communication skills (Prince & Felder, 2006; Chuchalin et al., 2015). However, many students, particularly those in chemistry education programs, still face significant limitations in their experimental practice competency that require further improvement and development, especially in alignment with the CDIO framework. This study aims to enhance students' experimental chemistry competency by establishing a competency framework for experimental chemistry practice and developing an assessment toolset. The framework and toolset will serve as a foundation for evaluating the growth of students' experimental skills and contribute to improving the quality of chemistry teacher preparation at universities.

2. Literature Review

Research on CDIO-based curricula has been ongoing worldwide since 2000. The CDIO framework was initially developed by three higher education institutions: the Massachusetts Institute of Technology, Chalmers University of Technology in Gothenburg, and Linköping University in Linköping. Subsequently, Crawley et al. from the Royal Institute of Technology in Stockholm expanded the framework into a collaborative international approach to engineering education reform. This development is detailed in their book, "Rethinking Engineering Education: The CDIO Approach" (Boden, 2007). Since its inception, the CDIO framework has evolved into a global association, quickly expanding beyond the United States and Europe. Currently, over 116 universities across seven regions, Europe, North America, Asia, the UK-Ireland, Latin America, Australia, New Zealand, and Africa are involved in the program (CDIO Organization, 2014).

The CDIO approach to higher education reform emphasizes three main components: (1) the development of program outcome standards; (2) the design of curricula through an integrated approach that actively involves stakeholders, including faculty, students, and institutional leaders; and (3) the organization of teaching and assessment methods that are aligned with these outcome standards. This approach promotes student autonomy and highlights integrated teaching strategies and experiential learning. Overall, CDIO provides an educational framework that comprises the CDIO syllabus, CDIO standards, and the CDIO assessment scale. These tools are essential for designing and developing curricula that meet established outcome standards. They aim to produce well-rounded graduates with the knowledge, skills, attitudes, practical competencies, and social responsibility (Dinh et al., 2012). Singapore was the first Asian country to implement the CDIO framework, successfully applying it across five institutions and 15 disciplines since 2007. By 2010, Singapore received the "Excellence in Education and Training in Chemical Engineering" award from the Institution of Chemical Engineers (IChemE) in recognition of its successful implementation of the CDIO approach (Pham, 2016).

Research on the CDIO approach in Vietnam began in 2008 with the "Establishing the Scientific, Practical Foundations, and Process for Developing CDIO-based Curricula for the High-Quality Foreign Trade Economics Program at Vietnam National University, Hanoi". This project aimed to explore the core principles of the CDIO approach to curriculum development and analyze the experiences of implementing CDIO-based curricula at various global institutions (Giac et al., 2024; Nguyen et al., 2020). It also provided a framework for designing CDIO-aligned curricula at Vietnam National University, Hanoi. In 2009, Vietnam National University in Ho Chi Minh City initiated the project "Piloting the CDIO Model at VNUHCM for the Manufacturing Engineering and Information Technology Programs" to develop a model for adopting and applying CDIO in engineering education throughout Vietnam. The project ran from 2010 to 2017, following a detailed phased implementation plan to ensure comprehensive adoption of the CDIO framework. The implementation plan included several key components (Terano, 2019): defining program outcomes, designing integrated curricula, redesigning learning environments (such as classrooms, workshops, and laboratories), training faculty and staff in the CDIO pedagogical model (Huang, 2015), reforming teaching methods and assessment strategies for all courses, and evaluating the curriculum against CDIO standards (Le, 2022). The Ministry of Education and Training (Pham et al., 2021) has been overseeing the pilot implementation of the CDIO approach at National Universities and has organized three thematic workshops on "Curriculum Development Based on the CDIO Model" in Hanoi, Da Nang, and Ho Chi Minh City. These workshops aimed to introduce higher education institutions nationwide to an approach successfully adopted by many prestigious technical universities worldwide (Nguyen et al., 2020). In addition to Vietnam National University in Ho Chi Minh City, institutions such as Vinh University, Da Lat University, Duy Tan University, and several others have officially joined the global CDIO Association (Torsakul et al., 2021; Qingfeng, 2012). Among these, universities offering programs in Chemistry Education, including Vinh University, Da Lat University, An Giang University, and Da Nang University, have integrated the CDIO-based curriculum.

Other studies on the CDIO approach have shown that it not only provides specific learning outcomes but also offers clear guidance on educational practices and management. This includes leadership strategies, higher education administration, and faculty development with deep subject expertise (Vo, 2011). The integration of outcome-based standards through the CDIO approach is highly adaptable and can be applied to curricula in engineering as well as a wide range of other academic disciplines (Nguyen & Tran, 2012; Nguyen, 2012). However, the process and application of CDIO remain relatively new in developing integrated curricula for both vocational and higher education sectors (Pham, 2015; Pham, 2016b). Even in the context of undergraduate engineering programs, curriculum reform based on the CDIO approach is both a new challenge and an urgent necessity to enhance the quality of higher education and meet societal demands (Pham, 2016a). Moreover, successful implementation of the CDIO approach requires institutions to meet essential conditions, including adequate infrastructure, qualified faculty, competent administrative staff, well-structured curricula, engaged students, etc. All these elements must adhere to the core standards of CDIO within a unified system of standardized procedures. The CDIO approach also provides a comprehensive framework for developing learning outcomes in teacher education programs aligned with modern pedagogical practices (Dinh et al., 2016). Additionally, integrating rubrics and CDIO in course syllabus design empowers both instructors and students to engage in the teaching and learning process actively, thereby enhancing the quality of instruction and meeting the needs of all stakeholders (Le, 2019).

