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METHODS OF CONDUCTING LABORATORY CLASSES IN HIGHER EDUCATION INSTITUTIONS: A REVIEW OF INSTRUCTIONAL APPROACHES AND THEIR PEDAGOGICAL EFFECTIVENESS

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Abstract. Laboratory classes are a central component of science, engineering, and technical education, yet the way they are conducted varies widely across higher education institutions. This article reviews the principal methods of organizing laboratory instruction and compares their pedagogical characteristics. A narrative review of peer-reviewed literature on laboratory instruction was conducted, and the identified approaches were classified by the degree of student autonomy, the type of learning environment, and the role of the instructor. Four groups of methods were identified: (1) expository (traditional "cookbook") laboratories, (2) inquiry-based and discovery laboratories, (3) problem-based and project-based laboratories, and (4) technology-mediated laboratories, including virtual, remote, and blended formats. The literature suggests that expository laboratories are efficient for developing basic manipulative skills but limited in fostering conceptual understanding and scientific reasoning, whereas inquiry- and problem-based approaches better support higher-order thinking when adequately scaffolded. Virtual and remote laboratories can achieve learning outcomes comparable to hands-on work, and the strongest results are often reported for blended designs. The article concludes that no single method is universally superior; effective laboratory instruction depends on aligning the method with explicit learning outcomes, providing pre-laboratory preparation, and using structured assessment and feedback.

Keywords: laboratory instruction; higher education; inquiry-based learning; virtual laboratories; blended learning; experiential learning; engineering education

Introduction. Laboratory work has long been regarded as a distinctive and indispensable element of university education in the natural sciences, engineering, medicine, and related fields. It is expected to connect theory with practice, develop practical and experimental skills, foster scientific reasoning, and cultivate attitudes such as precision, teamwork, and responsibility (Hofstein & Lunetta, 2004; Feisel & Rosa, 2005).

Despite this recognized importance, the effectiveness of laboratory instruction has been repeatedly questioned. Early reviews concluded that the educational value of laboratory work was often assumed rather than demonstrated, and that many laboratory courses focused on following procedures rather than on thinking about the underlying science (Hofstein & Lunetta, 1982; Hodson, 1993). Later work argued that the outcomes depend less on the mere presence of a laboratory than on how it is designed and conducted (Hofstein & Lunetta, 2004).

In recent years, several developments have added complexity to this question. Growing student numbers, limited equipment budgets, and safety requirements put pressure on traditional laboratory formats. At the same time, digital technologies have made simulations, remote-access laboratories, and hybrid formats widely available (de Jong et al., 2013). Higher education institutions therefore face a practical choice among many possible methods of conducting laboratory classes.

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The purpose of this article is to systematize the main methods of conducting laboratory classes in higher education and to analyze their pedagogical strengths and limitations. The review addresses three questions:

1. What main methods of organizing laboratory classes are described in the literature?
2. How do these methods differ in terms of student autonomy, learning environment, and the instructor's role?
3. What conditions make laboratory instruction effective in a university setting?

Methods. Research design. A narrative literature review was chosen because the aim was to synthesize and compare conceptual and empirical work on instructional approaches, which differ substantially in context, discipline, and outcome measures. A meta-analytic procedure was therefore not appropriate.

Sources and selection. Sources were identified through searches of major academic databases and journals in science education, chemistry education, and engineering education. Search terms combined *laboratory instruction*, *laboratory teaching methods*, *inquiry-based laboratory*, *problem-based laboratory*, *virtual laboratory*, *remote laboratory*, *pre-laboratory activities*, and *higher education*. Foundational reviews and frequently cited empirical and comparative studies were prioritized. The following inclusion criteria were applied:

- the work addressed laboratory instruction at the undergraduate or university level;
- the work described, compared, or evaluated a method of conducting laboratory classes;
- the work was published in a peer-reviewed journal or a recognized scholarly outlet.

Analytical framework. The selected works were analyzed thematically. Each described method was coded according to three dimensions: (a) the degree of student autonomy in designing the procedure and interpreting results, (b) the type of environment (physical, virtual, remote, or blended), and (c) the role of the instructor (director, facilitator, or coach). This coding was used to group the methods into the categories presented in the Results section. Domin's (1999) classification of laboratory instruction styles served as a starting framework and was extended to include technology-mediated formats.

Limitations of the method. As a narrative review, the study does not claim exhaustiveness, and the selection of sources may reflect the author's judgment. Findings from different disciplines and countries are not directly interchangeable, and the conclusions should be interpreted accordingly.

Classification of laboratory instruction methods. The analysis identified four main groups of methods. Their characteristics are summarized in Table 1.

Table 1. Main methods of conducting laboratory classes in higher education

Method	Problem posed	Procedure	Student autonomy	Instructor's role	Typical purpose

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Method	Problem posed	Procedure	Student autonomy	Instructor's role	Typical purpose
Expository ("cookbook")	Given by instructor	Given by instructor	Low	Director	Skills, verification of known theory
Inquiry / discovery	Given or partly open	Designed by students (fully or partly)	Medium to high	Facilitator	Reasoning, concept building
Problem-based / project-based	Open, often real-world	Designed by students or teams	High	Coach / mentor	Integration, teamwork, design
Technology-mediated (virtual, remote, blended)	Varies	Varies	Varies	Facilitator / designer	Access, flexibility, preparation

Expository laboratories. In expository laboratories, students receive a detailed procedure and a known expected outcome, and their task is to carry out the steps and report results. This format is the most widespread because it is predictable, easy to administer with large groups, and relatively inexpensive to prepare (Domin, 1999). It is effective for teaching standard manipulative skills, safe equipment handling, and basic measurement techniques. However, the literature repeatedly notes that students can complete such laboratories while thinking little about the purpose of the experiment, since the cognitive demand is concentrated on following instructions (Hodson, 1993; Domin, 1999).

