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Inquiry Laboratory – Application of Inquiry-Based Learning in Technical Education*

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Abstract

The dynamic transformations in engineering education necessitate a shift from reproductive teaching methods towards active, student-centered approaches. Inquiry-Based Learning (IBL) has emerged as an effective tool for developing students' cognitive autonomy and research-oriented thinking. The purpose of this paper is to propose and analyze the Inquiry-Based Laboratory for Engineering (IBL-E) model as an educational framework supporting the development of engineering competencies through Inquiry-Based Learning. The IBL-E model was developed based on a literature review and didactic observations. It consists of four phases: problem definition, experimentation, reflection, and validation of results. Simulation tools such as *MATLAB, VISSIM, PyroSim,* and *Ansys* were used, along with a digital portfolio system for assessing students' progress.Implementation of the IBL-E model enhanced student engagement and independence, promoted the development of systemic and critical thinking, and improved understanding of complex technical processes. The study also identified limitations related to staff preparation and laboratory infrastructure, which constitute directions for future research in engineering pedagogy.

Keywords: engineering pedagogy, technical education, Inquiry-Based Learning, inquiry laboratory, IBL-E model, research-based teaching

Introduction

Contemporary higher education, particularly in the fields of engineering and technical sciences, is undergoing an intensive phase of transformation driven by the dynamic development of technology, the ongoing digitalization of industrial processes, and the global shift toward a knowledge-based economy. These transformations create the need for a new approach to educating future engineers—individuals capable not only of applying established technical solutions but, above all, of engaging in creative thinking, critical analysis of problems, the search for innovative solutions, and decision-making under conditions of uncertainty. In this context, traditional teaching models, based on knowledge transmission and the mechanical execution of tasks, have become insufficient for developing the competencies required in the twenty-first century. Increasingly, there is a growing emphasis on transitioning from a transmissive to a constructivist model, in which the student becomes an active participant in the learning process, while the teacher assumes the role of moderator and guide in the exploration of science and technology.

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One of the most promising approaches responding to this paradigm shift is **Inquiry-Based Learning (IBL)**, a method that assumes the research process itself as the core mechanism of learning. IBL emphasizes independent formulation of questions, planning of experiments, collection and analysis of data, and interpretation of results in the light of existing theoretical knowledge. In the didactic dimension, IBL aligns with the tradition of discovery learning while extending the principles of social constructivism, where learning is a communal process built upon dialogue, collaboration, and reflection on experience. In the context of engineering education, IBL serves as a tool that not only strengthens students' cognitive engagement but also prepares them for work environments that demand continuous learning, the ability to solve complex technical problems, and the integration of knowledge from multiple disciplines.

The introduction of IBL into engineering and technical education requires rethinking the role of the laboratory, which traditionally functions as a setting for consolidating theoretical knowledge and acquiring practical skills under controlled conditions. In the **inquiry laboratory** model, the focus shifts from reproducing known procedures to processes of exploration—searching, experimenting, reasoning, and discussing. Students confronted with open-ended problems, whose solutions are not predetermined, take on the role of researchers: they formulate hypotheses, design experiments, analyze results, and subject their findings to critical evaluation. Such forms of activity promote the development of higher-order cognitive competencies—particularly analysis, synthesis, evaluation, and creative thinking—as well as soft skills such as communication, teamwork, and accountability for shared outcomes.

The application of Inquiry-Based Learning in technical disciplines, however, presents specific challenges. It requires that academic teachers shift their role—from transmitters of knowledge to mentors who facilitate self-directed learning. It also necessitates adjustments in the didactic infrastructure: traditional laboratories are often designed for replicating fixed experiments, while inquiry laboratories must provide space for open exploration and hypothesis testing. Organizational and cultural factors also play an important role—students must be ready to take greater responsibility for their own learning processes and to accept ambiguity and error as natural elements of scientific inquiry.