Based on the existing published research, it is evident that the development of competencies and implementation of the CDIO approach in curriculum design and teaching have received considerable attention from various scholars. However, research focused on creating a framework for developing student's CEC and proposing strategies to enhance these competencies within the Chemical Education program using the CDIO approach is still relatively limited. Therefore, this article aims to examine the application of the CDIO approach in developing laboratory skills for students, encompassing both theory and practice. The specific research questions are as follows:

1) How can practical laboratory skills in chemistry be enhanced through the CDIO methodology?

2) What are the fundamental principles for designing a CDIO learning environment?

3) What are the procedural steps involved in organizing a CDIO-based laboratory space?

4) How effectively is the CDIO learning environment improving students' laboratory competencies?

3. Methodology

3.1. Research Goal

Research on measures to enhance the CEC of students in the Chemistry of Education program through the CDIO approach, contributing to the improvement of Chemistry teacher training quality at universities nationwide. The proposed measures include:

1) Designing the Chemistry laboratory space to align with the experiential learning principles of the CDIO framework;

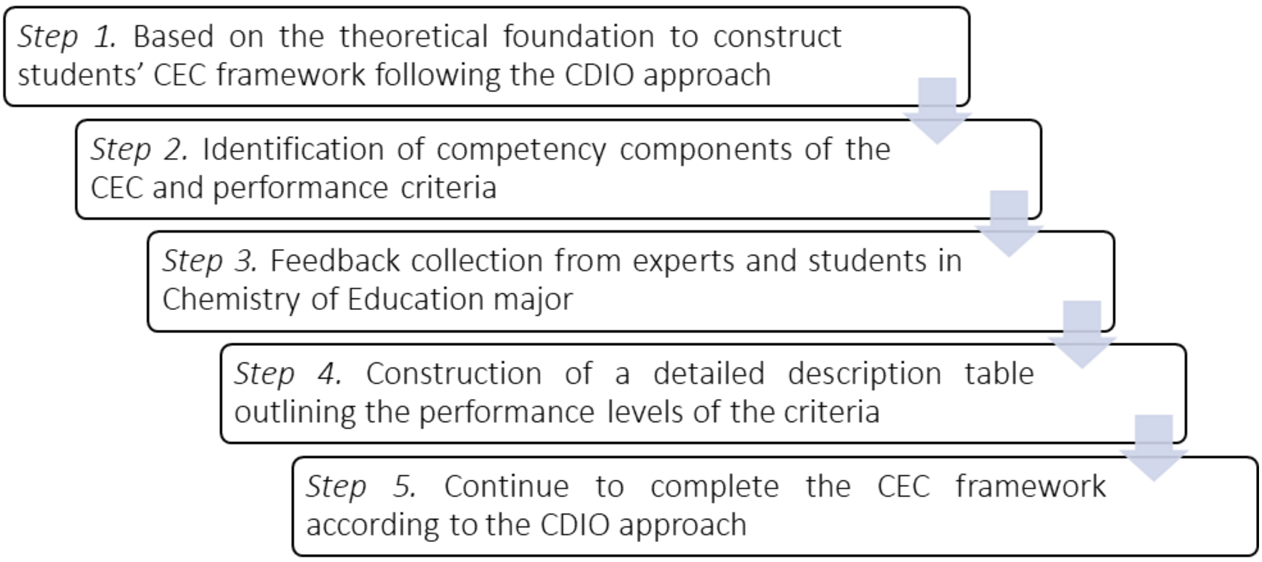
2) Developing a comprehensive procedure for conducting Chemistry experiments and a set of evaluation criteria for assessing practical Chemistry exercises for students in the Chemistry of Education program based on the CDIO approach;

3) Implementing micro-teaching strategies in conjunction with role-playing techniques to foster the development of experimental competencies in Chemistry students within the Chemistry of Education program, guided by the CDIO approach.

3.2. Sample and Data Collection

The author conducted a pedagogical experiment during the 2022-2023 academic year to collect exploratory information and implement an official pedagogical experiment in the 2023-2024 academic year. The courses taught included Organic Chemistry Practice, Inorganic Chemistry Practice, and Chemistry Teaching Method Practice. The selected subjects for the pedagogical experiment must meet two criteria: (1) They are 3rd and 4th-year students enrolled in the full-time Chemistry Pedagogy training program; (2) They training program based on the CDIO approach. The institutions involved in the instructional trial were four universities: the Faculty of Education at Vinh University (with 3 instructors and 41 students), Dalat University (3 instructors and 34 students), the Faculty of Education at Da Nang University (3 instructors and 61 students), and An Giang University – Vietnam National University, Ho Chi Minh City (3 instructors and eight students). They are member universities of the World CDIO Association and are currently applying the CDIO approach to the Chemistry of education major.

The process for constructing the CEC framework according to the CDIO approach was carried out in five steps, as outlined below (Le, 2024):



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Step 1. Based on the theoretical foundation to construct students' CEC framework following the CDIO approach. They include reference documents on experimental practice competencies, outcome standards of training programs in the Chemistry of Education following the CDIO approach, and detailed outlines of practical modules related to Organic chemistry, Inorganic chemistry, and Chemistry teaching methods. In particular, 12 CDIO standards and an analysis of the current situation of CEC are closely followed in the process of building the CEC competency framework of students.

Step 2. Identification of competency components and performance criteria. The competency framework for laboratory-based chemistry teaching following the CDIO approach consists of 9 competency components and 27 corresponding performance criteria. The competency components are developed in close alignment with the CDIO standards.

Step 3. Feedback collection from experts and students in Chemistry of Education. The development of the competency framework for laboratory-based chemistry teaching following the CDIO approach requires widespread feedback from both experts and students in the Chemistry Education program. Specifically:

- For the expert survey group, feedback should focus on the following areas: Assessing the current state of students' competency in laboratory-based chemistry teaching within the CDIO framework; Evaluating the suitability of the construction of the 9 competency components and the 27 corresponding performance criteria.