Inquiry-based and discovery laboratories. In inquiry-based laboratories, students investigate a question, plan or modify the procedure, collect data, and construct explanations. Discovery laboratories typically keep the procedure guided but hide the expected outcome, so that students identify patterns themselves (Domin, 1999). These approaches are consistent with broader evidence that active learning improves performance in science and engineering courses (Freeman et al., 2014) and with structured models of instruction such as the 5E cycle (Bybee et al., 2006). Reviews indicate that inquiry formats can improve conceptual understanding and scientific reasoning, but they also increase cognitive load and require carefully designed guidance, particularly for novice students (Hofstein & Lunetta, 2004).

Problem-based and project-based laboratories. In problem-based and project-based formats, students work, usually in teams, on open, authentic problems that may extend over several sessions. These formats are described as effective for integrating knowledge across topics, developing design and communication skills, and encouraging collaboration, which aligns with the objectives that engineering educators set for laboratories (Feisel & Rosa, 2005). Reported challenges include higher instructor workload, difficulties in assessing individual contributions, and the need for more time and resources.

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Technology-mediated laboratories. Virtual laboratories use simulations, while remote laboratories give students real-time control of physical equipment through a network. Comparative reviews report that, in many studies, learning outcomes in virtual and remote laboratories are equal to or better than those in traditional hands-on laboratories, although the results depend on the outcome measured and the quality of design (Ma & Nickerson, 2006; Brinson, 2015). Simulations are particularly useful when equipment is costly, experiments are hazardous, or phenomena are difficult to observe directly. However, they cannot fully replace the development of practical skills that arise from manipulating real apparatus. de Jong et al. (2013) argue that physical and virtual environments are complementary and that combining them can leverage the strengths of each.

Kolb-based and pre-laboratory designs. Two design features appear across several methods. First, applying the experiential learning cycle (concrete experience, reflective observation, abstract conceptualization, active experimentation) to laboratory design has been proposed to structure work, and virtual or remote activities have been used to support the preparatory and reflective phases (Kolb, 1984; Abdulwahed & Nagy, 2009). Second, pre-laboratory activities such as short quizzes, videos, or simulations are reported to reduce cognitive overload during the session and to help students concentrate on the purpose of the experiment (Agustian & Seery, 2017).

Conditions associated with effective laboratory instruction. Across the reviewed literature, several conditions recur:

- **Clear learning outcomes.** Laboratory objectives should be stated explicitly and matched to the chosen method. Skill acquisition, conceptual understanding, and design competence require different approaches (Feisel & Rosa, 2005).
- **Scaffolding.** Greater student autonomy requires structured support, such as guiding questions and staged tasks, to avoid overloading novices (Hofstein & Lunetta, 2004).
- **Preparation and follow-up.** Pre-laboratory and post-laboratory activities strengthen the link between the session and the theory (Agustian & Seery, 2017).
- **Feedback and assessment aligned with objectives.** Assessing only the final report tends to reward procedure-following; assessing planning, interpretation, and reflection supports deeper engagement.
- **Instructor and teaching assistant preparation.** The quality of facilitation strongly influences the outcome of inquiry-oriented formats.

Discussion. The reviewed literature indicates that the question "which laboratory method is best?" is poorly posed. The methods identified serve different purposes and differ in what they demand from students and instructors. Expository laboratories remain appropriate where the objective is the mastery of standard techniques or safety procedures, but relying on them alone leaves broader goals, such as scientific reasoning and problem solving, insufficiently addressed. This supports the long-standing critique that laboratory work should not be equated with verification exercises (Hodson, 1993).

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Inquiry- and problem-based approaches respond to this critique by moving cognitive effort to the planning and interpretation stages. Their effectiveness, however, is conditional. Without scaffolding, students may become confused or focus on completing tasks rather than understanding, which explains why reviews emphasize guided rather than fully open inquiry in early undergraduate courses (Hofstein & Lunetta, 2004). A gradual progression from guided to open formats across a program appears to be a practical strategy for balancing autonomy and support.

Technology-mediated formats extend what universities can offer, particularly where resources, safety, or scheduling constrain hands-on work. The evidence that virtual and remote laboratories can match traditional ones (Ma & Nickerson, 2006; Brinson, 2015) suggests that institutions with limited equipment need not treat simulation as a lesser option. Nevertheless, the objectives must determine the format: if the goal includes hands-on skills, physical experience remains necessary, and blended designs offer a reasonable compromise (de Jong et al., 2013).

For higher education institutions, several practical implications follow. Curricula should specify what each laboratory course is meant to develop and select methods accordingly. Laboratory manuals can be redesigned to include pre-laboratory tasks and questions that require reasoning rather than only data recording. Instructors and assistants need training in facilitation. Digital resources can be integrated as preparation or extension rather than replacing all practical work.

Limitations and directions for further research. This review is narrative and does not provide quantitative effect sizes. Comparisons across disciplines are cautious because laboratory goals differ between, for example, chemistry, physics, and engineering. Future empirical studies in local institutional contexts, using comparable outcome measures such as conceptual tests, practical assessments, and student perception surveys, would clarify which methods work best under specific resource conditions.

Conclusion. Laboratory classes in higher education can be conducted through expository, inquiry-based, problem- or project-based, and technology-mediated methods, each with distinct advantages and constraints. The effectiveness of laboratory instruction depends less on the specific label of the method than on the alignment between learning outcomes, task design, scaffolding, preparation, and assessment. A well-planned combination of methods, moving from guided to more open work and integrating physical and virtual environments, offers the most promising path for improving the quality of laboratory teaching in universities.

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