Research on the effectiveness of IBL in engineering education indicates that the method can significantly improve learning outcomes, particularly in understanding complex technical processes, transferring knowledge between theory and practice, and developing cognitive self-regulation skills. Numerous academic institutions around the world have implemented IBL in technical courses such as mechanics, automation, electrical engineering, and computer science, often incorporating digital and simulation-based environments. The results of these implementations show that inquiry learning fosters deeper conceptual understanding, greater motivation to learn, and enhanced research competencies among students. At the same time, questions remain concerning the scalability of the method in large groups, assessment of student progress in open-ended tasks, and the integration of IBL with formal requirements of engineering curricula.

The purpose of this article is to propose and analyze the Inquiry-Based Laboratory for Engineering (IBL-E) model as an educational framework supporting the development of engineering competencies through the application of Inquiry-Based Learning. The authors seek to identify the potential and limitations of IBL in technical education, highlighting its connections with constructivism, problem-based pedagogy, and project-based learning. The paper also presents the design assumptions and examples of implementing inquiry laboratories in selected technical disciplines, with attention to organizational, methodological, and evaluation aspects. These reflections aim not only to demonstrate the practical adaptability of IBL in engineering and technical education but also to consider its broader implications for the didactic culture of technical universities.

Literature Review

The Inquiry-Based Learning (IBL) method has gained significant recognition in recent decades, particularly in science education, where it is frequently applied in the teaching of biology, chemistry, and physics, with a strong emphasis on the development of higher-order cognitive skills such as analysis, evaluation, and creation. In a meta-analysis of 26 studies, Antonio and Prudente (2024) report that inquiry-based approaches exert a strong and positive effect on higher-order learning outcomes, with an average effect size of *Hedges'g = 0.893* (ERIC). They also note that the effectiveness of IBL is not strongly dependent on educational level, subject domain, or degree of inquiry (confirmation, guided, or open); all levels can be effective, provided adequate pedagogical support is available (ERIC).

However, most existing research focuses on science education, while the application of IBL in engineering and technical education, particularly in laboratory contexts, remains relatively limited. In this regard, Beck et al. (2014) observe that *guided inquiry* formats dominate in laboratory settings, whereas fully *open inquiry* approaches are rarely implemented due to logistical, resource, and pedagogical constraints (PMC). The authors emphasize the need for *scaffolding* and differentiated levels of guidance to ensure student success in exploratory tasks.

Within the field of engineering education, the literature highlights both the potential benefits and the challenges of applying IBL. Jungmann, in the chapter *"Inquiry-Based Learning in the Engineering Sciences"* (Springer), argues that IBL can serve as a design principle for educational environments, supporting not only the development of technical competencies but also interdisciplinary and critical thinking skills (SpringerLink). The authors of this approach suggest that engineering laboratories and experimental lectures are natural interfaces for integrating IBL into academic curricula (SpringerLink).

Luo et al. (2023) explore the integration of *Process Oriented Guided Inquiry Learning (POGIL)* into an engineering course as a modification of traditional IBL, combining procedural structure with elements of independent inquiry (Taylor & Francis Online). Their findings suggest that POGIL models can serve as an intermediary form between full guidance and full student autonomy, thereby lowering entry barriers for less experienced learners (Tandf Online).

In a more recent study in the area of software engineering education, Ahmed et al. (2025) apply a multi-level inquiry approach (confirmation, structured, guided, open) in a programming course using the *MILOS* system, which allows students to progress through increasing levels of inquiry. In an experiment involving 54 students, the system demonstrated higher learning effectiveness and acceptance compared to traditional tools such as *Sololearn* (Frontiers). This multi-level model appears to be a promising direction for technical education, as it enables a gradual introduction of students into the process of research and exploration.

Shi et al. (2025), in *Physical Review Physics Education Research*, examine the effects of inquiry-based learning and group composition on learning outcomes in physics education. Their results show that such approaches can significantly enhance conceptual understanding, although the outcomes depend on group organization and the nature of instructional support (link.aps.org).