- For the student survey group, feedback should address the following: Assessing the current state of students' competencies in laboratory-based chemistry teaching; Measuring students' interest in further developing the 9 competency components and 27 performance criteria identified.

- The comprehensive feedback from both experts and students in the Chemistry of Education program regarding the 9 competency components and 27 performance criteria ensures the objectivity, scientific rigor, and comprehensiveness of the competency framework for laboratory-based chemistry teaching based on the CDIO approach.

Step 4. A detailed description table outlining the performance levels of the criteria will be constructed. To build the CEC framework for laboratory-based chemistry teaching for students in the Chemistry of Education program following the CDIO approach, a detailed table must be developed that outlines the performance levels for each criterion corresponding to the competency components in the laboratory-based chemistry teaching framework. Each criterion is structured to be assessed at 4 levels, in increasing order of proficiency, including level 1 (Weak), level 2 (Satisfactory), level 3 (Good), and level 4 (Excellent).

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Table 1. Competence framework for chemical experiment practice according to the CDIO approach (Source: Authors' elaboration)

Oder	Component competences	Criteria	Rating Level			
			Level 1 (Weak)	Level 2 (Satisfactory)	Level 3 (Good)	Level 4 (Excellent)
C1	Perform laboratory safety	C1. Follow rules and regulations for safety in the laboratory	Incomplete adherence to laboratory safety regulations and rules.	Relatively complete adherence to laboratory safety regulations and rules.	Full adherence to laboratory safety regulations and rules.	Full and creative adherence to laboratory safety regulations and rules.
C2	Conducting Chemical Experiments	C2.1. Make a plan for the experiment	Incomplete planning of the experiment.	Relatively complete planning of the experiment.	Full planning of the experiment.	Full and creative planning of the experiment.
		C2.2. Take steps to conduct the experiment	Incomplete execution of experiment steps.	Relatively complete execution of experiment steps.	Full execution of experiment steps.	Full and creative execution of experiment steps.
		C2.3. Describe and explain the experiment's phenomenon	Incomplete description and explanation of the experiment's phenomenon.	Relatively complete description and explanation of the experiment's phenomenon.	Full description and explanation of the experiment's phenomenon.	Full and creative description and explanation of the experiment's phenomenon.
		C2.4. Reason the experiment results and propose alternative solutions if the experiment fails	Incomplete reasoning of experiment results and alternative solutions.	Relatively complete reasoning of experiment results and alternative solutions.	The whole reasoning of experiment results and alternative solutions.	Full and creative reasoning of experiment results and alternative solutions.
C3	Organising Chemical Experiment Teaching	C3.1. Select experiments suitable for teaching objectives and learner groups	Choosing experiments not suitable for teaching objectives and learner groups.	Relatively suitable experiments for teaching objectives and learner groups.	Entirely suitable experiments for teaching objectives and learner groups	Fully and creatively suitable experiments for teaching objectives and learner groups
		C3.2. Use teaching methods appropriate for experiments in an active teaching approach	Use of teaching methods not suitable for experiments in an active teaching	Use of teaching methods relatively suitable for experiments in an	Use of teaching methods entirely suitable for experiments in an	Use of teaching methods entirely suitable for experiments in an active

			approach.	active teaching approach.	active teaching approach.	teaching approach and frequently.
		C3.3. Ask guiding questions for learners to observe phenomena and draw conclusions	Guiding questions for learners to observe phenomena and draw conclusions are not suitable.	Guiding questions for learners to observe phenomena and draw conclusions are relatively suitable.	Guiding questions for learners to observe phenomena and draw conclusions are entirely suitable.	Guiding questions for learners to observe phenomena and draw conclusions are entirely suitable and creative.
		C3.4. Handle situations and guide learners to conduct experiments	Handling situations and guiding learners to conduct experiments is not reasonable.	Handling situations and guiding learners to conduct experiments is relatively reasonable.	Handling situations and guiding learners to conduct experiments is reasonable.	Handling situations and guiding learners to conduct experiments is reasonable and frequent.
C4	Work in groups	C4.1. Forming a group	Group formation is unreasonable in quantity, gender, language, etc.	Group formation is relatively reasonable regarding quantity, gender, language, etc.	Group formation is reasonable regarding quantity, gender, language, etc.	Group formation is reasonable in terms of quantity, gender, language, etc., and creativity.
		C4.2. Organise group activities	Group activities are not effectively organised.	Group activities are relatively effectively organised.	Group activities are effectively organised.	Group activities are effectively organised and frequent.
		C4.3. Develop the group	Group development is not uniform.	Group development is relatively uniform.	Group development is uniform.	Group development is uniform and frequent.
		C4.4. Lead the group	Group leadership is not effective.	Group leadership is relatively effective.	Group leadership is effective.	Group leadership is effective and frequent.
C5	Interdisciplinary Knowledge Integration	C5.1. Integrate core knowledge to solve practical situations in lab experiments	Integrating core knowledge in Chemistry Education to solve practical teaching situations is ineffective.	Integrating core knowledge in Chemistry Education to solve practical teaching situations is relatively effective.	Integrating core knowledge in Chemistry Education to solve practical teaching situations is effective.	Integrating core knowledge in Chemistry Education to solve practical teaching situations is effective and creative.
		C5.2. Participate in	Incomplete	Relatively complete	Full participation in	Full and frequent