The didactic literature also includes a discussion on combining IBL with more traditional teaching strategies. De Jong et al. (2023) argue that the most effective results arise from *hybrid approaches*, where inquiry is complemented by direct instruction—particularly in cases where students need preliminary orientation or conceptual scaffolding (ScienceDirect).

A critical issue in inquiry-based laboratories is the management of student teams and fairness in role distribution. Quinn et al. (2020) demonstrate that in less structured laboratory environments (those closer to open inquiry), systematic gender-based differences tend to emerge in how roles are distributed within teams. This highlights the need for deliberate instructional design and moderation of group work to ensure equitable participation (arXiv).

In the context of engineering education and online laboratories, Dunmoye et al. (2023) review the effectiveness of remote laboratory implementations. Although not all such laboratories are explicitly inquiry-oriented, the authors note that many online solutions lack sufficient opportunities for exploration and interaction (peer.asee.org). This points to the necessity of designing online laboratory environments that integrate inquiry mechanisms—such as simulation tools and shared virtual platforms—to sustain student engagement and inquiry processes.

In summary, the literature review reveals several key conclusions and research gaps:

Effectiveness of IBL in developing higher-order cognitive competencies.

Meta-analyses and studies in science education confirm a strong, positive influence of IBL on analytical, critical, and creative thinking (Antonio & Prudente, 2024; ERIC), although its success depends on the level of instructional support and the degree of inquiry (guided vs. open).

Preference for guided inquiry in educational contexts.

Most academic laboratories adopt *guided inquiry* formats due to constraints related to time, resources, student preparedness, and curricular requirements (Beck et al., 2014; PMC).

Hybrid and multi-level models as promising directions for adaptation.

Combining structured elements (instruction, cues) with autonomy—such as in the *POGIL* model for engineering (Luo et al., 2023; Tandf Online) or *MILOS* in programming education (Ahmed et al., 2025; Frontiers)—appears to be an effective way to introduce IBL in technical education.

Organizational, pedagogical, and social challenges:

- The need for instructor competence in facilitating and scaffolding inquiry.
- The requirement for flexible infrastructure (experimental labs, simulation tools, online platforms).
- Difficulties in assessing student performance in open-ended tasks.
- Asymmetry of student roles (e.g., workload distribution) in less structured laboratories (Quinn et al., 2020; arXiv).
- The risk of frustration or error when autonomy is not adequately supported.

Lack of interdisciplinary and long-term studies in engineering education.

Despite well-established IBL frameworks in science education, its adaptation in technical and engineering contexts remains insufficiently documented. There is a particular lack of longitudinal studies, comparative analyses of open vs. guided models, and large-scale research across student populations.

Despite the growing body of research on Inquiry-Based Learning in science education, the engineering and technical education domains remain relatively underexplored. Existing studies focus predominantly on natural sciences, while empirical analyses and methodological models tailored specifically to engineering laboratory environments are scarce. There is a noticeable absence of structured frameworks that integrate inquiry-based processes with simulation tools, interdisciplinary teamwork, and authentic industrial contexts. This gap in the literature demonstrates a need for conceptual and methodological development that would allow the adaptation of IBL principles to the realities of technical universities. The present study addresses this deficiency by proposing a coherent model – the Inquiry-Based Laboratory for Engineering (IBL-E) – designed to operationalize inquiry learning in engineering education.

Therefore, the purpose of this article—to propose and analyze the Inquiry-Based Laboratory for Engineering (IBL-E) model as a framework for developing engineering competencies—addresses a significant research gap. The proposed model should incorporate recommendations from the literature (such as the use of hybrid formats, structured support, and group balance) while remaining experimentally verifiable in real-world technical and laboratory settings.