		Experiential activities	participation in learning activities following the chemistry practical teaching process based on the CDIO approach.	participation in learning activities following the chemistry practical teaching process based on the CDIO approach.	learning activities following the chemistry practical teaching process based on the CDIO approach.	participation in learning activities following the chemistry practical teaching process based on the CDIO approach.
C6	Designing and Arranging CDIO Learning Spaces	C6.1. Design the CDIO workspaces	The design of the CDIO learning space is not reasonable	The design of the CDIO learning space is relatively reasonable	The design of the CDIO learning space is reasonable	The design of the CDIO learning space is reasonable and creative
		C6.2. Arrange and arrange experimental equipment to meet the requirements of teaching and practice experiments according to the CDIO approach	The arrangement of lab equipment does not meet the requirements of teaching chemistry practicals based on the CDIO approach.	The arrangement of lab equipment is relatively reasonable for teaching chemistry practicals based on the CDIO approach.	The arrangement of lab equipment is reasonable for teaching chemistry practicals based on the CDIO approach.	The arrangement of lab equipment is reasonable and creative for teaching chemistry practicals based on the CDIO approach.
		C6.3. Arrange chemicals, supplies, tools, and samples to meet the requirements of teaching practice and experiment according to the CDIO approach	The arrangement of chemicals, materials, tools, and specimens does not meet the requirements of teaching chemistry practicals based on the CDIO approach.	The arrangement of chemicals, materials, tools, and specimens is relatively reasonable for teaching chemistry practicals based on the CDIO approach.	The arrangement of chemicals, materials, tools, and specimens is reasonable for teaching chemistry practicals based on the CDIO approach.	The arrangement of chemicals, materials, tools, and specimens is reasonable and creative for teaching chemistry practicals based on the CDIO approach.
		C6.4. Using technical means to support teaching practice and experimentation, according to the CDIO approach	Using technical means to support teaching chemistry practicals based on the CDIO approach is ineffective.	Using technical means to support teaching chemistry practicals based on the CDIO approach is relatively effective.	Using technical means to support teaching chemistry practicals based on the CDIO approach is effective.	Using technical means to support teaching chemistry practicals based on the CDIO approach is effective and creative.
C7	Presentation,	C7.1. Student - student	Communication	Communication	Communication	Communication

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	Explanation, and Communication	communication	between learners is not effective.	between learners is relatively effective.	between learners is effective.	between learners is effective and frequent.
		C7.2. Lecturer - student communication	Communication between instructors and learners is not effective.	Communication between instructors and learners is relatively effective.	Communication between instructors and learners is effective.	Communication between instructors and learners is effective and frequent.
C8	Evaluation competence	C8.1. Learners self-assess	Self-assessment by learners is not effective.	Self-assessment by learners is relatively effective.	Self-assessment by learners is effective.	Self-assessment by learners is effective and frequent.
		C8.2. Learners evaluate learners (peer assessment)	Peer evaluation is not effective.	Peer evaluation is relatively effective.	Peer evaluation is effective.	Peer evaluation is effective and frequent.
		C8.3. Lecturer evaluate learners	The instructor's evaluation of learners is not effective.	The instructor's evaluation of learners is relatively effective.	The instructor's evaluation of learners is effective.	The instructor's evaluation of learners is effective and frequent.
C9	Career development	C9.1. Developing soft skills	Soft skill development is incomplete.	Soft skill development is relatively complete.	Soft skill development is complete.	Soft skill development is complete and creative
		C9.2. Develop experimental skills	Practical skill development is incomplete.	Practical skill development is relatively complete.	Practical skill development is complete	Practical skill development is complete and creative.
		C9.3. Developing skills in organizing teaching and practice experiments	The development of teaching organization skills for practical teaching is incomplete.	The development of teaching organization skills for practical teaching is relatively complete.	The development of teaching organization skills for practical teaching is complete.	The development of teaching organization skills for practical teaching is complete and creative.

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3.3. Analyzing of Data

To collect and assess the quantitative results of measures for developing the CEC according to the CDIO approach for students in the Chemistry of Education major, the research carried out the process in two steps:

Step 1: Research Design Selection

We used a pre-test and post-test research design with a single group to evaluate students' progress in both before-impacting and after-impacting.

Step 2: Measurement

Based on the designed tools, the research group measured the development of chemical problem-solving skills of students through Teacher assessment forms for students' problem-solving skills, Self-assessment forms for students' problem-solving skills, Test scores evaluating the CEC before-impacting and after-impacting, and Student survey forms after the intervention. The raw data tables of scores are collected from the results of the assessment forms.

The data processing for the experimental results was conducted using mathematical statistics with SPSS 20.0 statistical software. The steps were as follows:

1. Enter the survey data into the Variable View table.

2. Calculate the standard deviation (Std. Deviation) and mean value (Mean).

3. Create a summary data table.

4. Draw a correlation chart of before-impacting and after-impacting.

5. Conduct a Paired T-Test.

The Paired T-Test helps us determine whether the difference between the mean values of the before-impacting and after-impacting groups is significant, whether it is due to random chance or the effect of the proposed and implemented measures for developing chemical problem-solving skills.

The steps for performing the Paired T-Test are as follows:

Step 1: Find the P value of the T-test (Sig).

Step 2: Depending on the p-value, discuss:

If P (Sig) $\geq \alpha = 0.05$: The difference in mean scores between the before-impacting and after-impacting groups is not significant, meaning it is likely due to random chance rather than the effect of the measures.

If P (Sig) $< \alpha = 0.05$: The difference is statistically significant, meaning it is due to the effect of the measures, not random chance.

6. Effect Size (ES)

The effect size value indicates the extent to which the research impacts the outcomes.

$$ES(SMD) = \frac{\overline{X}_{after\ impact} - \overline{X}_{before\ impact}}{SD_{before\ impact}}$$

Impact level value (ES)	Impacting
> 1.00	Very large
0.80 – 1.00	Large
0.50 – 0.79	Medium
0.20 – 0.49	Small
< 0.20	Very small

According to the steps followed using SPSS 20.0 statistical software, the research performed:

1) Described the concentration of the data: Created frequency distribution tables of the CEC according to the CDIO approach for experimental groups at the pre-test and post-test moment; calculated the mean values of the obtained scores; computed the standard deviation (SD) as a statistical parameter to describe the dispersion of the data.