Methodology

Implementing the Inquiry-Based Learning (IBL) method in engineering and technical sciences requires a fundamental shift in the didactic paradigm—from a reproductive model based on the execution of predetermined procedures to an exploratory model in which the student assumes the role of an active researcher. The proposed Inquiry-Based Laboratory for Engineering (IBL-E) model was developed based on an analysis of the relevant literature and observations of teaching practices in technical higher education environments. This model integrates the student's cognitive process with engineering practice through four consecutive phases that together form a closed research–educational cycle.

The first stage, Problem Framing, involves confronting the student or student team with an open-ended engineering problem, typically rooted in a real-world technical context. The aim of this phase is for students to independently define the scope of inquiry, formulate working hypotheses, and identify key input data and experimental parameters. In this approach, the role of the instructor is redefined—from a transmitter of knowledge to a mentor and facilitator of learning who inspires students to formulate research questions, supports problem identification, and helps them refine the focus of their inquiry.

The second phase, Exploration and Experimentation, includes the planning and execution of the research process. This stage covers the design of experiments, the selection of tools and measurement methods, the execution of laboratory or simulation-based experiments, and the preliminary interpretation of results. The flexibility of the laboratory environment is crucial here—its infrastructure should support both classical physical experiments and complex digital or hybrid analyses. Contemporary engineering laboratories increasingly employ integrated computational tools such as MATLAB, Simulink, FlexSim, LabVIEW, ArcGIS, and Power BI, as well as data drawn from real technical environments, including IoT systems and open data repositories. The use of these technologies enables students to engage in authentic exploratory research and enhances their understanding of processes occurring within real engineering systems.

The third stage, Reasoning and Reflection, represents a pivotal point in the inquiry cycle. At this stage, participants analyze the collected data, compare the obtained results with literature, technical standards, and theoretical assumptions, and then formulate conclusions addressing their initial hypotheses. A critical aspect of this phase is the development of metacognitive reflection, which includes evaluating one's own research strategies, decision-making processes, and interpretation of findings. The instructor's role focuses on moderating the analysis process, posing questions that deepen understanding, and guiding discussions toward theoretical generalizations. This phase is essential for cultivating critical thinking, data analysis, and scientific argumentation skills.

The final stage, Validation and Application, concerns the practical verification and application of the research results within the context of real engineering requirements. Students confront their findings with applicable technical norms, safety regulations, design standards, or efficiency criteria. The outcomes of the inquiry typically take a practical form—a prototype, technical report, system improvement proposal, simulation model, or recommendations for engineering practice. This phase concludes with the presentation of results in the form of a research report, scientific poster, or short publication, reinforcing students' skills in technical communication and the dissemination of research outcomes.

The proposed IBL-E model is supported by a set of complementary elements that facilitate its effective implementation in academic settings. A key component is didactic scaffolding—a system of gradual methodological support that diminishes as students' competencies develop, transitioning from guided inquiry in the early stages to open inquiry at advanced levels. This allows the level of autonomy to be aligned with students' experience and cognitive readiness. Another essential component is a multi-level assessment system, which evaluates not only the technical outcome but also the inquiry process itself—student engagement, teamwork, reflective capacity, and the ability to construct scientific arguments.

The IBL-E model also assumes the operation of interdisciplinary teams, involving students from various specializations—such as safety engineering, logistics, or transport—which fosters the exchange of perspectives and the integration of knowledge across technical domains. Furthermore, the model emphasizes the role of a digital learning environment, incorporating data repositories, electronic portfolios, project management systems, and communication platforms that support documentation, collaboration, and real-time research exchange.

Applying the inquiry laboratory methodology in engineering and technical education creates an educational environment in which learning becomes closely aligned with the research and design practices of modern industry. The IBL-E model enables students to develop not only technical knowledge and skills but also higher-order cognitive competencies—critical thinking, problem solving, scientific reasoning, and teamwork. Consequently, the laboratory evolves from a space of procedural training into a setting for the authentic construction of engineering knowledge through processes of inquiry, experimentation, and reflection.

Analysis of the Model's Application in Selected Disciplines

The proposed Inquiry-Based Laboratory for Engineering (IBL-E) model represents an innovative tool for supporting engineering education through the integration of research, simulation, and professional practice. Its implementation potential is particularly evident in disciplines characterized by complex technical processes and the need for risk analysis and system optimization—such as safety engineering, transport and technical logistics, and materials engineering. In each of these domains, the inquiry laboratory transforms the learning process from a transmissive to an exploratory mode, enabling students to develop research, reflective, and decision-making skills.

In the field of safety engineering, the inquiry laboratory enables in-depth modeling and analysis of risk phenomena in technical, process, and infrastructure environments. During laboratory sessions, students engage with problems inspired by real industrial contexts that require hypothesis formulation, selection of research methods, and interpretation of results. Typical topics include the analysis of causes of technical system failures, evacuation simulations in buildings or vehicles, modeling of environmental hazard effects, and evaluation of the effectiveness of personal protective equipment. The use of specialized tools such as Pathfinder, PyroSim, FDS, and CFD simulations allows for realistic visualization of phenomena and hypothesis testing under controlled conditions.

In this context, students act as safety analysts and system designers who not only seek answers to research questions (for example, "How can the alarm system in an industrial facility be optimized?") but also construct their own risk assessment models and formulate recommendations for technical systems. Such activity fosters the development of competencies related to hazard identification, risk analysis, decision-making under uncertainty, and critical interpretation of safety standards and procedures.

Comparable educational benefits are observed in the area of transport and technical logistics, where the inquiry laboratory takes the form of a simulation-analytical environment. Participants analyze vehicle flow, design transportation systems, model disruptions in supply chains, or develop intelligent mobility strategies. Using tools such as VISSIM, SUMO, AnyLogic, and MATLAB/Simulink, students formulate research problems focused on improving traffic throughput, reducing collision points, or optimizing logistics routes. The outcomes of such inquiry processes may include decision models, Smart Mobility projects, or policy recommendations for sustainable transport systems.

In materials engineering, the inquiry laboratory allows students not only to conduct experiments but also to develop an independent understanding of the causes and mechanisms underlying material behavior under specific technological conditions. Students learn to reason critically based on observations and to connect experimental results with the functional properties of materials. The inquiry laboratory enables them to formulate research questions (e.g., "Why does the hardness of steel change after heat treatment?" or "Which factors influence its microstructure?"), to hypothesize about relationships between structure, process, and properties, and to design and conduct experiments using measurement techniques, empirical data analysis, and theoretical interpretation.

From a didactic perspective, such laboratories foster the development of systemic analysis, modeling, and data interpretation skills. The IBL-E model supports the cultivation of social responsibility and ecological awareness among future engineers. Through teamwork and interdisciplinary collaboration, students develop technical communication, cooperation, and critical evaluation skills—all of which are essential competencies in professional engineering practice.

The indicators presented in Table 1 provide a systematic framework for evaluating the effectiveness of the IBL-E model implementation within the context of engineering education. They encompass cognitive, procedural, and organizational dimensions, allowing for an assessment of the academic environment's maturity in adopting inquiry-based methodologies. This multidimensional evaluation supports continuous improvement of teaching practices, the optimization of laboratory infrastructure, and the enhancement of student research competencies.

Table 1. Criteria and Indicators for Assessing the Effectiveness of IBL-E Model Implementation

Evaluation Category	Criterion	Qualitative / Quantitative Indicators	Method of Measurement / Observation
Didactic Process	Active student participation	Participation in discussions; number of research initiatives	Observation; analysis of project reports
	Cognitive autonomy	Number of formulated hypotheses; degree of experiment modification	Student portfolio assessment; interviews
	Metacognitive reflection	Quality of self-reflection in reports; identification of errors	Content analysis of research reports
Learning Outcomes	Understanding of technical phenomena	Accuracy of models; validity of conclusions	Expert evaluation; competency tests
	Knowledge transfer	Ability to apply theoretical concepts in practice	Analysis of applied project work
Laboratory Organization	Infrastructure availability	Number and diversity of simulation tools	Audit of educational resources
	Instructor competencies	Participation in training; didactic publications	University documentation; surveys
Overall Effects	Student satisfaction and motivation	Evaluation results in surveys; attendance rate	Questionnaire surveys; semester analysis
	Project interdisciplinarity	Number of cross-disciplinary teams	Analysis of project team composition

Source: Author's own elaboration based on didactic implementation observations (2025).