2) Performed the paired T-test (P) at the before-impacting and after-impacting time points to compare the mean values of the same group to determine whether the differences in scores occurred by chance. A difference between the time points is considered significant if $P < 0.05$.

3) Calculated the Standardized Mean Difference (SMD), which is a measure of effect size, based on the results from before and after the impact assessments. This calculation was used to evaluate the Effect size (ES) of the measures implemented to develop students' CEC following the CDIO approach.

4. Results

4.1. Assessment of the Effectiveness of Chemistry Laboratory Space Planning Based on the CDIO Experiential Approach in Developing Chemistry Experimentation Competencies of Students

Expert Survey Results

The laboratory's spatial planning is based on the CDIO approach, aligning with established principles designed to enhance the learning and teaching environment, as illustrated in Figure 2. It will be equipped with essential safety features, including fume hoods, emergency first aid kits, first responder equipment, and fire safety tools. To further enrich the educational atmosphere, we will incorporate educational models, visual aids, and portraits of renowned scientists, creating a stimulating and pedagogically rich environment for both instructors and students.

Figure 2. The 3D space of the chemical laboratory based on the CDIO program

(Source: Authors' elaboration)

The study gathered the opinions of 78 educational experts regarding the proposed layout of the chemistry laboratory space (in Figure 2). These experts include lecturers with master's, doctorate, and associate professor degrees who currently teach practical courses in chemistry laboratories at universities that specialize in training chemistry teachers. The evaluation results are presented in Figure 3 below.

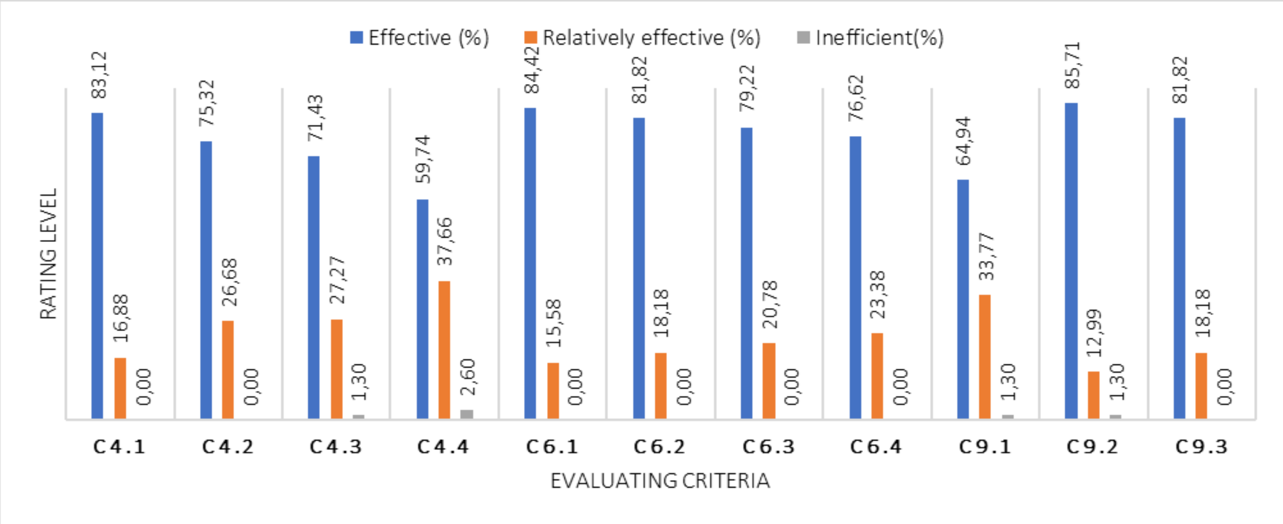

Figure 3. Chart of results from expert assessments on the effectiveness of chemical laboratory design, based on CDIO guidance for developing students' CEC

The research focused on emphasising the core of the CEC of students, including collaborative skills, the design and organization of a CDIO-based learning environment, and professional development. The chart indicates that most experts rated the effectiveness of the design and organization of the chemistry laboratory space, which follows the CDIO approach, as either highly effective or moderately effective. The assessment particularly highlights the development of CEC for students within the CDIO framework.

Survey Results from Students After the Pedagogical Experiment

The research conducted a survey to evaluate students' perceptions after the pedagogical experimentation about the effectiveness of the chemistry laboratory design, which was based on the CDIO framework. The focus was on how this design enhances students' practical chemistry competencies, specifically assessed according to Competency 4 (C4), Competency 6 (C6), and Competency 9 (C9). The findings are presented in Figure 4.