Table 2: Application of the IBL-E Model in Selected Technical Disciplines

Discipline	Example Areas of Application	Tools / Research Environments	Expected Didactic Outcomes
Safety Engineering	Analysis of technical system failures; evacuation modeling; environmental risk assessment; testing of personal protective equipment	Pathfinder, PyroSim, FDS, ANSYS CFD, MATLAB	Development of risk analysis skills, decision-making under uncertainty, and interpretation of technical standards
Transport and Technical Logistics	Traffic flow analysis; infrastructure optimization; supply chain modeling; electromobility simulations	VISSIM, SUMO, AnyLogic, FlexSim, ArcGIS, Power BI	Development of systemic competencies, modeling skills, and awareness of safety and sustainable development
Materials Engineering	Support for selecting engineering materials in technical design using Ashby charts, databases, and simulations; analysis of material microstructure and 3D modeling; analysis of thermodynamic and microstructural relationships in metallic materials and alloys without the need for costly laboratory experiments	ANSYS Granta EduPack, DREAM.3D, Thermo-Calc	Learning data-driven and analytical engineering thinking; developing awareness of engineers' responsibility in material-related decisions that impact safety, cost, and the environment
Automation and Robotics (possible extension)	Adaptive process control; simulation of cyber-physical system failures	Simulink, LabVIEW, TwinCAT	Enhanced competencies in simulation, automation, and integration of technical systems

Source: Author's own elaboration.

The data summarized in Table 2 indicate that the IBL-E model possesses a universal character and can be adapted to various technical disciplines through the appropriate selection of tools, the scope of research problems, and the level of methodological support (*scaffolding*). In safety engineering, the focus is placed on risk analysis and hazard modeling, while in transport engineering, the emphasis shifts toward the simulation of flow processes and infrastructure planning. In each case, the inquiry laboratory functions as a project-oriented research environment in which learning occurs in a reflective, iterative, and practically oriented manner.

The implementation of the IBL-E model yields measurable didactic and cognitive benefits, including increased student motivation, improved understanding of complex technical phenomena, and the development of research and innovation competencies. However, successful application requires academic staff preparation for the role of mentors, the enhancement of simulation and laboratory infrastructure, and the development of assessment systems that recognize the inquiry process as an educational value in its own right.

The application of this model in fields such as safety engineering and transportation confirms its potential as an effective tool for supporting the transformation of technical education toward the cultivation of reflective, responsible, and innovative engineers.

Discussion

The results of the analyses and the developed Inquiry-Based Laboratory for Engineering (IBL-E) model indicate that the application of the Inquiry-Based Learning (IBL) method in engineering and technical sciences can serve as an effective tool for enhancing educational quality and supporting the development of students' cognitive and practical competencies. The model, which consists of four phases—problem framing, experimentation and exploration, reasoning and reflection, and validation and application—aligns with the shift from transmissive to constructivist pedagogy, consistent with the recommendations of De Jong et al. (2023), who advocate for a balance between direct instruction and autonomous inquiry. Observations confirm that a structured approach based on the gradual introduction of students into the research process helps maintain equilibrium between cognitive autonomy and didactic safety, a critical factor for success in engineering education.

The application of the IBL-E model in teaching materials engineering is particularly justified by the interdisciplinary nature of this field, which combines elements of both fundamental and applied sciences. The IBL-E approach, grounded in scientific inquiry and self-directed knowledge construction, is especially effective in disciplines where learning is driven by observation, experimentation, and empirical data analysis. Students are required to plan experiments, perform measurements, process and interpret data using software tools such as ANSYS Granta EduPack, Dream 3D, or Thermo-Calc. This fosters data analysis, result visualization, and research reporting skills essential for industrial and scientific environments. Instead of relying on predetermined solutions, the IBL-E model encourages students to formulate their own questions, hypotheses, and conclusions—developing causal reasoning, technical argumentation, and the ability to make engineering decisions based on experimental data and multi-criteria evaluation (strength, cost, environmental impact, durability).

The application of the IBL-E model in safety engineering and transport demonstrates important differences in implementation arising from the specific nature of each discipline. In safety engineering, problems are often characterized by a high degree of uncertainty and risk, requiring students to critically analyze and assess the technical consequences of decisions. Inquiry-based laboratories in this field allow students to develop competencies in risk assessment, interpretation of standards and procedures, and the simulation of complex phenomena using tools such as Pathfinder, PyroSim, FDS, and ANSYS CFD. In transport and technical logistics, inquiry takes the form of process and system modeling, enabling simulations of flows, analysis of infrastructure efficiency, and supply chain optimization through tools such as VISSIM, SUMO, and AnyLogic. In both contexts, the primary didactic outcome is the enhancement of analytical and systemic thinking and a deeper understanding of the relationship between theory and practice.

The implementation results of the IBL-E model are consistent with the findings of Beck et al. (2014), who note that even partial adoption of inquiry-based forms (guided inquiry) can significantly improve student engagement and comprehension. Similarly, Luo, Chen, and Li (2023) show that intermediate models such as Process Oriented Guided Inquiry Learning (POGIL) may serve as effective transitional frameworks between directive teaching and fully open inquiry. For engineering students still developing research experience, this approach mitigates cognitive risk while preserving autonomy and discovery-oriented learning.

From a didactic perspective, the findings corroborate the observations of Antonio and Prudente (2024), who emphasize that IBL significantly strengthens higher-order cognitive skills such as analysis, evaluation, and creation. In engineering disciplines, these competencies translate directly into the ability to solve complex technical problems, interpret experimental data, and design innovative solutions. Moreover, the application of IBL-E in digital environments (simulation tools, IoT data, CAD/CAE software) supports the acquisition of skills relevant to Industry 4.0, including data analytics, process modeling, and human-machine collaboration.

However, the discussion also reveals certain limitations and areas for further research. First, the model's effectiveness depends heavily on the competence of teaching staff, particularly their ability to moderate the inquiry process. The instructor assumes the role of mentor and facilitator, which requires pedagogical preparation and familiarity with scaffolding strategies. As emphasized by Beck et al. (2014) and De Jong et al. (2023), inadequate instructor support may reduce the effectiveness of IBL, especially among less advanced groups.

Second, organizational and infrastructural challenges remain significant. The model requires flexible laboratory spaces, access to advanced simulation tools, and sufficient time to complete the full research cycle.

Third, assessment of learning outcomes poses an additional challenge. As noted by Shi et al. (2025), evaluating student performance in open inquiry environments requires a multidimensional approach that considers not only the final product but also the process itself—reflection, argumentation, collaboration, and metacognitive development. In the context of IBL-E, this necessitates the use of tools such as e-portfolios, peer assessment, and individualized progress criteria, as reflected in Table 1 of this study.

Social and cultural factors also play an important role. Quinn et al. (2020) highlight the unequal distribution of roles in laboratory teams, often influenced by gender or working styles, which can affect cognitive balance and collaboration efficiency. In engineering laboratories, this underscores the importance of deliberate team design and rotation of roles to ensure equitable participation in experimental activities. Finally, there is a need for comparative and longitudinal studies to verify the long-term effectiveness of the IBL-E model across larger student populations.