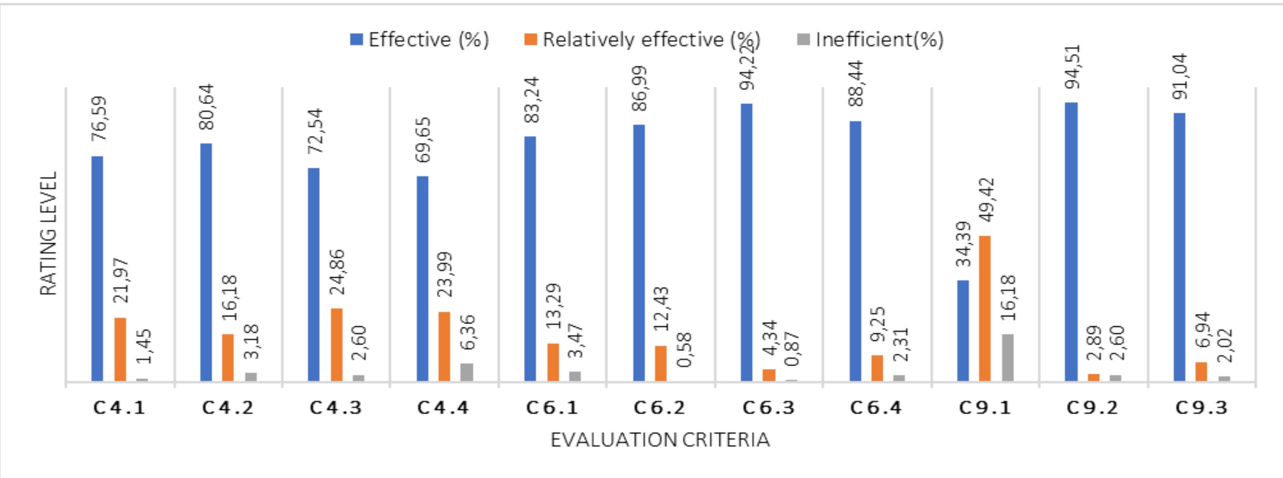

Figure 4. The chart detailing student evaluations of the chemistry laboratory layout's effectiveness based on the CDIO approach in enhancing the CEC of students

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Results show that most evaluations of the layout of the chemistry laboratory space according to the CDIO framework focus on the development of chemistry-related practical skills in students of the Chemistry Education program. In this context, criteria such as team leadership (accounting for 6.36%) and soft skills development (accounting for 16.18%) show relatively low effectiveness. This suggests that more attention should be focused on these criteria to fully develop the CEC of students in the Chemistry Education program, following the CDIO approach.

4.2. Evaluation of the development process for laboratory practice guidelines and the evaluation criteria toolset for chemistry laboratory exercises based on the CDIO framework for students

Implementing the laboratory practice process, including preparation, instruction, and feedback, is conducted twice to track students' progress. The evaluation results of the key performance indicators through the faculty's assessment of students' CEC are shown in Table 2 below:

Table 2. Key performance indicators at institutions with CDIO-based curricula

Subject	Characteristic Parameters / Educational Institution	X		SD		P value of T-test	SMD
		Before Impact	After Impact	Before Impact	After Impact		
Inorganic chemistry practice	Vinh University	2.49	3.47	0.347	0.313	0.00001	3.74
	Dalat University	2.48	3.37	0.39	0.3	0.00002	2.49
	Da Nang University	2.66	3.44	0.513	0.423	0.00022	1.51
	An Giang University	2.34	3.73	0.403	0.343	0.00001	3.44
Organic chemistry practice	Vinh University	2.55	3.49	0.358	0.282	0.00003	3.57
	Dalat University	2.53	3.41	0.403	0.297	0.00043	2.70
	Da Nang University	2.43	3.47	0.401	0.392	0.00141	2.59
	An Giang University	2.44	3.59	0.4	0.33	0.00005	2.87

The results in Table 2 show the evaluation of competencies for each subject area before and after the experiment (Yi - Xi) > 0. The standard deviation of students after the intervention is consistently smaller than that of before the intervention. The T-test for the homogeneity of mean values ($p < 0.05$) indicates that the difference in average scores before and after impact is not random but is due to the intervention. The effect size (ES) is more significant than 1.0, indicating an enormous impact. The results of the intervention on the development of the components of the CEC, including C1, C2, C4, C6, and C9, according to the CDIO approach, are very significant. Therefore, it can be affirmed that the outcomes of students' CEC in the areas of knowledge (inorganic chemistry practice and organic chemistry practice) have markedly demonstrated progress and improvement.

4.3. Evaluation of the effectiveness of using microteaching combined with role-playing methods to develop the CEC for students following the CDIO approach

The micro-teaching method involves a structured process of lesson planning, teaching, and receiving feedback, allowing students to receive timely and constructive critiques. This process enables both external evaluation and self-assessment of their teaching practices. The iterative nature of this method helps to progressively refine and enhance students' competencies in conducting chemistry experiments, ensuring ongoing professional development and skill mastery. The overview of the mean scores for the competency standards components of the CEC and key parameters in the Chemistry teaching method practice course is presented in Table 3.

Table 3. Summary of the average scores for the standards of competency components of the CEC and characteristic parameters in Chemistry teaching method practice subject

		Vinh University		Dalat University		An Giang University		Da Nang University	
		Before Impact	After Impact	Before Impact	After Impact	Before Impact	After Impact	Before Impact	Before Impact
Components of the CEC	C3	2.37	3.42	2.45	3.5	2.39	3.54	2.38	3.28
	C5	2.33	3.33	2.4	3.47	2.55	3.24	2.31	3.19
	C7	2.57	3.57	2.37	3.57	2.39	3.68	2.5	3.81
	C8	2.37	3.4	2.29	3.36	2.37	3.4	2.29	3.25
Characteristic Parameters	X	2.41	3.43	2.38	3.48	2.43	3.47	2.37	3.38
	SD	0.495	0.408	0.452	0.449	0.448	0.306	0.45	0.248
	P value of T-test	0.000004		0.000068		0.003915		0.002089	
	SMD	2.06		2.43		2.32		2.25	

The results presented in Table 3 indicate that the standard deviation for the experimental group at the post-intervention stage is smaller than at the pre-intervention stage. The mean difference in the results achieved (Yi - Xi) is greater than 0, and the t-test value for homogeneity of means ($p < 0.05$) confirms that the difference in mean scores before and after the intervention is significant and attributable to the intervention applied. Additionally, all effect size (ES) values are greater than 1.0, indicating a substantial impact. Besides, the evaluation score after impacting various competency components, such as designing and implementing chemistry experiments (C3), integrating interdisciplinary knowledge (C5), developing presentation and communication skills (C7), and enhancing evaluation competency (C8), were all rated at 3.0 or higher in the post-intervention stage. This suggests that the integration of the micro-teaching approach with role-playing techniques has effectively contributed to the improvement of these competencies.