Overall, the findings confirm that the IBL-E model constitutes a valuable instrument for transforming technical education. Its implementation leads to greater student engagement, improved understanding of complex technical phenomena, and the development of research and innovation competencies. At the same time, its adoption requires organizational adaptation, academic staff support, and assessment system redesign. Due to its flexibility, the IBL-E model can be successfully applied across various engineering disciplines, serving as a bridge between traditional laboratory instruction and the research-oriented learning environments of modern technical education. Despite its demonstrated potential, the IBL-E model also entails several methodological and practical limitations. First, its effectiveness depends strongly on the pedagogical competence and engagement of instructors, who must act as facilitators rather than transmitters of knowledge. Second, the model requires flexible laboratory infrastructure and sufficient time to complete the full inquiry cycle, which may be difficult to achieve in courses with limited contact hours or resources. Third, assessment of student performance in open inquiry environments remains challenging and may lead to subjectivity if not supported by clear rubrics and reflective tools such as e-portfolios. Finally, students' preparedness and motivation levels can vary significantly, necessitating differentiated scaffolding strategies to maintain both autonomy and didactic safety. These constraints indicate that successful implementation of the IBL-E methodology requires institutional support, instructor training, and gradual integration into existing curricula.

The novelty of this study lies in the development and conceptualization of the Inquiry-Based Laboratory for Engineering (IBL-E) model, which adapts the principles of Inquiry-Based Learning to the specific requirements of engineering education. Unlike existing approaches that focus mainly on science disciplines or general didactic frameworks, the IBL-E model integrates inquiry processes with simulation tools, interdisciplinary teamwork, and multi-level assessment tailored to technical fields. This study provides a structured framework linking the phases of inquiry—problem framing, experimentation, reflection, and validation—with engineering practice, thus bridging the gap between theoretical IBL models and their application in laboratory-based technical education. The paper therefore contributes to the advancement of research in engineering pedagogy by defining a transferable model that can be adapted to diverse technical disciplines and validated in real academic environments.

Summary

The conducted analysis confirms that the implementation of the Inquiry-Based Learning (IBL) method in engineering and technical education significantly enhances the quality and effectiveness of the learning process. The paper has proposed and analyzed the Inquiry-Based Laboratory for Engineering (IBL-E) model as an educational framework for enhancing engineering competencies through Inquiry-Based Learning. The proposed Inquiry-Based Laboratory for Engineering (IBL-E) model, comprising four interrelated phases—problem framing, experimentation and exploration, reasoning and reflection, and validation and application—forms a coherent research–didactic cycle that integrates scientific inquiry with engineering practice. This model transforms traditional laboratories into spaces of discovery, reflection, and innovation, where students construct knowledge through investigation rather than the reproduction of predefined content.

The application of the IBL-E model in disciplines such as safety engineering, transportation, and materials engineering confirms its flexibility and interdisciplinary character. In the field of safety engineering, the model supports the analysis of complex risk phenomena and the development of decision-making competencies under conditions of uncertainty. In transport and technical logistics, it fosters systemic and analytical thinking through modeling, simulation, and data interpretation. In materials engineering, the model encourages the integration of knowledge from physics, chemistry, mechanics, and thermodynamics in addressing practical material-related problems. Students do not acquire information passively but apply it in solving authentic engineering challenges—for example, selecting materials with specific performance parameters, analyzing the influence of microstructure on mechanical properties, or assessing the operational durability of components.

In all these cases, the method promotes the development of higher-order skills—critical thinking, problem-solving, and evidence-based reasoning.

At the same time, the findings highlight certain limitations of the model related to faculty preparedness, infrastructural requirements, and assessment methods. Therefore, institutional support and the enhancement of pedagogical competencies among academic staff are essential for successful implementation. Despite these challenges, the IBL-E model represents a valuable instrument for modernizing engineering education, facilitating the transition toward the training of reflective, responsible, and innovative engineers—aligned with the principles of Industry 4.0 and the concept of lifelong learning.

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