4.4. Evaluation of the Impact of Developing Practical the CEC According to the CDIO Approach for Students

To diversify the evaluation methods, the research conducted a survey of 291 students who participated in the pedagogical experiment using self-assessment forms both before and after the intervention. The statistical results show the percentage of students scoring based on the evaluation criteria for the competency components displayed in Figure 5.

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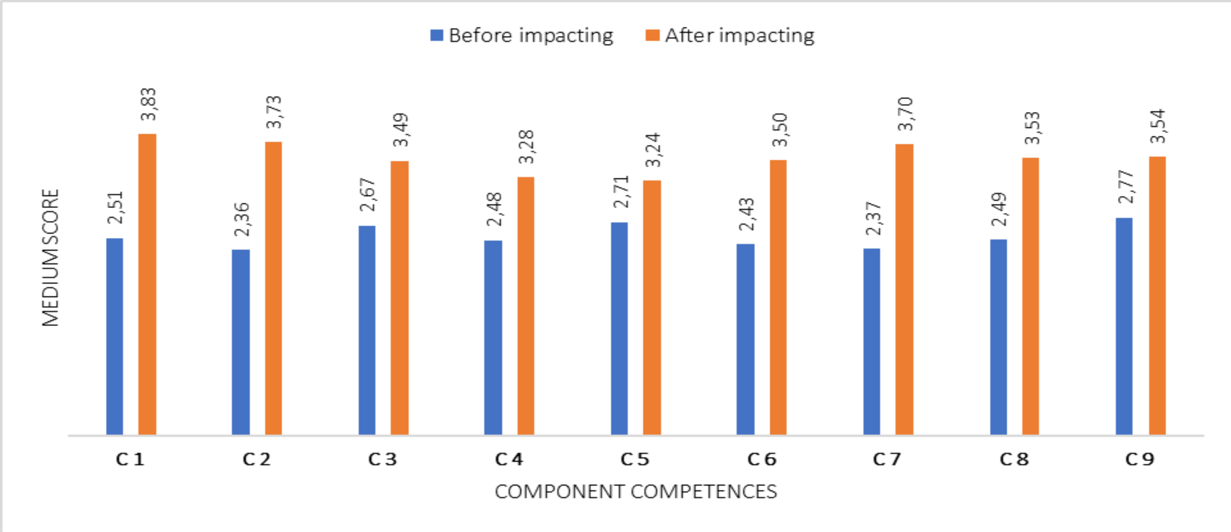

Figure 5. Chast of the average score of the CEC according to the CDIO approach as assessed by students before and after impact

A self-assessment of the components of the CEC involving 291 students reveals that all competency criteria improved. The criteria included C2, C3, and C9, which exhibited the most significant changes with average score increases of 1.16, 1.11, and 1.19, respectively. These criteria are essential components of a student's CEC. By planning the laboratory setup and experimental procedures and engaging in a cycle of planning, teaching, and receiving feedback through methods like microteaching and role-playing, students have effectively improved their competency in using experiments for teaching as well as their practical skills in chemistry experiments, following the CDIO approach.

4.5. Evaluation of the Impact on the Development of Student's CEC According to the CDIO program

The analysis is based on comparing student scores from two competency assessment tests administered before and after the intervention to assess the effectiveness of the process in developing practical chemistry experiment skills according to the CDIO approach. The results for the average scores of the CEC components are shown in Figure 6 below:

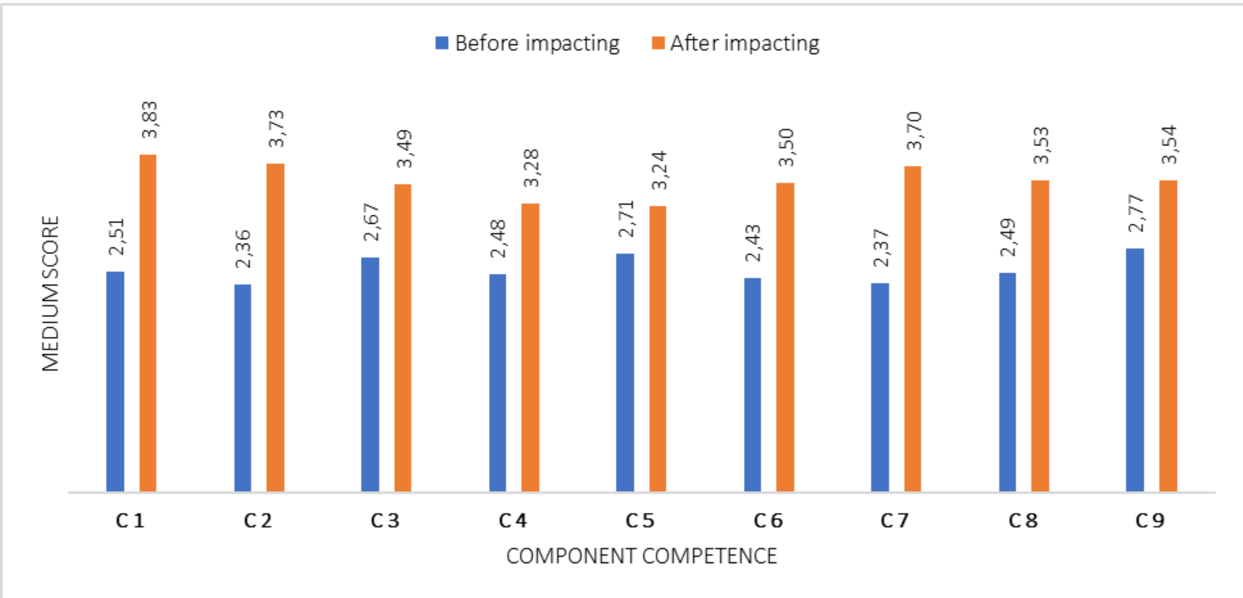

Figure 6. Chart of the average scores of the test evaluating the CEC of students before and after impacting time points

Figure 6 clearly shows a significant difference in the average test scores between before and after the intervention. Specifically, the average score after the intervention is consistently higher than the pre-intervention score across all competency components. The components C1, C2, and C7 showed the most rapid development, with the differences in average scores between the pre- and post-intervention time points being 1.32, 1.37, and 1.33, respectively. The T-test result was 1.03×10^{-5} (less than 0.05), indicating that the difference between the pre-intervention average score (2.53) and the post-intervention average score (3.53) is statistically significant and not due to random chance but rather the effect of the implemented measures. Additionally, the effect size (ES) was significant (1.12), confirming that the measures applied to develop the CEC for students have had a significant positive impact according to the CDIO approach.

5. Discussion

The paper investigated the implementation of the CDIO framework to develop the CEC of students by optimizing laboratory infrastructure, employing effective teaching methods, and utilizing competency-based assessments. Expert evaluations confirmed the effectiveness of designing laboratory space following the CDIO approach in enhancing students' practice and experiment skills (Edström & Kolmos, 2014). Post-experimental surveys conducted with students indicated a significant improvement in their CEC (Malmqvist, 2012). However, enhancements in collaborative leadership and soft skills require further pedagogical strategies (Lattuca et al., 2006). Besides, incorporating microteaching and role-playing techniques improved competency clusters of the CEC, including experimental design, interdisciplinary integration, communication skills, and evaluative abilities. A large-scale self-evaluation among students reinforced the validity of the CDIO framework in enhancing experimental skills, highlighting significant advancements in laboratory coordination and procedural execution (Crawley & Brodeur, n.d). Finally, a comparative analysis of student's CEC assessments before and after the interventions revealed statistically significant improvements across all competency areas, with the most notable progress seen in experimental methodologies, analytical reasoning, and interdisciplinary synthesis (Prince & Felder, 2006).

5.1. Educational Implications and Theoretical Significance

These findings substantiate the pedagogical potency of the CDIO approach in scaffolding laboratory-based skill acquisition in chemistry education (Giac et al., 2024). The deliberate structuring of laboratory spaces following CDIO principles enhances students' engagement in collaborative, inquiry-driven learning. The pedagogical amalgamation of microteaching and role-playing facilitates experiential learning cycles, enabling iterative refinement of instructional strategies and cognitive scaffolding.

The study also highlights the key role of competency-based assessment (Wang & Maa, 2021) frameworks in systematically monitoring learner progress and adapting instructional strategies to close identified competency gaps. determined with actual requirements. The results ("NSTA reader's guide to a framework for K-12 science education, second edition: Practices, crosscutting concepts, and core ideas", 2013) of significant improvement in students' CEC initially show the effectiveness of this research for the chemistry of education programs at universities, helping to modernize the program teaching in the laboratory and ensuring alignment with professional standards in STEM education.

5.2. Comparative Analysis with Prior Research

This paper's findings demonstrate enhancements in the development of the CEC when the CDIO approach is applied in an applied laboratory setting. This aligns with previous empirical studies on CDIO-based teaching methods in engineering education. However, this research stands out due to its thorough empirical evaluation, which includes expert assessments, student self-assessments, and

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rigorous competency-based testing. This comprehensive approach strengthens the foundational experiment exploring the application of CDIO in chemistry education.

6. Conclusion

The research provides robust empirical validation for the application of the CDIO framework in developing the CEC of students. The confluence of optimized laboratory infrastructure, innovative pedagogical approaches, and rigorous competency assessments has demonstrably enhanced student learning outcomes. While certain domains, such as collaborative leadership and metacognitive skills, necessitate further refinement, the overarching findings affirm the viability of the CDIO model as a transformative approach to laboratory education. Future research should focus on refining this framework and evaluating its longitudinal impact on professional competency development in chemistry education and allied disciplines.

7. Suggestion

Based on the study's findings, several key recommendations can enhance the application of the CDIO approach in chemistry education. First, it is essential to strengthen collaborative skills and leadership among students. Additionally, expanding the use of microteaching and role-playing methods will foster deeper student engagement, particularly in the areas of experimental design and interdisciplinary integration. Emphasizing the development of soft skills within laboratory settings is also crucial. Furthermore, improving laboratory design and ensuring that resources align with experiential learning principles will enhance the overall learning experience. To support reflective learning and competency growth, continuous feedback mechanisms, such as self-assessments and peer evaluations, should be integrated into the curriculum. Faculty development programs that align with CDIO principles are necessary to refine teaching strategies and improve the learning environment. Finally, further research should investigate the long-term impact of CDIO interventions on the retention of laboratory competencies and explore its potential application across various academic disciplines to broaden its benefits in educational settings.

Declarations

Author Contributions. Giac Cu Cao. & Giang Van Thi Cao.: Literature review, conceptualization, Hiep Thu Thi Le., Duc Mau Nguyen. & Huyen Bich Thi Vo.: methodology, data analysis. Giac Cu Cao. & Duc Mau Nguyen.: review-editing and writing, original manuscript preparation. All authors have read and approved the final version of the article.

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Ethical Approval. Data for this quantitative study were collected through anonymous surveys, and the personal information of the participants was not collected. Additionally, instructors and students' consent was granted before the data collection process.

Ethical statement. The authors stated that the study was conducted in accordance with ethical standards and meets the ethical standards stipulated in Decision No 3077/QĐ-ĐHSPHN dated August 15th, 2024, on "Academic Integrity Regulations of Hanoi National University of Education" The research was conducted in strict compliance with academic ethics and research ethics. Informed consents were obtained from the participants.

Data Availability Statement. Data for this study is available upon request.

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